WETENSCHAPPELIJK EN TECHNISCH CENTRUM VOOR HET BOUWBEDRIJF

CRITERIA FOR THE AVOIDANCE OF MOULD GROWTH IN DWELLINGS

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1. ABSTRACT

Over the last few years frequent cases of mould growth in dwellings have occurred. The problem is essentially due to an excessive moisture content of the building elements, which can result from hygroscopic adsorption or from frequent surface condensation. In order to restrict the hygroscopic moisture content of materials, the relative humidity of the indoor air must be limited.

Surface condensation occurs when the surface temperature of a building element drops below the dew point of the air. Surface temperatures and the dew point of the indoor air are influenced by a great number of parameters such as : indoor and outdoor temperatures, outdoor vapour pressure, vapour production inside the dwelling, thermal resistance of the building elements, relative position of the wall in the room, ventilation input, presence of cold elements, etc...

The temperature factor τ of a building element takes all these parameters into account. If one wishes to avoid, or to limit, surface condensation, a sufficiently high τ-value must be obtained. Increasing τ-values lead to stricter building performance requirements and to less severe requirements as regards occupation conditions.

On the basis of statistical data on the indoor climate in dwellings and taking into account the presence of double glazing, a minimum τ-value of 0.7 to limit surface condensation is proposed.

Thermal bridges seem to be problematic building details. A minimum τ-criterion of 0.7 leads to better thermal insulation of these details.

2. INTRODUCTION

Over the last few years mould growth has frequently caused building damage. It is notable that mould growth occurs essentially in room corners and, in certain cases, behind furniture. Bedrooms, bathrooms, kitchens and washrooms seem to be the most vulnerable rooms.

3. CONDITIONS FOR MOULD DEVELOPMENT

Important conditions for mould development on building elements are :

- an adequate nutritional base : mould needs small quantities of decomposable organic matter.
  It seems that even in very clean dwellings sufficient traces of dirt (handmarks) are present to allow mould development. Some wall finishes themselves provide a more or less adequate nutritional base;

- a relatively stable indoor climate;

- a sufficient quantity of moisture : mould spores draw the necessary water essentially from the base on which they develop. Fungal growth cannot take place in the absence of moisture.

Since an adequate nutritional base and a stable indoor climate are available in most dwellings, it is necessary to examine how moisture arises in building elements.

4. MOISTURE IN BUILDING ELEMENTS

A number of case studies have shown that a sufficiently high moisture content in building elements can result from :

- residual moisture : i.e. moisture remaining in the building elements at the end of the construction process. Estimations of the quantity of residual moisture in traditionally built new one-family houses indicate that 3000 to 5000 litres of water remain to be evaporated after construction;

- the hygroscopic moisture content of hygroscopic materials which remain in humid surroundings for a considerable time;

- frequent surface condensation on porous materials followed by poor drying conditions.

The factors mentioned above can lead to an excessive moisture content in building elements, which creates favourable conditions for fungal growth.

It is therefore necessary to take measures

- to accelerate the evaporation of residual moisture,
- to limit hygroscopic moisture content,
- to limit or to avoid surface condensation.

Favourable drying conditions for the residual moisture content require :

- that vapourtight wall finishes (certain paints, plastified wallpaper, etc.) should only be applied on sufficiently dry walls;

- that the building should be both well ventilated and adequately heated.

To minimize hygroscopic moisture content long periods of high relative humidity in the indoor air must be avoided. Therefore the vapour content x of the indoor air should not be allowed to exceed the limit value corresponding to a given indoor temperature.
It is accepted that the weekly mean value of the relative humidity of the indoor air (φ_{im}) should not be higher than 80 %.

In order to avoid or to limit surface condensation :

- the surface temperatures in the room must not be too low. This requires a good level of thermal insulation and an adequate indoor temperature;

- the dew point of the indoor air must be sufficiently low, i.e. the vapour content x of the room air must be restricted.

5. VAPOUR CONTENT OF INDOOR AIR

5.1. Theoretical approach (steady state conditions)

5.1.1. No condensation in the room

Under steady state conditions the vapour mass evacuated by the ventilation per unit of time is equal to the sum of the vapour mass introduced by the fresh air intake per unit of time and the vapour mass produced in the room.

A consideration of this moisture balance leads to the expression below :

$$x_i = x_e + \frac{D.R_D.T_i}{n.V_L.p_a}\left(x_e + \frac{R_L}{R_D}\right) \qquad (1) \qquad (kg/kg)$$

5.1.2. With surface condensation in the room

The condensation process removes a certain quantity of moisture from the room air. Thus the moisture balance given in 5.1.1. must include an additional term, i.e. the quantity of moisture condensing per unit of time on a given surface A (m^2) in the room.

The new moisture balance leads to the expression :

$$x_i = x_e + \frac{D.R_D.T_i}{n.V_L.p_a}\left(x_e + \frac{R_L}{R_D}\right) - \frac{3600.R_L.T_i.\beta_i.\Sigma A}{n.V_L} \cdot \frac{(x_i - x_{sA})\left(x_e + \frac{R_L}{R_D}\right)}{\left(x_i + \frac{R_L}{R_D}\right)\left(x_{sA} + \frac{R_L}{R_D}\right)} \qquad (2) \qquad (kg/kg)$$

Assuming that $x_i^2 \simeq x_i\ x_e$

and with : $x_e + \frac{D.R_D.T_i}{n.V_L.p_a}\left(x_e + \frac{R_L}{R_D}\right) = x_i^\circ$, i.e. the value of x_i without condensation in the room (see expression 1), expression (2) becomes :

$$x_i = \frac{x_i^\circ + \frac{3600.R_D.T_i\ x_{sA}\beta_i\Sigma A}{n.V_L} \cdot \frac{x_e + R_L/R_D}{x_{sA} + R_L/R_D}}{1 + \frac{R_D.T_i}{nV_L}\left(x_e + \frac{R_L}{R_D}\right)\left[\frac{3600\beta_i\Sigma A}{x_{sA}+R_L/R_D} - \frac{D}{p_a.R_L/R_D}\right]} \qquad (3) \qquad (kg/kg)$$

If one assumes further that :

$$\frac{D}{p_a.R_L/R_D} \simeq 0$$

$$\frac{x_e + R_L/R_D}{x_{sA} + R_L/R_D} \simeq 1$$

expression (3) becomes :

$$x_i = \frac{x_i^\circ + 3600.T_i.R_D.\beta_i.x_{sA}\frac{\Sigma A}{n.V_L}}{1 + 3600.T_i.R_D.\beta_i\frac{\Sigma A}{n.V_L}} \qquad (4) \qquad (kg/kg)$$

5.1.3. Discussion

1° The x_i-values obtained from expressions (1) and (4) are valid under steady state conditions, i.e. with constant values for D, T_i and n (e.g. bedrooms); this represents the highest possible values which would be attainable in reality.

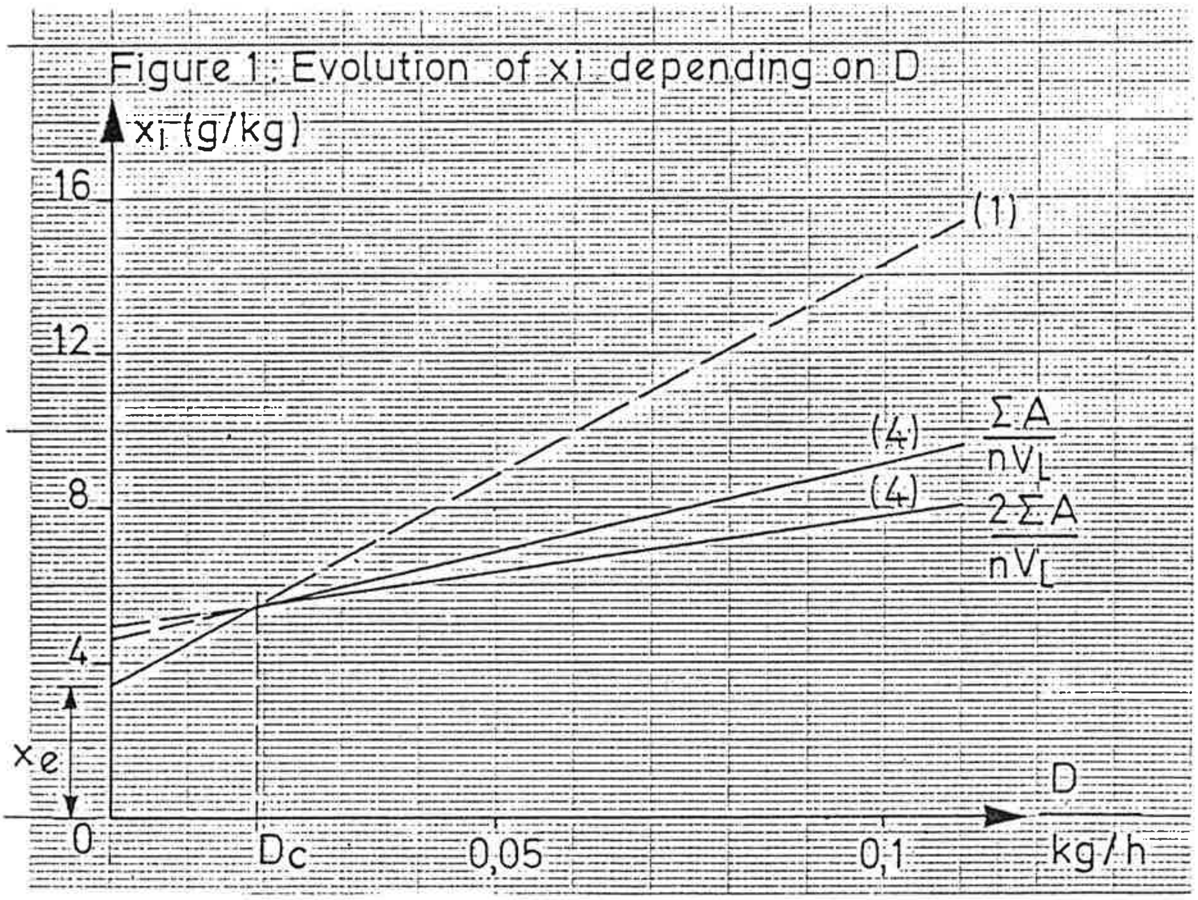
2° Formulae (1) and (4) indicate that the vapour content of the indoor air depends on the following factors :

- without condensation in the room :
  x_e, D, T_i, nV_L
- with condensation in the room :
  x_e, D, T_i, nV_L, x_{sA} and ΣA

Since x_{sA} depends on the surface temperatures in the room, which are determined by T_i, T_e, U and h_i, one can conclude that the following factors are of importance :

- x_e and T_e (characteristics of the outdoor climate)
- U and ΣA (characteristics of the building elements)
- D, T_i, nV_L (characteristics of the building occupation)
- h_i depends on the relative position of the surface A in the room

3° The evolution of expressions (1) and (4) is illustrated in graph 1.



One finds that :

- an increase in vapour production D (kg/h) at a constant ventilation flow nV_L (m^3/h), leads to an increase in x_i,
- surface condensation occurs at a given value of vapour production D_C in the room,
- when surface condensation occurs x_i reaches lower values than when no condensation occurs,
- x_i decreases if the proportion of cold surfaces increases.

4° Graph 2 shows x_i plotted against the ventilation rate n.

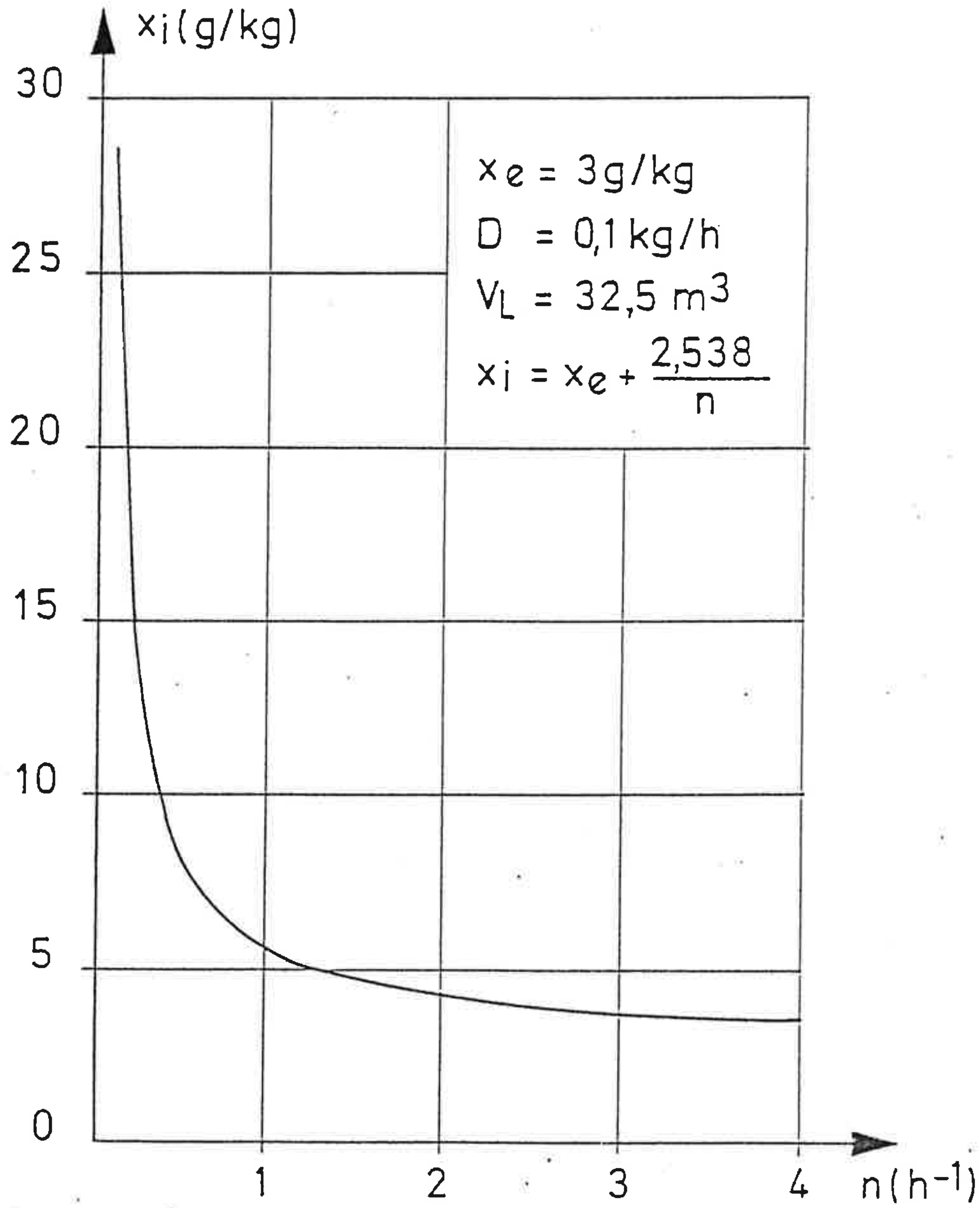


Figure 2 : evolution of x_i depending on n

One notes that :

- very low ventilation rates lead to very high values of x_i,
- if the room is well ventilated, a further increase of the ventilation rate has very little influence on x_i. On the other hand energy consumption for space heating increases.

In practice n should vary between 0.5 and 1 (h^{-1}) depending on the room occupation conditions.
We have measured air infiltration rates of about 0.25 h^{-1} in new buildings with weatherstripped windows.

5.2. Results of measurements of the indoor climate in dwellings (*)

Findings based on a large number of measurements of the vapour content of the indoor air in occupied dwellings, and on the statistical interpretation of the results, have shown that :

- the 95% limit for the mean weekly values of x_i can be expressed by the following equations :

  for $\theta_e \geq 0$ °C : $x_i - x_e = 5.17 - 0.13\ \theta_e$ (g/kg) (5a)

  for $\theta_e \leq 0$ °C : $x_i - x_e = 5.17$ (g/kg) (5b)

- an approximate value of the mean temperature in unheated rooms of occupied dwellings is provided by expression (6). The dwellings are insulated at a reasonable level

  $\theta_i = 13.05 + 0.37\ \theta_e$ (°C) (6)

5.3. Interpretation and conclusions

1° The vapour production of a normal adult involved in light activity is in the order of 0.05 kg/h.

2° Due to physiological considerations (limitation of the CO_2 concentration : < 0.50 %) it is absolutely necessary to obtain a minimum ventilation flow of 5 m^3/h per adult.
From the point of view of comfort a minimum ventilation flow of 20 m^3/h per adult is required (to remove odours - CO_2 concentration < 0.15 %).
Assuming that D = 0.05 kg/h.pers and nV_L = 5 and 20 m^3/h.pers, one obtains respectively D/nV_L = 0.01 kg/m^3 and 0.0025 kg/m^3.

(*) the measurements were carried out by the University of Leuven (KUL) - Building Physics Department

3° If we accept a minimum ventilation flow of 10 m^3/h.pers, it follows from 1 and 2 above that $D/nV_L = 0.005$ kg/m^3.

4° The value of D/nV_L can be derived from the results of the measurements. Considering $\theta_e \leq 10$ °C (winter conditions), it seems that the 95% limit for $D/nV_L \geq 0.005$ kg/m^3. Thus the results indicate that the ventilation flow is too low in certain dwellings.

5° The greater the value of D/nV_L, the greater the value of x_i which leads to :

- an increase in the relative humidity of the room air and consequently to an increase in the hygroscopic moisture content of hygroscopic materials and furniture,
- an increase in the risk of surface condensation in the room.

6° Once x_i is known one can calculate the dew point of the room air θd (°C). If there is an area or a point in the room where the surface temperature θ_{oi} (°C) is below the dew point of the room air, surface condensation will occur on that area or point.
Thus the following condition must be satisfied if surface condensation is to be avoided :

$$\boxed{\theta_{oi} > \theta d} \quad (°C) \qquad (7)$$

7° Temporary surface condensation in certain rooms and at certain moments (kitchen when cooking, bathroom when bathing, etc.) can be reasonably considered to be unavoidable.
It is important, however, that drying conditions be optimized in such rooms once the period of high vapour production is over.

6. THE TEMPERATURE FACTOR τ

6.1. Definition

The temperature factor τ defines the difference between the temperature θ_{oi} at any point on the inner surface of the room envelope and the outdoor temperature θ_e for a difference of 1K between the indoor and the outdoor temperature.

Thus $$\tau = \frac{\theta_{oi} - \theta_e}{\theta_i - \theta_e} \qquad (8)$$

In what follows it is assumed that the comfort temperature θ_{rs} equals the indoor temperature θ_i.

6.2. Requirement for the avoidance of surface condensation

The general criterion for avoiding surface condensation is given by $\theta_{oi} > \theta d$. This requirement has to be fulfilled at any point of the room. Thus also at the point where θ_{oi} is minimal. So we can write that in order to avoid surface condensation we must have $\theta_{oi\ min} > \theta d$.

From expression (8) one obtains :

$$\frac{\theta_d - \theta_e}{\theta_i - \theta_e} < \frac{\theta_{oi\ min} - \theta_e}{\theta_i - \theta_e} \qquad (9)$$

or $$\frac{\theta d - \theta_e}{\theta_i - \theta_e} < \tau_{min} \qquad (10)$$

6.3. Temperature evolution in a wall (steady state conditions)

The graph (R ; θ) in figure 3 illustrates the temperature evolution in a wall for 2 values of R_i ($R_i = 1/h_i$).
From this figure one obtains

$$\frac{\theta_{oi} - \theta_e}{\theta_i - \theta_e} = \frac{R_w + R_e}{R_T} = \frac{R_T - R_i}{R_T} = \tau \qquad (11)$$

With $\theta_{oi\ min}$ we can then deduce that

$$\frac{\theta_{oi\ min} - \theta_e}{\theta_i - \theta_e} = \frac{R_{T\ min} - R_i}{R_{T\ min}} = \tau_{min} \qquad (12)$$

Therefore surface condensation can be avoided if the following criterion is respected :

$$\boxed{\frac{\theta_d - \theta_e}{\theta_i - \theta_e} < \frac{\theta_{oi\ min} - \theta_e}{\theta_i - \theta_e} = \frac{R_{T\ min} - R_i}{R_{T\ min}} = \tau_{min}} \qquad (13)$$

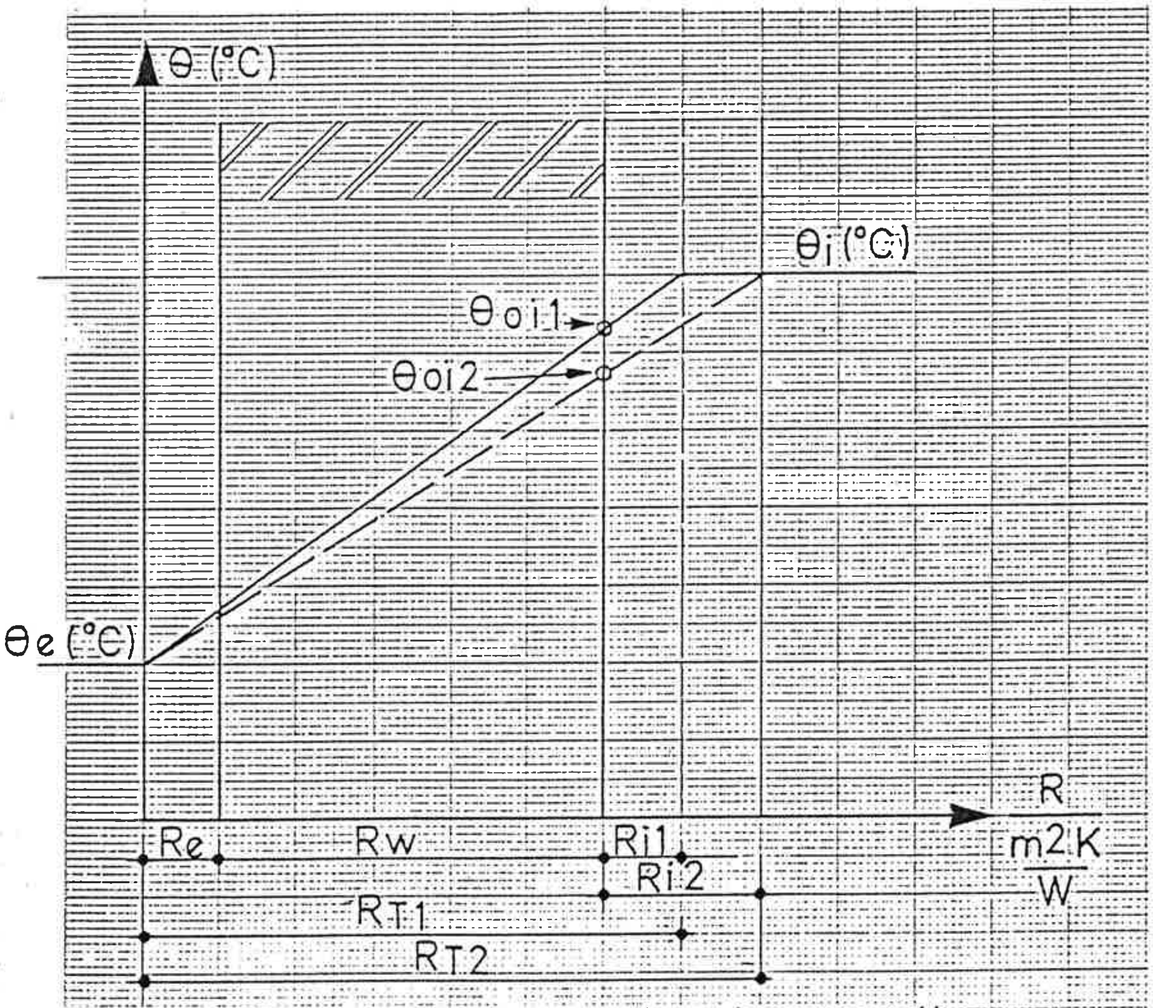


Figure 3 : Temperature evolution in a wall

6.4. Use of the temperature factor

Expression (12) enables one to calculate the τ_{min}-value of a building element. It is rarely possible to define $R_{T\ min}$ accurately at thermal bridges. Nevertheless computer programs based on the finite differences or the finite elements method can be used to calculate $\theta_{oi\ min}$ with accuracy. Equation (12) is used for such building elements. Another difficulty is the correct determination of an accurate value for R_i.

When checking θ_{oi} for thermal bridges (situated in room corners) we assume a R_i-value of 0.2 m^2K/W (i.e. h_i = 5 W/m^2K; in certain cases, e.g. behind furniture, h_i drops to lower values).

Fig. 3 shows that θ_{oi} drops if R_i increases.

6.5. Discussion

1° The general condition given in (13) takes into account :

- the outdoor climate (θ_e)
- the indoor climate (θ_i and θd, θd depends on x_i)
- the thermal insulation characteristics of the building elements ($R_{T\,min} = 1/U_{max}$)
- the relative position of the element in the room (R_i)

2° Condition (13) is independent of real temperature conditions because the result is expressed in terms of the unit temperature difference between the outdoor and indoor environments.

3° The calculation of $R_{T\,min}$ for plane building elements does not cause any difficulty. The determination of $\theta_{oi\,min}$ for thermal bridges requires the use of an adequate calculation program.

7. MINIMUM τ-FACTOR FOR DWELLINGS

7.1. Assumptions

In order to fix the minimum temperature factor applying to dwellings, a series of calculations were made based on the following assumptions :

1° the x_i-values considered correspond to the 95% limit for the weekly mean values calculated from the measurements made in dwellings (§ 5.2.). Thus the calculations are based on high D/nV_L-values.

2° The x_e-values correspond to φ_e = 90 %. Periods of high outdoor relative humidity are very frequent in winter.

3° The minimum θ_i-values correspond to the mean values measured in unheated rooms of normally occupied dwellings.

4° The dwellings are fitted with normal double glazing (D.G.) with a nominal U_{DG}-value of 3 W/m²K (with h_i = 8 W/m²K). However it is assumed that the glazing is relatively well heated on the inside and therefore that $h_i \simeq 10$ W/m²K rather than 8 W/m²K. Consequently the R_T-value of the glazing is 0.308 m²K/W. Under these conditions the τ-factor of the double glazing is

$$\tau_{DG} = \frac{R_{T\,min} - R_i}{R_{T\,min}} = \frac{0.308 - 0.1}{0.308} = 0.675$$

7.2. Appreciation criteria

The following appreciation criteria are introduced :

1° with acceptable relative humidities φ_i of the indoor air no condensation must occur on opaque building elements.
It is unreasonable to accept very high φ_i-values since such conditions lead to high hygroscopic moisture contents in hygroscopic building materials and furniture and consequently to favourable conditions for mould development.
It is accepted that the weekly mean φ_i-value should not exceed 80 %;

2° if surface condensation occurs, the phenomenon should start on the glazing before it appears on opaque elements, i.e. it is assumed that the glazing is the coldest surface in a dwelling. Thus the glazing fulfils the role of a safety valve when surface condensation occurs.
Since condensation on glazing is clearly perceptible, the phenomenon constitues an indication to the occupants that the indoor climate should be modified;

3° the above criteria indicate that the minimum τ-factor of opaque building elements must be greater than the τ-factor of the double glazing, thus

$$\tau_{min} > 0.657$$

7.3. Proposed minimum τ-factor

From the calculation results it was deduced that :

1° with given outdoor conditions, the minimum τ-factor required drops when the indoor temperature increases;

2° very high τ-factors ($\tau > 0.9$) are needed to avoid surface condensation in unheated rooms exposed to extremely low outdoor temperatures ($\theta_e = -10°C$);

3° in normally heated rooms (i.e. $\theta_i \geq 18°C$) surface condensation occurs on opaque elements if $\tau < 0.657$;

4° the x_i-values considered lead to surface condensation on double glazing if $\theta_i \leq 16°C$;

5° the x_i-values lead to relative humidities of about 90 % in occupied unheated rooms;

6° the x_i-values lead to D/nV_L-values greater than 0.005 kg/m^3, i.e. to more unfavourable values from a hygienic point of view, than those acceptable for long occupancy periods.

Given the considerations above and bearing in mind the practical difficulties involved in insulating thermal bridges (existing buildings) a minimum τ-factor for opaque elements of 0.7 is proposed.

8. THERMAL BRIDGES

A systematic study of thermal bridges which frequently occur in structural concrete elements reveals that the τ-factor of such thermal bridges lies between 0.45 and 0.60.

Measures should be taken to correct the situation. Thermal bridges can be neutralized by applying three basic methods :

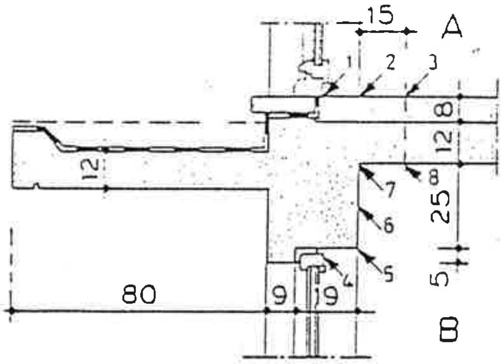
- internal thermal insulation,
- external thermal insulation,
- a thermal break

Nevertheless one has to bear in mind that isotherms are attracted by the insulation layer which, in the case of internal insulation, can sometimes generate critical situations. Internal insulation should therefore be avoided.

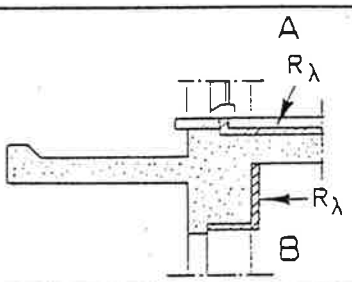
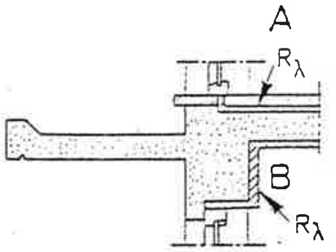
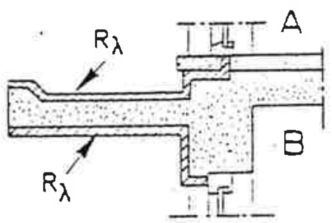
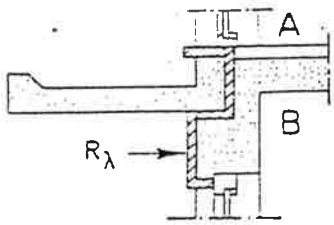
When applying insulation externally it is absolutely necessary to envelop the thermal bridge completely. Partial envelopment frequently causes a displacement of the cold surfaces, thus creating critical situations elsewhere.

When providing thermal breaks attention should be paid to the construction aspects of the problem. Whatever the solution adopted, the insulation layer should generally have a thermal resistance greater than 0.5 m^2K/W in order to obtain a minimum τ-factor of 0.7.

Table I lists the τ-factor of some insulation combinations applying to overhanging concrete terraces



1-2-3-4-5-6-7-8 points where τ is calculated

N°	Insulation combination	R_λ (m^2K/W)	Temperature factor τ in A	Temperature factor τ in B
1		0	τ_1 = 0.585 τ_2 = 0.80 τ_3 = 0.91	τ_4 = 0.455 τ_5 = 0.61 τ_6 = 0.55 τ_7 = 0.60 τ_8 = 0.84
		1,0	τ_1 = 0.705 τ_2 = 0.905 τ_3 = 0.955	τ_4 = 0.785 τ_5 = 0.98 τ_6 = 0.885 τ_7 = 0.545 τ_8 = 0.77
2		0,5	τ_1 = 0.57 τ_2 = 0.735 τ_3 = 0.755	τ_4 = 0,725 τ_5 = 0.95 τ_6 = 0.81 τ_7 = 0.83 τ_8 = 0.92
		1,0	τ_1 = 0.56 τ_2 = 0.715 τ_3 = 0.735	τ_4 = 0.785 τ_5 = 0.98 τ_6 = 0.88 τ_7 = 0.89 τ_8 = 0,945
3		0.5	τ_1 = 0.70 τ_2 = 0.87 τ_3 = 0.945	τ_4 = 0.655 τ_5 = 0.755 τ_6 = 0.72 τ_7 = 0.75 τ_8 = 0.90
		1,0	τ_1 = 0.73 τ_2 = 0.895 τ_3 = 0.955	τ_4 = 0,715 τ_5 = 0.795 τ_6 = 0.765 τ_7 = 0.79 τ_8 = 0.915
4		0.5	τ_1 = 0.73 τ_2 = 0.90 τ_3 = 0.96	τ_4 = 0.685 τ_5 = 0.78 τ_6 = 0.765 τ_7 = 0.805 τ_8 = 0.925
		1.0	τ_1 = 0.76 τ_2 = 0.925 τ_3 = 0.97	τ_4 = 0.76 τ_5 = 0.835 τ_6 = 0.825 τ_7 = 0.86 τ_8 = 0.945

9. OCCUPATION CONDITIONS

The question remains as to how the indoor climate should be adapted in order to avoid condensation, assuming that all the opaque building elements meet the minimum requirement $\tau = 0.70$.

We have already considered above that :

- $\varphi_{im} \leq 80$ % : to limit the hygroscopic moisture content of building elements and furniture

- $D/nV_L \leq 0.005$ kg/m³ : to create minimum hygienic conditions for long periods of occupation

An occupation condition can be defined on the basis of the φ_{ic}-value at which condensation occurs on opaque elements.
The calculation results listed in table II are based on the following considerations :

- for a range of outdoor temperatures θ_e, formula 6 is applied to estimate the indoor temperature θ_{inh} in unheated but insulated rooms;

- all the opaque parts of the room have a temperature factor $\tau = 0.70$. $\theta_{oi\,min}$ is derived from formula (I.2);

- the dew point of the room air should be at least equal to $\theta_{oi\,min}$. Once the dew point is known the saturation vapour content x_{sA} on opaque elements can be calculated;

- x_{si} follows from θ_{inh}.

Table II

θ_e (°C)	x_e g/kg	$\theta_{i\,nh}$ (°C)	$\theta_{oi\,min}$ (°C)	x_{sA} (g/kg)	x_{si} (g/kg)	φ_{ic} %	$\frac{D}{nV_L}$ (kg/m³)
- 10	1.44	9.35	3.54	4.88	7.31	67 %	0.0042
- 5	2.22	11.2	6.34	5.93	8.27	72 %	0.0045
0	3.40	13.05	9.14	7.20	9.38	77 %	0.0046
+ 5	4.86	14.9	11.93	8.71	10.54	82.9 %	0.0047
+ 10	6.86	16.75	14.72	10.42	11.93	87.6 %	0.0043

The figures in table II show that condensation occurs if $\varphi_i \simeq 77 + 1.05\ \theta_e$ (%). Occupants should therefore take measures to limit the indoor relative humidity to

$$\begin{cases} \varphi_i < 77 + 1.05\ \theta_e\ (\%) \\ \varphi_{im} \leq 80\ \% \end{cases}$$

From the D/nV_L-values obtained it follows that a ventilation flow somewhat higher than the minimum assumed is required in occupied unheated rooms. On the other hand the room should be lightly heated if the ventilation flow does not appreciably exceed this strict minimum.

10. CONCLUSIONS

Since thermal insulation of plane building elements is not usually a problem (high τ-values can be obtained), satisfying the minimum τ-requirement of 0.7 generally involves improved insulation of thermal bridges. Thermal improvement of existing dwellings, without adaptation of the existing thermal bridges, frequently leads to lower surface temperatures at these points, with surface condensation occurring on these surfaces before it appears on the glazing. If the phenomenon occurs frequently the moisture content of these elements rises to such an extent that favourable conditions for mould growth are created.

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12. NOMENCLATURE TABLE

V_L	(m^3)	room volume
D	(kg/h)	vapour production in the room
D_c	(kg/h)	D-value at which surface condensation starts
n	(h^{-1})	air change rate
T	(K)	absolute temperature