bre

information paper

Modelling condensation and airflow in pitched roofs

IP 5/06

Chris Sanders *Glasgow Caledonian University*

The risk of condensation in cold pitched roofs is dominated by airflows from the living areas of a house into the loft and through the loft to the outside. The effect of these airflows is excluded from the current British Standard procedure for assessing interstitial condensation risks. This paper discusses the factors that are necessary to construct a realistic model to predict condensation risk in structures with significant airflows, and describes the sources of the data needed to run such a model and the resulting outputs.

Condensation droplets on an undertiling membrane with adjacent rafters seen to have become very wet (top). This can lead to wood rotting fungi growing on fibreboard sarking and roof timbers (bottom)

Introduction

This Information Paper describes the general principles concerning the modelling of condensation in cold pitched roofs. It describes the system and the processes that have to be modelled, the sources of the climate data necessary to drive a model, and the output parameters that can be used to assess whether a roof is likely to suffer from problems.

Most houses (70–80%) – and some larger domestic-type buildings – in the UK have 'cold' pitched roofs with insulation on a horizontal ceiling and an accessible, cold loft space above. Heat and moisture are generated by the normal activities of the household within the occupied space of the house below the ceiling, raising the temperature and vapour pressure above those outside. Some of this heat and moisture leaves the house via the loft, passing through the ceiling by a combination of conduction, diffusion and air leakage. Studies have shown that about 20% of the air that enters a house leaves via the roof, and that typically 80% of the water vapour is transported into the roof by air leakage. BRE IP 4/06 discusses the airflow routes and methods for sealing the ceiling [1].

The procedure specified in BS 5250 for assessing the risks of condensation within structures uses a calculation procedure taken from BS EN ISO 13788. Structures with airflows through cracks and cavities are specifically excluded from the latter standard. As airflow dominates the movement of moisture into cold pitched roofs, assessments of condensation risk using this procedure are not valid. A new method taking account of airflows, is needed.

Condensation in pitched roofs

Moisture generated within the dwelling space of a house by the normal activities of the occupants, raises the vapour pressure above that outside. Much of this water vapour escapes by ventilation to the external air, or diffuses into the walls where it may cause problems of interstitial condensation in poorly designed structures. A proportion, however, leaves via the ceiling by a combination of diffusion and air leakage, and enters the roof structure where it will pass to the outside possibly causing problems on the way. The types of problems and the ways in which they may be analysed depend on the nature of the roof structure. There are two main types of pitched roof.

Interstitial condensation occurs within the thickness of building assemblies (eg in roofs). It is potentially more significant than visible condensation because it is usually difficult to detect until damage (eg rot) is well advanced.

- **'Warm' roofs** in which the insulation and ceiling follow the slope of the roof. Any air cavities present are only 25 – 100 mm deep and are usually sealed from internal water vapour due to properly installed vapour control layers and ceiling boards. In these cases the problems are essentially the same as in walling, and the structure and risk of condensation may be analysed by the methods specified in, for example, BS 5250 and IP 2/05 [2].

- **'Cold' roofs** in which insulation is laid on a horizontal ceiling with a loft space above. Depending on the size of the house and slope of the roof, the loft may have a very large volume and will usually be accessible from below via a hatch in the ceiling. The loft may contain water tanks and other plumbing fixtures and be used by the occupants for storage. In this case the problems and methods of analysis are essentially different from other structures because the moisture flows through the structure are determined mainly by airflows.

Moisture can cause two types of problem in cold pitched roofs.

- **Condensation** on the underlay or tiles can run or drip onto the rafters, battens and joists, and onto insulation on the ceiling, with consequent risk of damage to the roof structure and interior decoration of the house (top photograph on page 1). This is the factor of most concern to householders and forms the basis of most complaints to landlords, housebuilders and roofing contractors.

- **Absorption of moisture** from the air by the rafters and other internal timbers when they are exposed to high relative humidities. This, in the longer term, can lead to rot (bottom photograph on page 1) and even structural failure.

The traditional view amongst researchers and those concerned with maintenance of buildings has been that the long term absorption of water vapour by timbers at high relative humidities is the more significant problem. Condensation on the membrane has been regarded as a short term nuisance that will evaporate quickly once conditions improve.

However, more recently it has become clear that absorption in high relative humidity (RH) atmospheres is rarely, if ever, a problem. Condensation on the underlay, though, runs or drips onto timber roof components and boards, promoting mould growth and rot.

This has implications for the type of outputs that a model might produce.

The system to be modelled

The materials used to construct a pitched roof, and the occupied and unoccupied spaces of the house, and the outside air interact in complex ways. The various components to be modelled are shown in Figure 1.

1 **The living spaces of the house**. In practice these will consist of a number of different rooms, some of which (eg the bathroom) will produce significantly higher moisture loads than others. As a simplification, the house is usually represented as a single volume with average internal temperature and humidity

2 **A plasterboard ceiling**. This is generally penetrated by a more-or-less well sealed access hatch, and services such as light drops, and hot and cold water pipes. Air can flow though these gaps into the loft

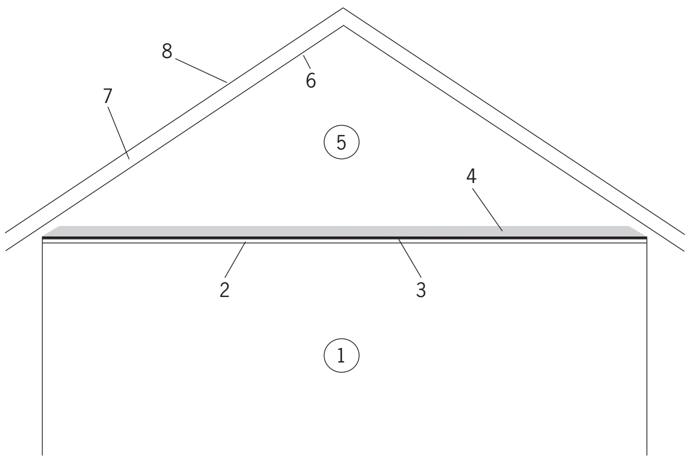

Figure 1 Components of the system to be modelled

3 **A vapour control layer (VCL)** may be present. This is a plastic membrane that is laid between the plasterboard and the ceiling joists and insulation ; it can alternatively be provided as aluminium foil bonded to plasterboard sheets with taped joints. The VCL will resist the diffusion of water vapour but will often have as many penetrations as the plasterboard

4 **Thermal insulation laid on the ceiling**. This is almost invariably mineral wool or glass fibre which effectively limits conduction of heat, but has little or no resistance to air movement or diffusion of water vapour when laid uncompressed

5 **The loft space**. This can be a simple triangular shape in section, but it may be more complex, such as ‘L’ or ‘T’ shape, on plan

6 **An undertiling membrane** is present in all but very old roofs. The membrane has traditionally been an impermeable BS 747 1F bitumen felt underlay (Type HR), but permeable breather underlays (Type LR) are starting to be used. Generally both types are laid over the rafters along the roof with unsealed laps through which air can flow. In most Scottish roofs the underlay is often used with sarking boards that traditionally have been butt-jointed 12 mm timber planks with significant gaps between the planks. However, continuous sheets of oriented strand board (OSB) or plywood are now more commonly used

7 **The batten spaces**. If only regular tiling battens are used, the roof design will comprise an air space between the battens beneath each tile and in the length of the roof; these airspaces are less well connected in the line of rafters. However, if counterbattens are used, there is a continuous air space between the tiles and membrane which can be ventilated at the eaves and ridge, and between the tiles. This airspace, then, is well connected in both the batten and rafter directions. Moreover, the batten spaces on each side of the roof may be connected, allowing air exchange and equalisation of the vapour pressure between them. In a dual-pitched roof, depending on its orientation, there may be temperature differences between the structures of the two slopes because of the effects of solar radiation and radiation to the night sky

8 **The roof tiles or slates**. These form a discontinuous sheet over the roof. Most tiling or slating shapes and systems are ‘air open’, allow ventilation of the batten spaces; however some unusual tile systems are much tighter fitting, allowing little ventilation.

Information needed for the model

Four processes affect conditions within a roof and the risk of moisture damage.

- Heat and water vapour are generated within a building by the normal activities of the occupants, raising the internal temperature and vapour pressure above those outside
- Temperature and vapour pressure differences between occupied and unoccupied spaces drive heat and water vapour through the separating materials by conduction and diffusion respectively
- Airflows from the house to the loft and through the loft to the outside carry heat and water vapour
- Solar radiation raises the temperature of the roof covering and underlay above the air temperature during the day, and night sky radiation lowers the roof temperatures below the air temperature overnight.

The information needed to account realistically for these processes is discussed in the following sections.

Internal conditions

The primary driving forces for all the flows of heat and water vapour through a roof are the raised temperature and humidity caused by the normal occupancy of the building. These can be taken into account in a number of ways.

Constant conditions

In modelling interstitial condensation in walls and floors, it is usual to assume a constant internal temperature of 20 °C all year. With the increasing use of full central heating in housing, this is a more reasonable assumption than it used to be. The simplest premise to make about internal vapour pressure is that it is also constant and can be represented by a constant internal RH, which would depend on the building occupancy. However, except when air conditioning is used, which is unusual in housing, this is a very unrealistic assumption as both the external conditions and the amount of ventilation vary substantially between summer and winter. An internal humidity that provides reasonable conditions in winter will lead to internal vapour pressures in summer which are considerably lower than those outside.

Humidity classes

A more realistic approach is based on the humidity classes that are defined in BS EN ISO 13788 and BS 5250. This assumes, as before, that the internal temperature is constant at 20 °C. The internal vapour pressure is dependant on both the external vapour pressure, which is high in the summer and low in the winter, the vapour load imposed by moisture generation within the building and the ventilation rate. Vapour load within a dry goods warehouse will be much less than in a laundry or swimming pool. Internal temperatures are also relevant for two reasons: higher temperatures will support higher vapour pressures at the same RH; and a high temperature difference between inside and outside creates stack pressure differences that drive air carrying water vapour through air permeable materials. This effect can be greatly exacerbated in buildings such as operating theatres and clean rooms which are operated as high pressure environments to avoid ingress of contaminants.

It is further assumed that the vapour load is high in the winter when buildings are more densely occupied and less well ventilated, and low in the summer when occupancy is less dense and ventilation rates higher.

These assumptions produce the distribution of vapour load, Δ_p, against outside temperature (shown in Figure 2) for five different types of building occupancy.

Table 1 shows the types of building expected to fall into each class, and the range of relative humidities covered by the class, in buildings with different internal temperatures but with an external temperature of 0 °C and a RH of 95%.

For design calculations, it is recommended that the upper limit value for each class be used unless the designer can demonstrate that conditions are less severe.

Drying out

In buildings built with components that have incorporated considerable amounts of water during construction – such as concrete screeds and wet plastering, or buildings that are drying out after flooding – the internal moisture load may be much higher. No information is available as to the actual humidities likely in these buildings. However, if it is thought that there is an issue with a particular building, the humidity class used should be increased to the next level.

Conduction and diffusion

Heat, H_1, flowing by conduction through a structural element (eg through an insulated ceiling from the house into the loft) is given by

$$H_1 = \frac{(T_{liv} - T_{loft}) \cdot A_c}{R_t} \text{ watts}$$

where T_{liv} and T_{loft} are the temperatures in the living space and the loft
A_c is the area of the ceiling in m^2
R_t is the thermal resistance of the ceiling in $m^2 \cdot K/W$.

Similarly water vapour transport, W_1, is given by

$$W_1 = \frac{(P_{liv} - P_{loft}) \cdot A_c}{R_v} \text{ grams/second}$$

where P_{liv} and P_{loft} are the vapour pressures in the living areas and loft in Pa
R_v is the vapour resistance of the ceiling in N · s/g (for convenience it is usual to express vapour resistance in MN · s/g; ie N · s/g x 10^6).

The thermal and vapour resistances of any structural component are made up from the sum of the resistances of the individual layers so that, for example, the thermal resistance of the ceiling is made up from the sum of the resistances of the plasterboard and the insulation laid on it.

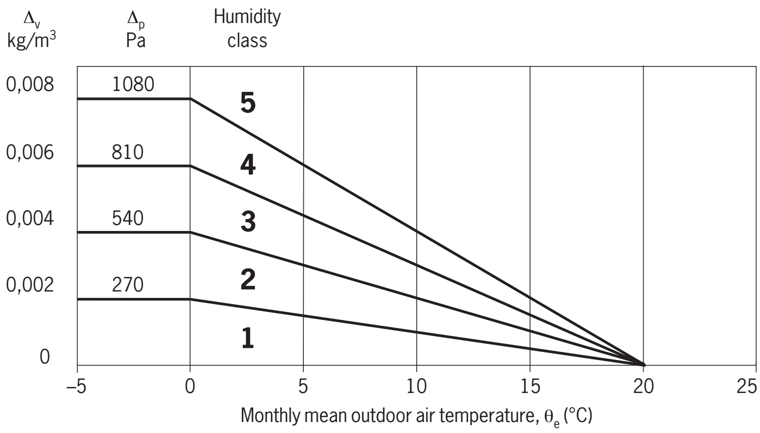

Figure 2 Variation of internal humidity classes with external temperature

Table 1 Internal humidity classes : building types and limiting relative humidities at external temperature = 0 °C and RH = 95%

Humidity class	Building type	Relative humidity at internal temperature		
		15 °C	**20 °C**	**25 °C**
1	Storage areas	<50	<35	<25
2	Offices, shops	50 – 65	35 – 50	25 – 35
3	Dwellings with low occupancy	65 – 80	50 – 60	35 – 45
4	High occupancy dwellings, sports halls, kitchens, canteens; buildings heated with unflued gas heaters	80 – 95	60 – 70	45 – 55
5	Special buildings (eg.laundry, brewery, swimming pool)	>95	>70	>55

For most elements, the thermal resistance is the product of the thickness and thermal resistivity, or the reciprocal of the thermal conductivity

$R_t = d / \lambda$ m$^2 \cdot$ K/W

where d is the thickness in m
λ is the thermal conductivity in W/m · K.

Some materials, such as an insulation/plasterboard composite, have a resistance quoted directly, as do the internal and external surfaces. Membranes, such as polythene VCLs or tiling underlays, are assumed to have no thermal resistance. If there are no airflows through the structure, the thermal resistance of any cavities is also taken into account. However, if there are significant airflows, as in cold pitched roofs, the effect of these on cavity conditions has to be calculated explicitly (see next section, 'Airflows').

Similarly the vapour resistance is the product of the thickness and vapour resistivity

$R_v = d \cdot r_v$

where r_v is the vapour resistivity in N · s/g · m.

For convenience it is more usual to quote vapour resistivities in MN · s/g · m. A wide range of other units for vapour resistance and resistivity are quoted in manufacturers' literature; Appendix E of BS 5250 gives conversions for these. In particular, European Standards and manufacturers' data sheets commonly quote vapour resistivities in the form of the water vapour resistance factor, μ, or resistances as the equivalent air layer thickness, s_d. To convert a μ-value to a vapour resistivity in MN · s/g · m, or to convert a s_d value into a vapour resistance in MN · s/g, divide by 0.2.

Table 2 shows typical values of the thermal and vapour transport properties of roofing materials. Membranes such as a polythene VCL and tiling underlays are assumed to have a vapour resistance independent of their thickness. For the purposes of vapour transfer through the structure, the vapour resistance of the internal and external surfaces is assumed to be negligible. However, if condensation occurs, it is necessary to assume a small surface resistance (see later section 'Calculation of condensate accumulation').

Airflows

When air flows between two volumes, for example through an insulated ceiling from a living area into a loft above, the heat transfer, H_2, is given by

$H_2 = Q \cdot \rho \cdot c \cdot (T_{liv} - T_{loft})$ watts

where Q is the airflow rate in m^3/s
ρ is the density of air in kg/m^3
c is the specific heat of air in J/kg °C
T_{liv} and T_{loft} are the temperatures of the living area and loft in °C.

The moisture transfer is given by

$W_2 = Q \cdot k \cdot (P_{liv} - P_{loft})$ grams/second

where k is a factor (= 2.17 / T_{abs}) relating vapour pressure in Pa to moisture content of the air in g/m^3. T_{abs} is the average absolute temperature

$$= \frac{T_{liv} + T_{loft}}{2} + 273.13\ °K$$

P_{liv} and P_{loft} are the vapour pressure of the living areas and loft in Pa.

To assess the condensation risk in a cold pitched roof, air exchanges between four volumes have to be taken into consideration, assuming the occupied space of the house to be a single volume.

These four routes for airflow are:

- from the occupied space into the loft, through gaps in ceilings and more complex routes up wall cavities and behind lining systems. Because of the temperature driven stack effect and the negative pressures caused by wind flows over a pitched roof, there is rarely any flow down from the loft into living areas
- between the loft and outside, through purpose-provided ventilators in the eaves and ridge and infiltration through other adventitious gaps. The latter may be particularly difficult to quantify since they are invariably related to quality of construction
- between loft and batten spaces through laps in the underlay
- between batten spaces and the outside air through the roof covering system and batten space ventilators, if they have been installed.

Table 2 Typical thermal and vapour transport properties of roofing materials

	Thermal conductivity (W/m · K)	Thermal resistance (m^2 · K/W)	Vapour resistivity (MN · s/g · m)	Vapour resistance (MN · s/g)
Internal surface		0.10		
Plasterboard	0.17		60	
Polythene vapour control layer				250
Mineral wool	0.04		5	
Low resistance (LR) underlay				0.25
High resistance (HR) underlay				200
Tiles	0.84		250	
Slates	2.2		2000	
External surface		0.04		

The size of these airflows needs to be determined to establish the heat and moisture movements which, in turn, determine the condensation risk. In principle the airflows can be determined from first principles by detailed analysis using such techniques as computational fluid dynamics (CFD). However, because this technique is very complex and requires extremely detailed information about each roof, it is not a practical prediction method at present, although it has a valuable role in sensitivity analysis of the roof design factors that affect airflows.

An alternative approach that has proved to be more useful is to develop empirical rules from a combination of tracer gas and wind tunnel studies. A series of measurements undertaken by BRE, and others, of the ventilation rates and air movement through ceilings in over 70 houses, including their lofts [3], enabled the following broad rules to be developed.

Airflow through the ceiling

With similar ventilation openings on the opposite sides of a house, about 20% of the air entering the living space leaves through gaps in the ceiling into the loft. About 20% of the air entering a loft comes through the ceiling from below. These measurements were made in houses in which no particular attention had been paid to the sealing of the ceiling. This flow can be reduced by 70% by taking reasonable steps to produce a 'well sealed' ceiling – see BS 5250 and IP 4/06.

Loft ventilation rates

When a loft has no eaves or ridge ventilators, and has not been sealed, the loft ventilation rate in air changes per hour (ach) is about equal to the wind speed in m/s.

When there is a 10 mm slot in the eaves on both sides of the house, the loft ventilation rate in ach is about equal to 2 times the wind speed in m/s.

When there is a 10 mm slot in the eaves on both sides of the house and a 5 mm ridge ventilator, the loft ventilation rate in ach is about equal to 2.5 times the wind speed in m/s.

Airflow through the underlay overlaps

Although most underlay materials are air-impermeable, some airflow will take place through overlaps which have not been sealed. This airflow will transfer moisture out of the loft and into the battenspace. Traditional bituminous (1F) underlay has sanded surfaces and a surface impression due to the reinforcing fibre mesh. For smooth-surfaced underlays, the gaps in the overlaps will be smaller, resulting in smaller airflow rates. Moreover, in roofs with unsupported underlays, the amount of drape in underlays will vary and the resulting gaps will provide routes for airflow. Clearly, if the overlaps of an underlay are sealed, this airflow path is not present.

Airflow through the roof covering

Most roof coverings are open to the external air to some degree. The amount of openness varies between specific types of roof covering. Measurements of the 'air openness' of many types of roof covering have been used to define an objective test based on Annex L of BS 5534, which is specified in BS 5250. It should be borne in mind that the air openness of roof coverings will be reduced if moss or lichen have grown on them; however, this would not apply to a newly built or re-roofed house. Some unusual systems, such as large metal sheets that resemble tiles, are effectively completely airtight.

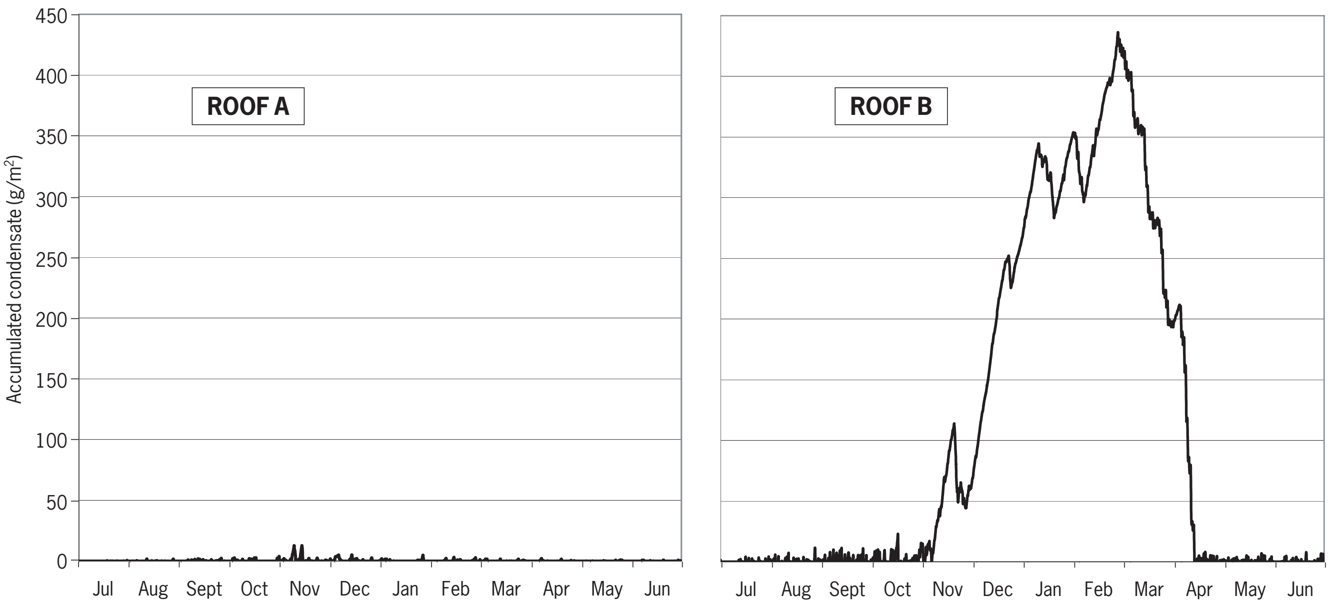

Figure 3 The accumulation of condensate in two roofs over a year

External conditions

Data required

The processes that determine the environment within a roof and the rates at which condensation or evaporation occur depend on the external environment. As condensation and evaporation frequently occur on daily timescales, data recorded at hourly intervals are needed to represent the moisture movement processes adequately.

The hourly values are required for the following variables:

- air temperature
- vapour pressure (or any other parameter such as RH or dewpoint from which vapour pressure can be calculated)
- wind speed
- global solar radiation
- long wave radiation.

Long wave radiation loss, which causes the outside surface to cool several degrees below the outside air temperature on clear nights, is rarely measured and is not generally available. To make up this deficiency, algorithms have been developed and validated that allow long wave loss to be calculated from the external temperature and humidity[4].

Almost all roofs are dry in the summer, with an accumulation of condensate and rise in timber moisture content over the winter, and drying in the following spring. Therefore, although some useful information may be gained from an analysis as short as a few days or a month, analysis over at least a full year, from summer to summer, is necessary to characterise the long term performance of a roof.

Figure 3 shows the accumulation of condensate in two roofs over a year, starting at the beginning of July. In Roof A condensation is not a problem; however small amounts (<10 g/m^2) of condensate accumulate on many nights in autumn and spring, with a peak accumulation of 12.8 g/m^2 in November. Condensation is a major problem in Roof B. There are frequent small accumulations overnight in late summer and autumn, but then a steady accumulation from early November until mid-April. There would be significant running and dripping of condensate over the whole winter in this roof. The behaviour of these two roofs could not be demonstrated without analysis of a whole year of hourly data.

Effects of solar and long wave radiation

Solar radiation during the day increases the temperatures of the external surfaces of a roof and the materials behind them, such as tiling underlays, above the external air temperature. The effect depends on the orientation and slope of the roof. Conversely long wave radiation to clear skies, commonly known as night sky radiation, lowers the roof temperatures below the temperature of the external air.

As an example of the effect of solar radiation on surface temperatures, Figure 4 (on page 8) shows the external temperature and calculated tile base temperatures on the north and south facing slopes of a 30° pitched roof over two summer days; the south facing tiles are almost 30 °C warmer than the air temperature during the day. However, it can also be seen that, even in summer, the overnight tile temperatures are below the external air temperature. Figure 5 shows the temperatures for the same roof as in Figure 4 over two typical winter days; night sky radiation is causing the base of the tiles to fall up to 2 °C below the external air temperature.

The raised surface temperatures due to solar radiation in summer will lead to rapid evaporation of any condensate generated overnight, preventing any accumulation. However, in the winter when condensation is likely to be a greater problem, the cooling effect of long wave radiation predominates over the solar gain. This is seen in Figure 6, which shows the underlay temperature – calculated with and without the effect of solar and long wave radiation – and the calculated accumulation of condensate over eighteen days in the winter. Neglecting the effect of radiation seriously underestimates the predicted accumulation of condensate.

Availability of data

Full years of hourly values of the variables specified in the ‘Data required’ section (on page 8) are very expensive to purchase; also the necessary solar radiation data are available from only a very few locations.

There are two other possible sources of data.

Test reference years

In 1972 the European Community published 27 test reference years from seven European countries [5]. These data, which are freely available, are composite years of hourly values of the specified parameters, made up from individual months from different years.

The four locations in the UK are:

- Kew in south west London
- Aberporth on the west coast of Wales
- Eskdalemuir at about 300 m in the Southern Uplands of Scotland
- Lerwick in the Shetland Islands.

Synthetic weather data

Software is available that can generate years of hourly data from monthly means [6]. While these data are extremely effective when applied to solar radiation problems, their use in areas such as humidity and ventilation is more uncertain. (Work is underway to validate these methods for use in condensation analysis.)

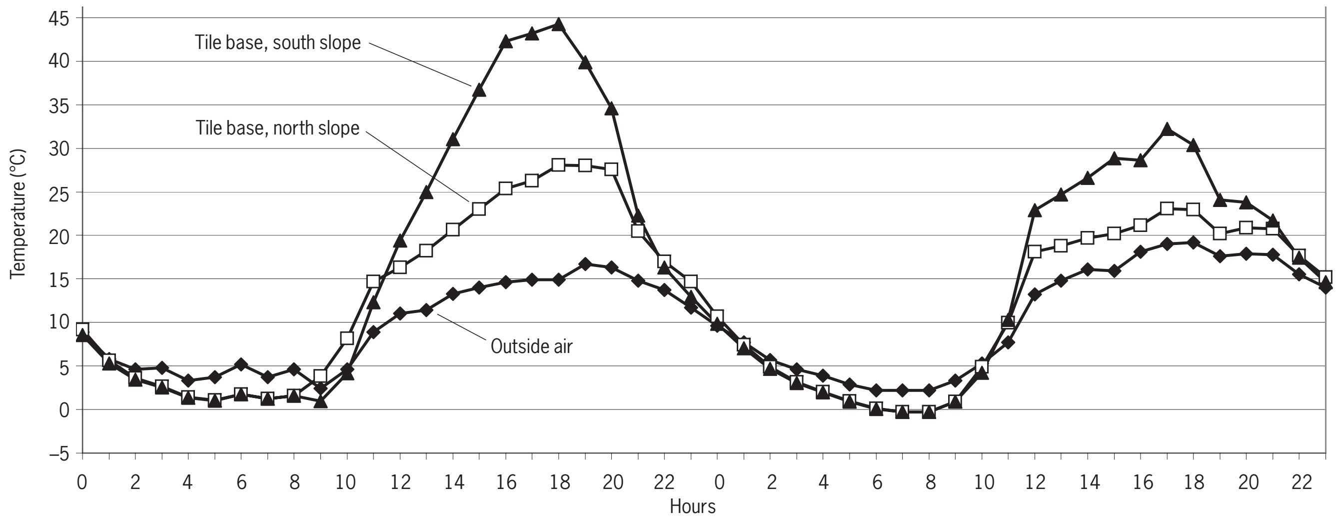

Figure 4 External and tile temperatures calculated from two summer days

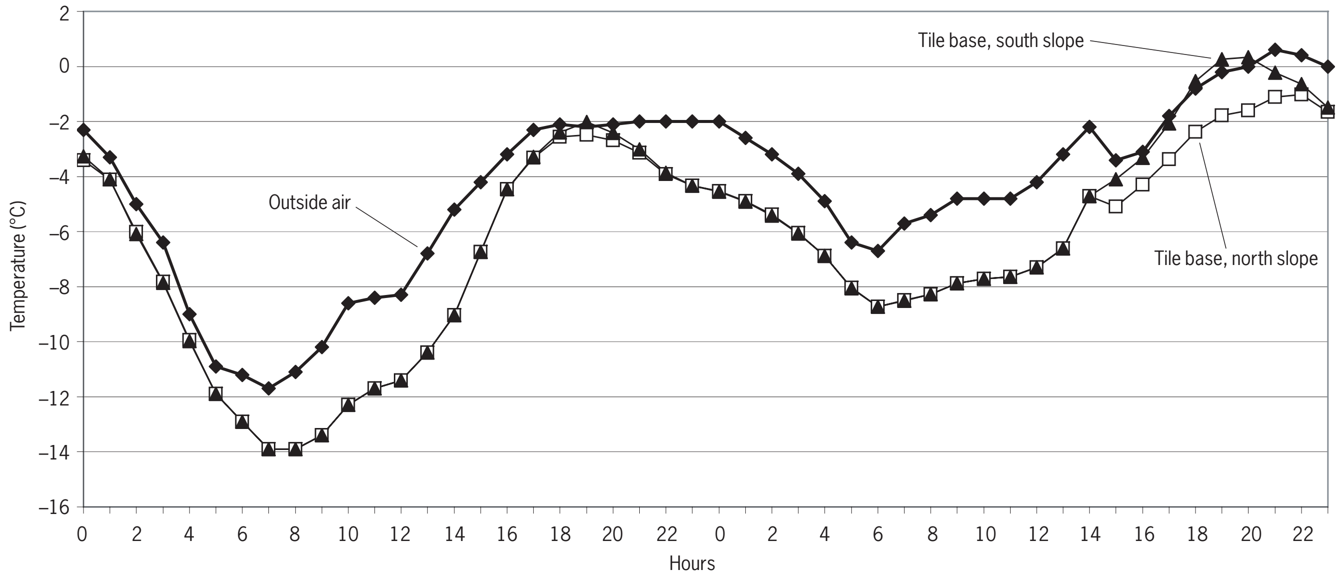

Figure 5 External and tile temperatures calculated from two winter days

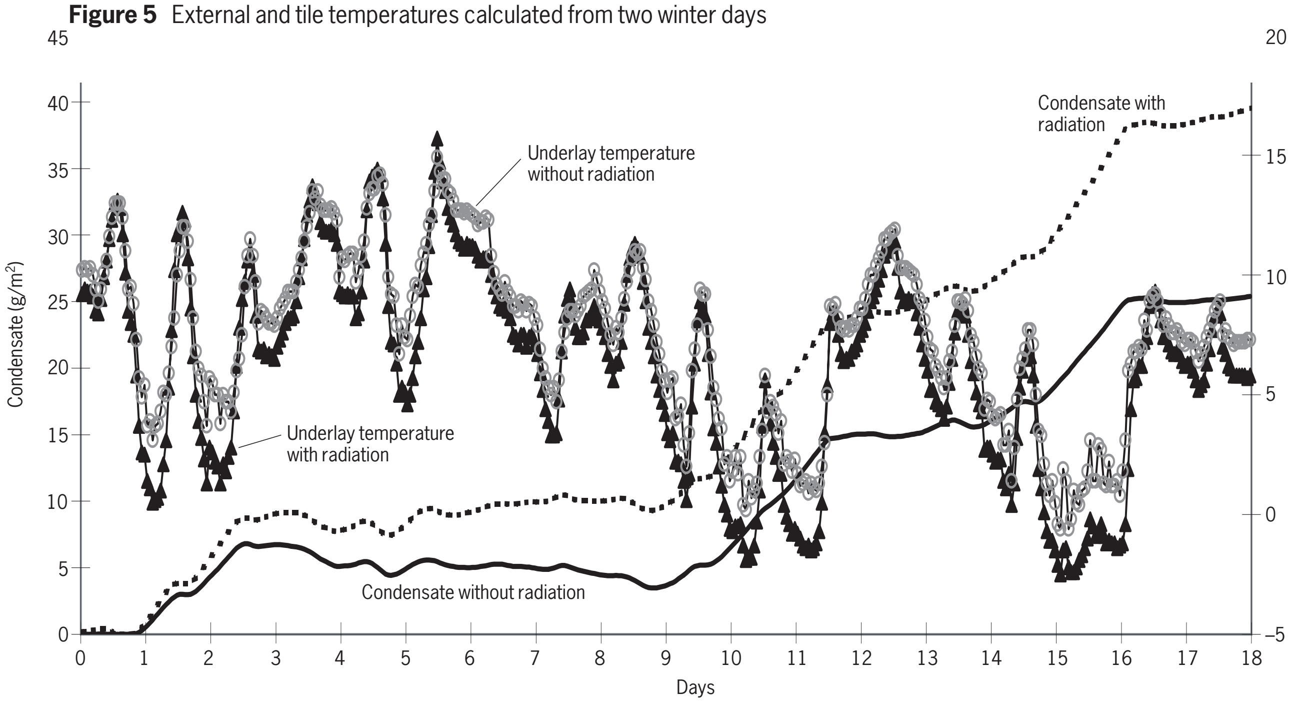

Figure 6 Underlay temperature and condensate accumulation, with and without the effects of solar and long wave radiation, over 18 days in winter

Calculation of condensate accumulation

The following stages are necessary to estimate for a year the amount of condensate on the underlay or base of the tiles in a cold pitched roof.

1 Calculate, on an hourly basis, the component temperatures by balancing the heat gains and losses to each component of the roof

Heat gains

- conduction from the heated space below the ceiling
- air movement from the heated space below
- solar radiation during the day
- heat storage within the material

Heat losses

- conduction to the outside
- air movement to the outside
- long wave radiation
- heat loss from the material

In normal cold pitched roofs, the heat stored in the underlay and tiles will be small compared to the other gains and losses, and can be ignored.

2 Calculate, on an hourly basis, the vapour pressure in the loft and batten space by balancing the vapour losses and gains

Vapour gains

- diffusion through the ceiling into the loft and through the underlay into the batten space
- air movement through gaps in the ceiling and through the underlay laps
- moisture storage in the materials

Vapour losses

- diffusion from the loft through the underlay into the batten space, and from the batten space though the roof covering to outside
- air movement from the loft directly to the outside and into the batten space, and from the batten space directly to outside
- Moisture loss from the material.

Moisture take-up and release from materials is very slow, taking place over periods of weeks. Therefore, while the moisture content of rafters, battens and other timber roof components will vary from summer to winter, their effect on diurnal moisture changes is negligible.

3 Calculate, on an hourly basis, the amount of water vapour condensing, *g*, on the surface of the tiles and underlay from:

$$g = \frac{(P_a - P_{ss}) \cdot ß_v}{R_w \cdot T} \text{ g/s}$$

where P_a is the vapour pressure in the air in Pa
P_{ss} is the saturated vapour pressure at the surface temperature in Pa
$ß_v$ is the surface transport coefficient for water vapour in m/s
R_w is the gas constant for water vapour = 461 J/kg · °K
T is the absolute temperature in °K

The surface transport coefficient, $ß_v$, can be taken to be 0.0036 m/s for vapour condensing on a downward facing surface.

The condensation rate will be positive, leading to an accumulation of condensate when $P_a > P_{ss}$ (ie when either the vapour pressure in the air has risen or the surface temperature has fallen). Conversely, any accumulated condensate will evaporate when $P_a < P_{ss}$ (ie when the vapour pressure in the air has fallen or the surface temperature has risen).

4 Add the amount of positive condensation or negative evaporation that has occurred in each hour to the previously accumulated condensate. This gives the total accumulated condensate over the year.

Key performance indicators for roofs

Possible outputs

The type of model discussed in the preceding sections can produce, potentially, a considerable amount of data including hourly values of:

- the temperature, vapour pressure and relative humidity in the loft and batten spaces
- the timber moisture contents in the rafters and tiling battens
- the mass of condensed water on the underlay and the tiles.

In practice, the most sensitive indicator of roof performance has been found to be the peak accumulation of condensate on the underlay in winter. Figure 3 (on page 8) shows the hourly values of condensate that has accumulated on the underlay in two roofs. In Roof A there is a very limited amount of condensation, peaking at only 12.8 g/m^2 in early November. In Roof B, though, there is a limited amount of condensation in the summer and early autumn; but from November there is a steady accumulation of condensate, peaking at over 400 g/m^2 in February with complete evaporation by mid-April.

Small amounts of temporary condensation on the underside of a membrane are unlikely to give rise to structural damage or affect the performance of insulation. The amount that can be safely held on the membrane, before running or dripping starts, will depend on the type of material and its slope. For cold roofs, or warm roofs where there is an air space between the underside of the membrane and the insulation, the following quantities have been shown by test to be held without dripping or running from a 30° roof slope:

- sanded bitumen felt, 230 g/m^2
- membranes with underside fleeces, 130 g/m^2
- membranes without underside fleeces, 70 g/m^2.

About 20% more can be held on a 15° slope, and about 20% less on a 45° slope.

Sensitivity analysis

There will always be uncertainty as to the appropriate external climate conditions to use and the exact performance of any model. One method for dealing with uncertainties is to define a 'base case' roof type that experience has shown to work well, and relate the peak accumulated condensate in any other roof, calculated with the same model under the same climate, to that occurring in the base case roof.

One possible base case is a roof with 10 mm ventilation slots in both eaves, an impermeable HR 1F felt underlay, an unsealed ceiling with 200 mm of mineral wool, and a roof covering of slates which have accumulated dirt and moss, limiting the airflow through them. There are many roofs like this in all parts of the UK which do not give problems.

To illustrate the effect of varying some important roof parameters, Figure 8 shows the relative condensation peak as the loft eaves gap is reduced in four roof types, all of which have 200 mm of insulation on the ceiling and a roof covering of clean interlocking tiles. Restricting the loft ventilation incrementally increases the condensate peak in all cases. However there are benefits in changing from a HR underlay, with a vapour resistance of $Z_m = 200$ MN · s/g, to an LR underlay of $Z_m = 0.25$ MN · s/g; and in reducing the leakage through the ceiling by 70% by improving the sealing of that ceiling.

Figure 9 shows the effect of increasing the thickness of mineral wool insulation from zero up to 400 mm in a range of roof types. As might be expected, because insulation on the ceiling will make the roof above colder, the condensation rate increases significantly with increasing insulation thickness. The picture is slightly more complex because the added insulation thickness will also increase the vapour resistance of the ceiling, reducing the condensation risk. This effect can been seen as the condensate peak falls slightly when insulation is added to the unsealed ceiling with a 10 mm gap at the eaves.

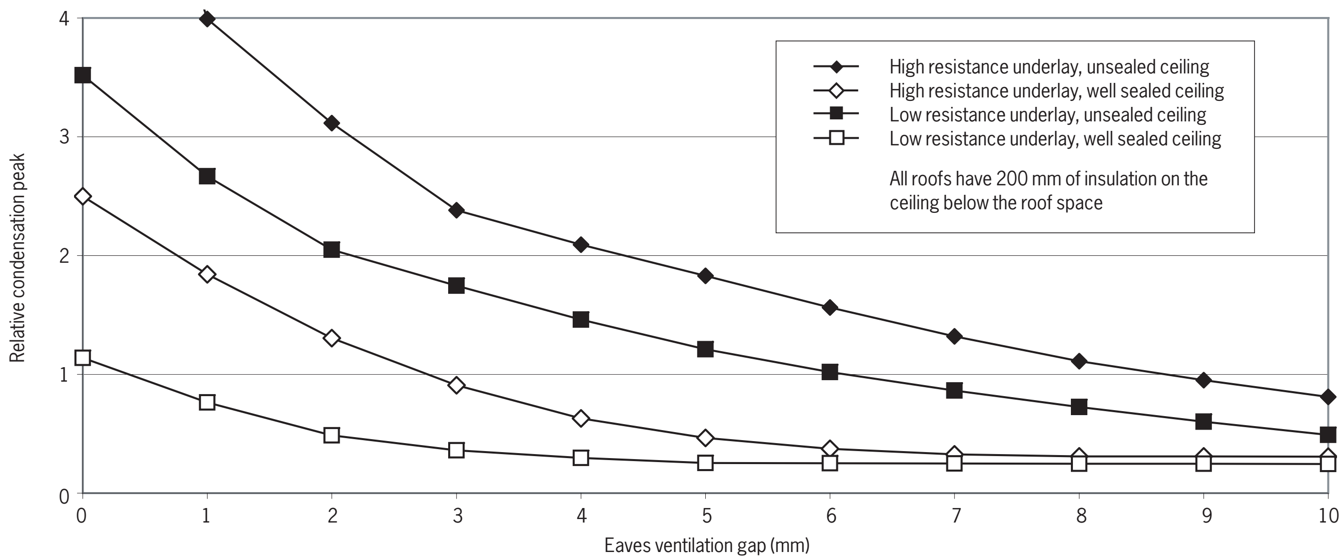

Figure 8 Relative condensate peak as a function of loft eaves gap for four roof types

Conclusions

This paper has described the essential features of a model to assess the risk of condensation in cold pitched roofs in which heat and moisture movement is dominated by airflows from the living areas of a house into the loft space, and through the loft to the outside. To represent the risk of condensation realistically a model must include the following features.

- **Hourly calculations over a whole year from summer to summer** since condensation is driven by diurnal temperature cycles, and accumulation can occur over several months in winter

- **The humidity conditions within the house** (which are the driving force for the vapour flows) comprise the variations in the external humidity and the ventilation of the building that occur over a year.

- **Hourly values of temperature, humidity, wind speed and solar radiation** are needed to represent the external climate. Long wave radiation, which cools the roof overnight, can be calculated from the external temperature and humidity; ignoring the effects of long wave radiation will seriously underestimate the risk of condensation.

- **Values for the thermal conductivity and vapour resistance of the various components of the roof**. Design values for these are available from a number of sources.

- **The rates for airflows from the living areas of the house into the loftspace, and through the loft and batten space to the outside**. Theoretically, these could be calculated from first principles using, for example, CFD software. This is very complex and depends on very detailed information about the house, its roof and the surroundings. An alternative approach is to use empirical rules based on tracer gas measurements carried out in a large number of houses and wind tunnels studies of flows though tiles and batten spaces.

Uncertainties as to the appropriate external climate conditions to apply to a model and the exact performance of the model may be resolved by defining a 'base case' roof type that experience has shown to work well. This can then be related to the peak accumulated condensate in any other roof, calculated using the same model under the same climate conditions, to that occurring in the base case roof.

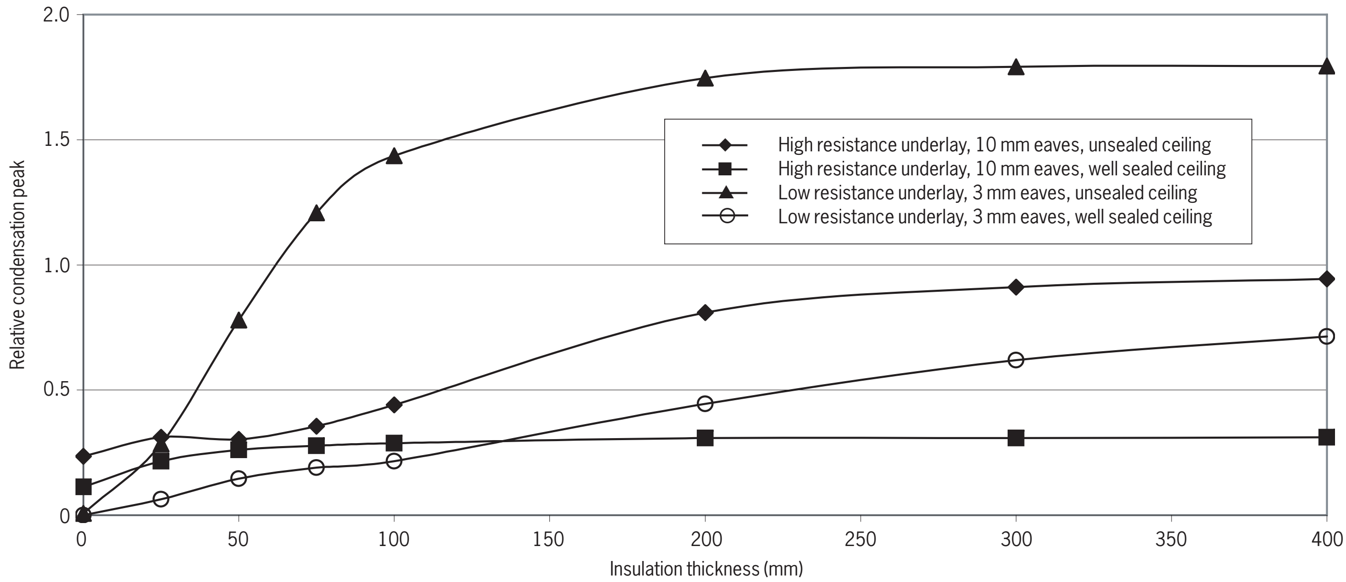

Figure 9 Relative condensation peak as a function of ceiling insulation thickness

References

[1] Sanders C, Haig J and Rideout N. Airtightness of ceilings. Energy loss and condensation risk. *BRE Information Paper* IP 4/06. Garston, BRE Press, 2006.

[2] Sanders C. Modelling and controlling interstitial condensation in buildings. *BRE Information Paper* IP 2/05. Garston, BRE Press, 2005.

[3] Sanders C H. Air movement in houses: a new approach. *Building Research and Practice*, 1982, pp 160–175.

[4] Pedersen C R. *Combined heat and moisture transfer in building constructions*. Report 214. Copenhagen, Thermal Insulation Laboratory, Technical University of Denmark, 1990.

[5] Commission of the European Communities Directorate General XII for Science, Research and Development. *Test reference years for energy calculations*. EC Report TR4357:1985. Brussels, CEC, 1985.

[6] Meteonorm (global meteorological database for solar energy and applied meteorology). Software available from Meteotest, Fabrikstrasse14, CH-3012 Bern, Switzerland.

British Standards Institution

BS 747:2000 Reinforced bitumen sheets for roofing. Specification
BS 5250:2002 (amended 2006) Code of practice for control of condensation in buildings
BS 5534:2003 Code of practice for slating and tiling (including shingles)
BS EN ISO 13788:2002 Hygrothermal performance of building components and building elements. Internal surface temperature to avoid critical surface humidity and interstitial condensation. Calculation methods

Further reading

BRE Report

BR 302 Roofs and roofing. Performance, diagnosis, maintenance, repair and the avoidance of defects

BRE Good Building Guides

GBG 37 Insulating roofs at rafter level: sarking insulation
GBG 51 Ventilated and unventilated cold pitched roofs
GBG 64 Tiling and slating pitched roofs.
- Part 1 Design criteria, underlays and battens
- Part 2 Plain and profiled clay and concrete tiles
- Part 3 Natural and manmade slates

GBG 67 Achieving airtightness.
- Part 1 General principles
- Part 2 Practical guidance on techniques: floors, walls and roofs
- Part 3 Practical guidance on techniques: windows and doors, sealing methods and materials

BRE Good Repair Guide

GRG 30 Remedying condensation in domestic pitched tiled roofs

Acknowledgements

This research was carried out under a Partners in Innovation project of the Office of the Deputy Prime Minister.

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IP 5/06

April 2006
ISBN 1 86081 912 5