

Summary The standard prediction method for assessing the risk of condensation in layered structures in the steady state is discussed, and it is pointed out that this is essentially an analysis method for a case which has to be pre-defined. Designers may prefer to have methods of synthesising a construction which avoids condensation under given humidity and temperature conditions, or of finding the limiting conditions for condensation to be avoided with a given construction. Equations are presented for the calculation of the necessary thermal and vapour properties of layers added to existing designs in order to eliminate condensation risk and permit a chosen safety margin, and for calculation of the limits on humidity for elimination of condensation in a given construction. Examples are given to illustrate the use of the equations.

Condensation avoidance in layered structures: Synthesis of designs

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List of symbols

G_1, G_2	Vapour resistances in a layered structure, to the inside and outside respectively of a condensation site (GN s kg^{-1})
G'	Calculated vapour resistance of an added layer (GN s kg^{-1})
P_i, P_o	Water vapour pressures in inside and outside air (Pa)
P_i'	Required water vapour pressure in inside air (Pa)
P_x	Calculated vapour pressure at a condensation site (Pa)
P_{xs}	Saturated vapour pressure corresponding to t_x (Pa)
P_x'	Required vapour pressure at a condensation site (Pa)
R_1, R_2	Thermal resistances in a layered structure, to the inside and outside respectively of a condensation site ($\text{m}^2\text{K W}^{-1}$)
R'	Calculated thermal resistance of an added layer ($\text{m}^2\text{K W}^{-1}$)
R_{si}, R_{so}	Inside and outside surface thermal resistances ($\text{m}^2\text{K W}^{-1}$)
t_i	Inside environmental temperature ($^{\circ}\text{C}$)
t_i'	Required inside environmental temperature ($^{\circ}\text{C}$)
t_o	Outside air temperature ($^{\circ}\text{C}$)
t_x	Calculated structural temperature at a condensation site ($^{\circ}\text{C}$)
t_{xd}	Dew point temperature corresponding to P_x ($^{\circ}\text{C}$)
t_x'	Required structural temperature at a condensation site ($^{\circ}\text{C}$)
ΔP	$P_i - P_o$ (Pa)
ΔP_x	$P_x - P_x'$ (Pa)
Δt	$t_i - t_o$ (K)
Δt_x	$t_x' - t_x$ (K)
ΣG	$G_1 + G_2$ (GN s kg^{-1})
ΣR	$R_{si} + R_1 + R_2 + R_{so}$ ($\text{m}^2\text{K W}^{-1}$)

1 Introduction

The accepted method of predicting condensation risk in structures has the advantage of simplicity, but it also has a number of disadvantages: it deals only with the steady state (which almost never exists in practice), it implies the possibility of the existence of vapour pressures higher than the local saturation vapour pressure, and it is a method of analysis rather than synthesis. The first two disadvantages

are technical consequences of the method, and permit the simplicity of a linear, 'once-through' calculation. The third disadvantage presents an inconvenience to the designer of a construction, who may frequently wish to know the necessary vapour or thermal properties of a design in order to avoid condensation, rather than wishing to know the condensation performance of a specified design. This paper discusses how the required properties of a construction may be synthesised to a limited extent, under the precondition that condensation is not predicted to occur under specific conditions.

2 Calculation procedure for analysis

The procedure as described in reference publications^(1,2,3) deals with two aspects of the properties of layered structures: the heat flow aspect, as a set of thermal resistances in series, with a temperature distribution which is determined by the relative magnitudes of the individual thermal resistances of the layers, and by the order of their appearance in the construction; secondly, the vapour flow aspect, as a set of vapour resistances in series (whose values are assumed to be independent of vapour pressure), with a vapour pressure distribution which is determined by the relative magnitudes of the resistances and their order. By converting the vapour pressures to dew point temperatures and comparing them with the structural temperatures, the existence and extent of condensation risk can be assessed. In each case, a change in either the thermal or vapour resistance of any one layer will produce a redistribution of the temperature or vapour pressure levels in all layers, so that the whole calculation must be repeated. The accuracy of the results depends on the accuracy with which the thermal and vapour properties of the materials are known. Where there is an uncertainty or a range of possible values, the results of the calculation may be strongly affected by the specific values chosen, as has been demonstrated in a previous paper⁽⁴⁾. It is also a considerable simplification to regard the vapour resistance values as being constant: results have been published which show the behaviour for plywood, for example, to be very nonlinear, with the value of vapour resistance dependent on the local relative humidity⁵.

The procedure described in the *CIBSE Guide*⁽³⁾ involves the conversion of the values of structural temperature to the corresponding saturated vapour pressures. These are then to be compared with the actual vapour pressure levels predicted

from the vapour resistances of the layers. If the actual vapour pressure at any point is predicted to be greater than the saturated vapour pressure corresponding to the structural temperature at that point, then condensation is predicted. This method, working in terms of vapour pressure, is just as valid as the alternative method described here, in terms of temperature. The main factor influencing the choice of this method for the *Guide* may lie in the availability of an accurate equation for converting from absolute temperature to saturated vapour pressure (equations C1.9 or A10.24). Patterns and levels expressed in terms of vapour pressure are probably rather less meaningful for most people in practice than when expressed in terms of temperature.

3 Synthesis of layer properties

If the calculation procedure predicts that condensation will occur for a specific construction and set of inside and outside air conditions, there are a number of ways in which the design of the construction may be modified so as to reduce or, more desirably, to eliminate the risk and to include a margin of safety.

Consider a layered construction with thermal and vapour conditions as shown in Figure 1. Point I in Figure 1 is at the internal environmental temperature t_i and the internal air vapour pressure P_i . Point O is at the outside air temperature t_o and the outside air vapour pressure P_o . The point X may lie at any position between the inside surface and the outside surface, and is to be regarded as a possible condensation site. The total thermal and vapour resistances between I and X are $(R_1 + R_{si})$ and G_1 respectively; between X and O they are $(R_2 + R_{so})$ and G_2 respectively. The thermal influence of the surface resistance can reasonably be neglected, being equivalent to a layer of plaster less than 1 mm thick.

The steady-state temperature and vapour pressure at X will be given by:

$$t_x = t_i - \Delta t(R_1 + R_{si})/\Sigma R = t_o + \Delta t(R_2 + R_{so})/\Sigma R \quad (1)$$

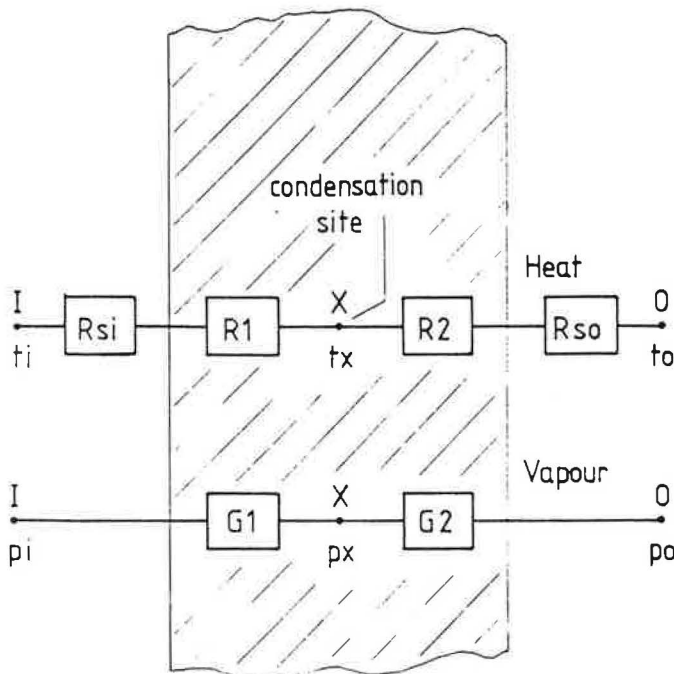


Figure 1 Thermal and vapour resistances, temperatures and vapour pressures in the original layered construction

and

$$P_x = P_i - \Delta P G_1 / \Sigma G = P_o + \Delta P G_2 / \Sigma G \quad (2)$$

The vapour pressure P_x at X corresponds to a certain value of dew point temperature, say t_{xd} , which can be found from psychrometric tables, charts or equations⁶. If $t_{xd} > t_x$, then condensation is predicted at the plane X. In some cases there may be more than one interface where the existence of condensation is predicted. In such a case the plane X should be taken as the interface where the predicted actual vapour pressure apparently exceeds the saturated vapour pressure by the greatest amount. To avoid this, we may modify the design of the construction in a number of ways. The two simplest extremes would be the addition of a vapour barrier or vapour check layer of negligible thermal resistance at the inside surface, and the addition of a thermal barrier (i.e. an insulation layer) of negligible vapour resistance at the outside surface. These would have the effects, respectively, of altering the vapour pressure distribution without affecting the temperatures, and of altering the temperature distribution without affecting the vapour pressures. In one case the dew point temperatures would be lowered; in the other, the structural temperatures would be raised. Each of these procedures can be considered in turn, to examine the performance which is required of the additional layer.

If the point X is at the inside surface and $t_{xd} > t_x$ then surface condensation is predicted rather than interstitial (or internal) condensation. In this special case, the addition of a pure vapour barrier to the inside surface will *not* eliminate the condensation, since the vapour pressure at X will still be the same as that of the adjacent inside air. The condensation risk at the surface could be eliminated by the second method, the addition of a thermal insulation layer towards the outside surface of the construction; this could raise the temperature of the inside surface above the local dew point temperature.

3.1 Adding a vapour barrier to the warm side

If a vapour barrier of resistance G' is added as in Figure 2, the vapour pressure distribution will be altered so that the vapour pressure at X is reduced to a new value P'_x . For a 'pure' vapour barrier there will be no change in the temperatures, so t_x will be given by equation 1 as before, but

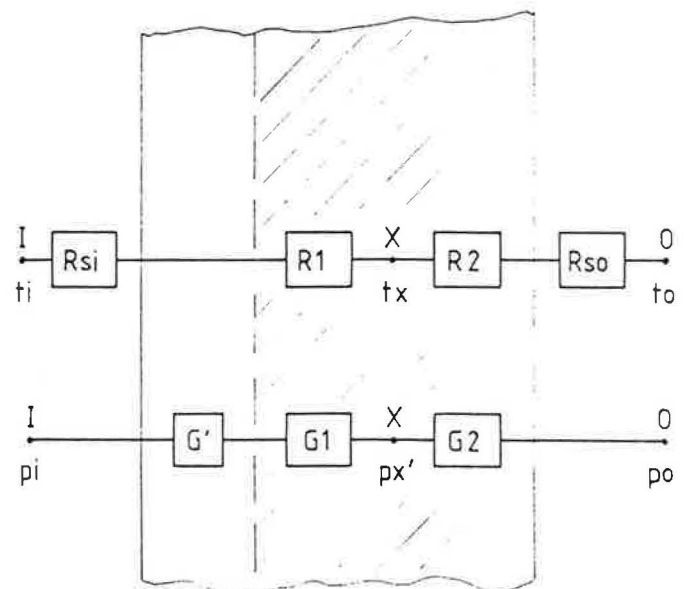


Figure 2 Vapour conditions modified by the addition of a pure vapour resistance G' to the inside surface

the new vapour pressure P'_x will be given by equation 3:

$$P'_x = P_i - \Delta P(G_1 + G')/(G' + \Sigma G)$$

$$= P_o + \Delta P G_2/(G' + \Sigma G) \quad (3)$$

Rearranging equation 3 for G' gives

$$G' = \frac{P_i G_2 + P_o G_1 - P'_x \Sigma G}{(P'_x - P_o)} \quad (4)$$

Alternatively, if the vapour barrier is regarded as being required to reduce the vapour pressure at X by an amount $\Delta P_x = P_x - P'_x$, then it can easily be shown that G' is given by the expression:

$$G' = \frac{\Delta P_x (\Sigma G)^2}{\Delta P G_2 - \Delta P_x \Sigma G} \quad (5)$$

It should be noted that equations 4 and 5 are not valid for cases with impermeable layers such as glass panes.

3.2 Adding a thermal barrier to the cold side

In the previous section it was possible to consider the addition of a vapour barrier to the warm side (i.e. the inside surface) of a construction as being a practical measure. Such barriers are normally thin plastic films, and the existing structure would provide protection from the weather. In practice it is not normally practical simply to add a layer of thermal insulation to the outside surface of a wall without extra protection against the weather and mechanical damage. It would therefore be necessary to take account of the thermal and vapour properties of such a protective layer. The theoretical aspects of the simple case are treated here.

In this case, illustrated in Figure 3, the temperature distribution will be altered, so that t_x will increase to a new value t'_x . For a 'pure' thermal barrier of resistance R' and with negligible vapour resistance, t'_x will then be given by the expression:

$$t'_x = t_i - \Delta t(R_1 + R_{si})/(R' + \Sigma R)$$

$$= t_o + \Delta t(R' + R_2 + R_{so})/(R' + \Sigma R) \quad (6)$$

Rearranging this for R' gives:

$$R' = \frac{t'_x \Sigma R - t_i(R_2 + R_{so}) - t_o(R_1 + R_{si})}{(t_i - t'_x)} \quad (7)$$

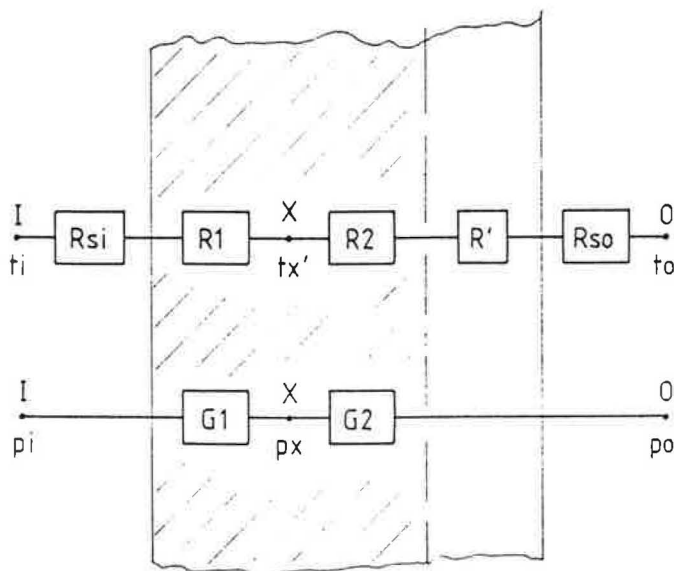


Figure 3 Thermal conditions modified by the addition of a pure thermal resistance R' to the outside surface

And, if we require the insulation to raise the temperature at X by an amount $\Delta t_x = t'_x - t_x$, then R' will be given by:

$$R' = \frac{\Delta t_x (\Sigma R)^2}{\Delta t (R_1 + R_{si}) - \Delta t_x \Sigma R} \quad (8)$$

which is analogous to equation 5.

3.3 Combinations of thermal and vapour barrier layers

In the cases described above, the extra layers were assumed to be either a pure vapour barrier or a pure thermal barrier. In practice this requirement may be satisfied for a vapour barrier by applying paint or a thin plastic film to an existing solid surface, which would give a vapour resistance without any significant extra thermal resistance. For a thermal barrier, forming a cavity between two existing layers would increase the thermal resistance with no significant extra vapour resistance.

In general, the net effect of adding a further layer to a structure depends upon the relative thermal and vapour resistivities of the material and of course upon its position in the structure. Materials with a large ratio of vapour to thermal resistivity should be placed near the inside surface. Materials with a small ratio of these resistivities should obviously be put near the outer surface. Table A10.4 of Reference 3 lists the vapour resistivities and thermal conductivities for a range of building materials. There are 28 cases where values are given for both the vapour resistivity (typical values in $\text{GN s kg}^{-1} \text{m}^{-1}$) and the thermal conductivity (in $\text{W m}^{-1} \text{K}^{-1}$) of a material. The product of these two quantities is of course equivalent to the ratio of vapour resistivity to thermal resistivity. The values of this ratio are listed in Table 1, and are expressed also as percentages of the mean value. The units used are irrelevant, since we are making comparisons between the different materials on the same basis. It can be seen from Table 1 that there are some materials for which the ratio is unusually high and some for which it is unusually low. If an extra layer is to be placed near the inside surface then it will reduce condensation risk only if the reduction of the dew point temperature at the critical point X by reducing the vapour pressure is greater than the reduction in the structural temperature at X. This requires a material with a high value of the ratio. Placing an extra layer near the outer surface reverses the criterion: we require that the rise in structural temperature at X due to the thermal insulating effect is greater than the rise in dew point temperature due to the vapour barrier effect. This requires a material whose ratio is small.

From Table 1 it can be seen that, apart from gravel concrete and dense pumice concrete (which are not suitable for sheet materials), the highest values are given by plywood and hardboard. We would expect film materials also to have high values, and calculations indicate that this is so, even if we associate an extra thermal surface resistance with their lowest resistance by conduction. As would also be expected, the lowest values are given by foamed plastics or fibrous insulation materials. It is notable that wood and plasterboard also have rather low values. As was mentioned in section 3.2, in practice some mechanical protection would be necessary for such materials when applied to the outer surface of a structure.

4 Temperature and humidity limits for condensation control

In some cases the design of the construction is fixed and it

Table 1 Comparison of the ratio of vapour resistivity to thermal resistivity for various materials⁽³⁾

Material	Density (kg m ⁻³)	Vapour resistivity Thermal resistivity	
		(GN s kg ⁻¹ m ⁻¹)	Percent of mean (%)
		(mK W ⁻¹)	
Common brick	1360	32.5	117
Brickwork	—	24.8	89
Brickwork	—	33.6	120
Concrete, gravel	2130	300	1080
Concrete, pumice	650	8.8	32
Concrete, pumice	840	11.2	40
Concrete, pumice	1140	18.0	65
Concrete, pumice	1580	80.5	289
Concrete, slag	1140	20.0	72
Concrete, aerated	520	6.0	22
Concrete, aerated	750	11.3	41
Concrete, aerated	950	16.5	59
Concrete, aerated	1350	24.8	89
Plaster	—	12.5	45
Plywood	—	72.8	261
Wood	—	7.0	25
Cork slab	128–230	1.8	6
Glass wool	1150	0.45	2
Mineral wool	—	0.24	1
Insulating fibreboard	—	1.1	4
Hardboard	—	67.6	242
Plasterboard	—	8.0	29
Strawboard	—	7.7	28
Woodwool/cement slab	380	2.0	7
Foamed phenolic	70–100	2.9	10
Foamed urea formaldehyde	12	1.1	4
Foamed polyurethane (open cell)	30–35	0.8	3
Foamed polystyrene	—	7.0	25
Mean values	—	27.89	100

is required to find the limits on the temperature and vapour pressure of the inside air for condensation to be avoided. If the outside condition is regarded as being fixed, the minimum value of inside temperature or the maximum value of inside air vapour pressure can be calculated. Referring again to Figure 1, we may wish to eliminate the condensation at the point X by raising the value of t_i . If the dew point corresponding to p_x is t_{xd} then we need to raise the structural temperature at X to at least this level. The minimum value of t_i will be given by

$$t'_i = \frac{t_{xd}\Sigma R - t_o(R_1 + R_{si})}{R_2 + R_{so}} \tag{9}$$

If the calculation is to be done in terms of the change Δt_i which is required at the inside in order to produce a change Δt_x at the point X, this is given by

$$\Delta t_i = \frac{\Delta t_x \Sigma R}{R_2 + R_{so}} \tag{10}$$

Alternatively, if the condensation is to be prevented by reducing the humidity of the inside air, the maximum permissible vapour pressure can be calculated. If we wish to reduce the vapour pressure at X to a level P'_x by reducing the inside air vapour pressure to P'_i , then P'_x will be given by

$$P'_i = \frac{P'_x \Sigma G - P_o G_1}{G_2} \tag{11}$$

and to produce a change ΔP_x at X will require a change ΔP_i given by

$$\Delta P_i = \Delta P_x \Sigma G / G_2 \tag{12}$$

The corresponding relative humidity or moisture content can then be found in the usual way from the combination of temperature and vapour pressure. There is of course no guarantee that these calculated limits on the inside conditions can be maintained in practice, but it is of some importance to designers to be aware of what these limits are.

5 Example calculations

To illustrate the use of the equations presented here, two example calculations are given. The first case taken is similar to one described in Reference 3, consisting of a wall with two leaves of brickwork, separated by a layer of insulating fibreboard. It should be noted that this construction is chosen for illustrative purposes only. The air conditions and material properties assumed are listed in Table 2.

The structural temperatures, dew point temperatures and vapour pressures are set out in Table 3. The two points of interest are the interfaces of the fibreboard with the inner and the outer leaves of brickwork.

At the interface with the inner leaf we have $t_x > t_{xd}$ and of course $P_x < P_{xs}$ so that condensation is not predicted at that point. At the interface with the outer leaf $t_x < t_{xd}$ and

Table 2 Details of the case for the example calculation. Inside air: 21°C dry bulb, 1457 Pa vapour pressure; Outside air: 2°C dry bulb, 593 Pa vapour pressure.

Material	Thickness (mm)	Thermal		Vapour	
		resistivity (mK W ⁻¹)	resistance (m ² K W ⁻¹)	resistivity (GN s kg ⁻¹ m ⁻¹)	resistance (GN s kg ⁻¹)
R_{si}	—	—	0.120	—	0
Inner leaf	110	1.61	0.177	40	4.4
Insulating fibreboard	50	17.54	0.877	20	1.0
Outer leaf	110	1.19	0.131	40	4.4
R_{so}	—	—	0.060	—	0
Totals			1.365		9.8

Table 3 Temperature and vapour pressure results for the example calculation

Interface of fibreboard with:	t_x (°C)	P_{xs} (Pa)	P_x (Pa)	t_{xd} (°C)
Inner leaf	16.87	1920	1069	7.96
Outer leaf	4.66	852	981	6.70

- t_x Predicted structural temperature at the interface
 P_{xs} Saturated vapour pressure corresponding to t_x
 P_x Predicted vapour pressure at the interface
 t_{xd} Dew point temperature corresponding to P_x

$P_x > P_{xs}$ so that interstitial condensation is predicted here, with a temperature deficit of 2.04 K and a vapour pressure excess of 129 Pa.

This predicted condensation can be eliminated either by raising the structural temperature at the interface by at least 2 K or by reducing the vapour pressure by at least 130 Pa. Choosing the former, we may decide to raise the structural temperature by, say, 3 K (rather than the minimum amount of 2.04 K) to 7.7°C. The substitutions in equation 7 are given in Table 4.

These substitutions give $R' = 0.31 \text{ m}^2\text{K W}^{-1}$, and this is the necessary thermal resistance of a layer to be added to the

Table 4

t'_x	= 7.7°C
t_i	= 21°C
t_o	= 2°C
$R_1 + R_{si}$	= 1.174 m ² K W ⁻¹
$R_2 + R_{so}$	= 0.191 m ² K W ⁻¹
ΣR	= 1.365 m ² K W ⁻¹

Table 5

P_i	= 1457 Pa
P_o	= 593 Pa
P'_x	= 981-200 = 781 Pa
G_1	= 5.4 GN s kg ⁻¹
G_2	= 4.4 GN s kg ⁻¹
ΣG	= 9.8 GN s kg ⁻¹

outer surface. A similar result is given by equation 8 with $\Delta t_x = 3 \text{ K}$.

For the second alternative, we choose to reduce the vapour pressure by, say 200 Pa (instead of the minimum amount of 129 Pa). The substitutions in equation 4 are shown in Table 5.

These substitutions give $G' = 10.4 \text{ GN s kg}^{-1}$ as the necessary vapour resistance of a layer to be added to the inner surface.

A similar result is given by equation 5 with $\Delta P_x = 200 \text{ Pa}$. In practice it may be more convenient to apply a combination of these measures, for example by installing both a plastic film vapour check on the inside surface and a thermal insulation layer such as tile hanging on the outside.

If we choose to eliminate the interstitial condensation by raising the inside temperature, then the necessary minimum value for t_i is given by equation 9 as 35.6°C when t'_x is 6.7°C. This is confirmed by setting $\Delta t_x = 2.04 \text{ K}$ in equation 10. An inside temperature as high as 35.6°C is probably unacceptable, so we may apply equations 11 or 12 to determine the maximum permitted inside humidity. Setting P'_x in equation 11 to 852 Pa gives a value for P'_i of 1170 Pa. This is confirmed by equation 12 with $\Delta P_x = 129 \text{ Pa}$, giving $\Delta P_i = 287 \text{ Pa}$ (1457 Pa - 287 Pa = 1170 Pa). The inside air relative humidity is required to be reduced from 58% to 47%, which is probably a much more acceptable alternative than raising the temperature to 36°C. Note that these are calculations of the limiting values, with no allowance made for a safety margin.

For a second example we take the case of a simple impermeable construction, a single glazed window. In this case the vapour pressure equations 3 and 4 are not valid since there is zero vapour flow, but the temperature equations 7 and 8 can be applied.

We assume the same inside and outside air conditions as in the first example, with $R_{si} = 0.12$, $R_{so} = 0.06 \text{ m}^2\text{K W}^{-1}$, and a negligibly small thermal resistance for the glass itself. The structural temperature t_x at the inside surface is calculated to be 8.33°C, and the dew point of the inside air t_{xd} is 12.5°C, so that severe condensation is predicted. The extra thermal resistance R' required to raise the structural temperature to, say, 14.5°C is calculated from either equation 7 or equation 8 to be $0.17 \text{ m}^2\text{K W}^{-1}$. This resistance can be provided most simply by converting the single glazing to a double glazed sealed unit.

If we wish to raise the inside surface temperature to 12.5°C by raising the inside environmental temperature, the required value t_i' is calculated from equation 9 to be 33.5°C. Alternatively the surface condensation on the glass can be eliminated by reducing the water vapour pressure in the inside air to a value below the saturated vapour pressure at 8.33°C, i.e. 1096 Pa. This gives a relative humidity of about 44% at 21°C instead of the previous value of 58%.

6 Conclusions

The standard method for prediction of condensation risk in layered structures has been shown to be suitable for analysis of existing designs, not for synthesis of satisfactory designs.

Equations have been developed which will allow the necessary properties of additional layers to be synthesised for a construction where condensation is predicted, and from which the condition of inside air to remove condensation can be calculated.

The suitability of existing materials as extra layers to eliminate condensation has been discussed.

Examples have been given of the application of the equations in practice.

References

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