information paper

BRE

Modelling and controlling interstitial condensation in buildings

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This paper considers the models that are available to analyse the risk of interstitial condensation within structures. To run the models, certain properties of materials need to be known. The paper discusses the availability of these properties and the appropriate boundary conditions that should be used, and makes recommendations on which models should be used for a range of different types of structure.

This guidance is intended for those involved in the design and construction of buildings.

Introduction

Interstitial condensation can occur in all types of buildings and cause a range of problems from staining of interior decoration, as the condensate leaks back into the building, to damage to the fabric that can affect structural integrity. Concerns have been expressed about the health implications of the growth of so-called 'toxic mould' that can occur when condensation persists within structures. Changes in construction, especially the use of more thermal insulation and impermeable claddings and the trend toward offsite manufacture of building elements, may increase these risks.

The recent revision to Part C of the England and Wales Building Regulations[1], which came into force on 1 December 2004, requires, for the first time, that: *'The floors, walls and roof of the building shall adequately protect the building and its users from harmful effects caused by…(c) interstitial and surface condensation'*. This introduces a new requirement for structures to be assessed for interstitial risks and emphasises the need for appropriate calculation techniques.

Theory

A method for analysing the risk of interstitial condensation within a structure was first developed by Glaser[2] in Germany in the 1950s. It was the basis of the procedure specified in Appendix D of BS 5250:1989, and of a number of software packages, including the BRE program BRECON, that have been widely used by industry over the past decade. The method was extended in BS EN ISO 13788:2002, which is referenced in the 2002 edition of BS 5250.

The Glaser method provides the physical background to these standards, and is based on a model which makes a number of assumptions, as follows.

- Water vapour generated within a building in the winter raises the internal vapour pressure above

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that outside, causing vapour diffusion through the structure. In air-conditioned buildings in warm humid climates, the vapour pressure gradient will be from inside to out; however, the basic process is the same.

- All the materials are dry until the vapour pressure and temperature within the structure combine to produce a relative humidity of 100%, when condensation occurs depositing liquid water.
- Diffusion processes are slow so that taking internal and external boundary conditions as constant over one or two months gives an adequate representation of the risks of condensation.
- All vapour transport is one-dimensional.

These assumptions are a simplification of the processes that occur when water interacts with building structures.

- Most building materials contain significant amounts of water, which may have been built into the construction, impacted on the structure as rainfall, or been directly absorbed into the pores of hygroscopic materials from the ambient air.
- Except in the presence of an impermeable layer, such as a polythene vapour control layer or a metal sheet, condensation does not suddenly 'switch on' when the relative humidity within a structure reaches 100% and 'switch off' when the humidity falls. The material pores absorb water at an increasing rate as the humidity rises and desorb water as it falls.
- There are complex vapour and liquid water flows through the material driven by relative humidity, temperature and vapour pressure gradients. In some structures, metal-sheeted roofs for example, moisture movement is dominated by air movement through cracks between the sheets, driven by wind- and stack-induced pressure differences.
- The driving forces that cause moisture movement vary on short timescales. External air temperature fluctuates daily, with its effect indoors greatly intensified by solar gain during the day and long-wave radiation loss at night. In spring, the outside surface temperature of a roof can change from –10 °C to +60 °C on clear days. Internal vapour pressures also vary on diurnal timescales owing to normal household activities.
- Ventilation of cavities within the structure from the outside can remove the water vapour before it causes problems.
- The performance of some structures can depend on two- or three-dimensional heat and moisture flows.

Several models have been developed which take account of some or all of these effects. Some of these, MATCH[3] and WUFI[4], for example, are commercially available software packages which have been widely used for consultancy work in Europe for a number of years. BRE has been using them in research and consultancy since 2001. Other models are research tools under development in universities and research institutes, which may or may not develop into user-friendly software.

At present no British or European standards cover the more complex methods of modelling described above. A Task Group of CEN/TC 89/WG 10 *Moisture* has developed such a standard under TC89 Work Item 29.3. The standard *Hygrothermal performance of building components and building elements – Assessment of moisture transfer by numerical simulation* is now complete and has been approved for CEN Enquiry.

Calculation methods

BRECON

BRECON is a software package developed by BRE to carry out the calculation procedure specified in Appendix D of BS 5250:1989. While this procedure is now superseded, the package is the only one available that can allow for the effect of ventilating a cavity within a building structure.

The structure to be analysed is divided into a series of parallel layers, each with uniform thermal resistance, $R_{t,i}$, and vapour resistance, $R_{v,i}$. The layers are usually chosen to consist of a separate material. However, a monolithic construction or an individual thick material layer can be subdivided if there is a chance of condensation occurring within the layer. The accumulated thermal and vapour resistance from the inside to each interface between layers is calculated and used to determine the temperature and vapour pressure (VP) at each interface, given appropriate boundary conditions (see *Boundary conditions* section). The saturated vapour pressure (SVP) corresponding to the temperature at each interface is calculated; if this exceeds the vapour pressure at all interfaces, no condensation is predicted.

If the VP exceeds the SVP in any part of the structure, the interface with the highest value of (VP – SVP) is identified and the VP set to equal the SVP at that point. This is then used as a new boundary condition for the calculation of the VP profile in two stages, from the inside to the condensation plane and from the condensation plane to the outside. It is possible that further condensation planes will then be identified. The process is repeated until the VP is less than or equal to the SVP at all points through the structure. The condensation rate at each condensation plane is given by the difference between the flow rate of water vapour to and away from the plane. The accumulation of condensation is calculated over 60 days of winter weather.

BS 5250:1989 stated (clause D1.1) 'Where condensation is predicted at interfaces, the designer should use his practical experience to assess if the materials on either side of these interfaces are likely to become wetted and if any degradation of properties or physical damage will result'. This did not give the necessary guidance as to how much condensation mattered in any circumstance.

To illustrate the process, Figure 1 shows a profile through a timber framed wall with no vapour control layer. The temperature, and therefore SVP, falls rapidly in the mineral wool insulation (layer 5), which offers little resistance to the passage of water vapour. The unmodified VP profile (VP(1)) is therefore higher than the SVP profile in large areas of the wall. The plane with the highest value of (VP – SVP) is that between the mineral wool and sheathing plywood (layer 4). When the VP is fixed equal to the SVP at this point, and the VP profile calculated (VP(2)), no further condensation planes are found.

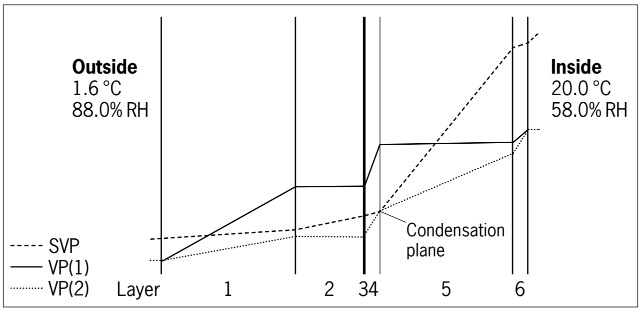

Figure 1 Saturated vapour pressure and vapour pressure profiles through a timber framed wall
Layers: 1 = back, 2 = cavity, 3 = breather membrane, 4 = plywood, 5 = insulation, 6 = plasterboard

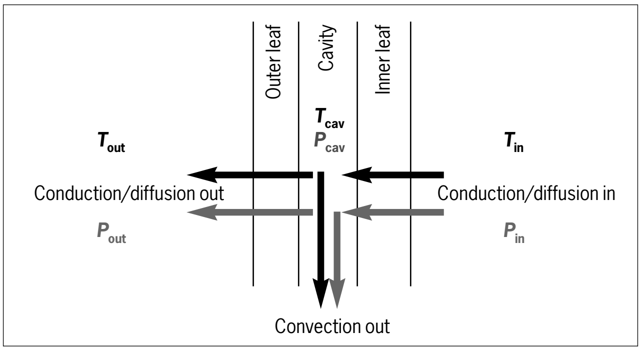

Figure 2 Heat and moisture flows into and out of a cavity

The effect of cavity ventilation is included by equating the flow of heat and moisture through the inner leaf into the cavity by conduction and diffusion, with the combined outward flows through the outer leaf and by convection carried by the flow of air through the cavity (Figure 2). This allows the temperature and vapour pressure within the cavity to be calculated and then used as a third set of boundary conditions for the assessment of the risk of condensation in the inner and outer leaves of the wall or roof separately.

Owing to the complexity of subdividing a structure with condensation planes and ventilated cavities, it is possible to analyse only one ventilated cavity and only one condensation plane in a structure with a ventilated cavity.

ICOND

The software package ICOND is under development. It implements the calculation procedure in BS EN ISO 13788:2002, which is referred to in the new British Standard Code of Practice for the control of condensation in buildings, BS 5250:2002, which came into force on 1 November 2002. At present the package is usable and gives results which comply with the standard, but it is being developed to remove bugs and make it more user friendly. Ventilation of cavities may be included as part of this development.

In the EN 13788 method the same calculations specified in the BS 5250:1989 method are carried out using boundary conditions representative of 12 months of a year (see *Boundary conditions* section). The monthly accumulation and evaporation of condensation from each interface between materials within the structure is calculated, and the following three criteria are used to assess the structure:

- **No condensation** predicted at any interface in any month: the structure is reported as being free of interstitial condensation.
- **Condensation** occurs at one or more interfaces but, for each interface concerned, all the condensate is predicted to **evaporate** during the summer months. The maximum amount of condensation that occurred at each interface, and the month during which the maximum occurred, is reported. The risk of degradation of building materials and deterioration of thermal performance as a consequence of the calculated maximum amount of moisture is considered according to regulatory requirements and other guidance in product standards.
- **Condensation** at one or more interfaces does **not** completely **evaporate** during the summer months. The structure has failed the assessment as it is assumed that further condensate will accumulate from year to year.

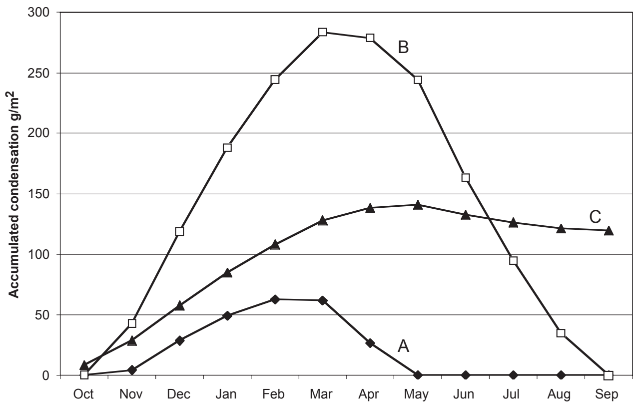

Figure 3 Accumulation and evaporation of condensation in three cases

Figure 3 shows examples of the possible results when condensation is predicted. In case A, a small amount of condensation is predicted, rising to a peak of about 60 g/m^2 in February and evaporating by May. This would not be considered a problem in all but the most sensitive of materials. In case B the accumulated condensation reaches 280 g/m^2, in March; this is likely to cause problems in most materials, even though it all evaporates by September. In case C, the peak accumulation is lower; 140 g/m^2 might not cause problems in itself but the evaporation in the spring and summer is limited, leaving 120 g/m^2 in September. More condensate will accumulate in successive years, and problems will result.

Advanced models

A number of commercially available software packages can be used to calculate interstitial condensation and moisture movement within structures. The most commonly used in the UK is the dynamic heat and moisture transfer program MATCH (Moisture and Temperature Calculations for Constructions of Hygroscopic Materials) is commercially available computer software developed in Denmark by Pedersen[3]. MATCH accounts for moisture transport by vapour diffusion and liquid suction, and therefore considers not only the vapour permeability but also the moisture retention properties of materials. MATCH has an extensive database of material properties, covering most of the common building materials. Materials are treated as either:

- hygroscopic – can absorb moisture (eg timber products, masonry, some insulation materials, etc), or
- non-hygroscopic – do not absorb moisture (eg most vapour control layer (VCL) materials, breather membranes, metal sheets, etc).

The values of 30 parameters are assigned to each hygroscopic material to describe the following properties and their variation with temperature and moisture content:

- Absorptivity
- Emissivity
- Density
- Thermal capacity
- Thermal conductivity as a function of temperature and humidity
- Vapour permeability as a function of humidity
- Moisture absorption (wetting) and desorption (drying) parameters, ie the moisture content as a function of humidity
- Liquid suction parameters

The non-hygroscopic materials are defined by single values of thermal and vapour resistance only.

MATCH offers the possibility of simulating the behaviour of a construction for periods of a year or more at hourly time-steps for climate data applicable to the UK. Four test reference years (TRY) at Kew, Eskdalemuir, Lerwick and Aberporth are supplied, each containing hourly values of the following climate variables:

- Dry bulb temperature
- Dew point temperature
- Global solar irradiance
- Diffuse solar irradiance
- Direct solar irradiance
- Wind speed
- Cloud cover

It is also possible to create custom climatic data for input, eg measured climate or test boundary conditions. The internal conditions (temperature and humidity) are usually specified in the input file as monthly values. However, it is possible to create a data file containing hourly values with the external boundary conditions.

The effect of water being entrapped, for example by rain falling on insulation during construction, can be simulated by setting the initial relative humidity in a layer to 100%. The program then automatically sets the moisture content to the highest value corresponding to this on the sorption curve for that material.

Air infiltration within a structure

In some structures, such as timber framed walls, timber flat roofs and especially domestic pitched roofs, warm humid air from inside the building can penetrate the structure to reach cold areas on the outside of the insulation. As moisture transfer by air movement is much greater than that by diffusion through materials, this can add greatly to the rate of condensation, exacerbating problems. Common routes are the joints where walls meet ceilings and floors and between lining boards, and through penetrations such as electrical sockets, plumbing fittings, hatches and light drops. The air flows can be much more important in buildings such as operating theatres, electronics factories or clean rooms that are operated at an over-pressure to reduce ingress of contaminants.

With the exception of domestic pitched roofs, where measured infiltration data and a prototype condensation model are both available, no data on the infiltration rates into structures are available and no models have been developed that can assess the effect of infiltration on the condensation rate.

Properties of materials

Properties needed for modelling interstitial condensation

If any estimate, however crude, is to be made of the risk of interstitial condensation within a structure, some information about the properties of the materials present must be available. Simple common-sense information such as 'steel sheets are impermeable to water vapour' or 'mineral wool is permeable' can be helpful when carrying out a preliminary assessment of whether a structure is likely to give problems and when an analysis method is being chosen. At the other extreme, if a full analysis using the advanced calculation techniques described above is necessary, detailed information on the thermal and moisture properties of each material and the ways in which these properties respond to changes in temperature and moisture content, will be necessary.

The simple properties needed for EN 13788:2002 calculations are generally, but not universally, available and standardised measurement methods exist. However, this is not so for the more complex properties needed for advanced calculations; measured data are available for few materials and the methods for measuring many of the parameters have yet to be standardised.

The following sections summarise the data needed for both Glaser and advanced calculations and give brief guidance on availability of the data and techniques for measurement.

Data needed for BS EN ISO 13788:2002 calculations

Only two material properties are necessary for BS EN ISO 13788:2002 calculations – thermal conductivity and vapour permeability.

Thermal conductivity

The thermal conductivity, λ (W/mK), of most building materials has been measured for many years for use in energy calculations and is widely available. Conductivity increases with material moisture content and published data include values for materials equilibrated at 50% and 90% relative humidity. The user should chose appropriate values, for example a high-humidity value for an outer leaf of brickwork, and a low-humidity value for an inner leaf.

Heat transfers across air cavities and at the inside and outside surfaces of buildings occur by a complex combination of conduction, radiation and convection. These processes are represented by the effective thermal resistance, R_T (m^2K/W), of the cavity or surface that depends on the direction of heat flow and the cavity width.

Thermal conductivities are measured by a guarded hot plate apparatus in accordance with ISO 8302, heat flow meters in accordance with ISO 8301 or a hot box apparatus in accordance with ISO 8990.

Measured data are available from manufacturers, BS 5250, EN 12524 and in references 5 to 9.

Vapour permeability

Vapour permeability, δ_p (g·m/MN·s), expresses the ease with which water vapour will flow through a material under a vapour pressure difference. It has been measured for most commonly used materials and tabulated data are available from a number of sources.

The apparent permeability of most porous materials rises with increasing moisture content, as more transport occurs by liquid water movement. Two values, the 'dry cup' representative of low humidities and the 'wet cup' representative of high humidities, are usually quoted. The user should choose the value appropriate to the location of a material in the structure. The method for measuring vapour permeabilities is standardised in BS EN ISO 12572:2001.

The vapour resistance, R_v (MN·s/g), of a layer is given by the thickness of the layer, d (m), divided by the permeability:

$$R_v = d/\delta_p$$

For materials such as plastics membranes or metal sheets, a vapour resistance is usually quoted directly, without reference to the thickness.

Although values for the permeability of still air are quoted, it is assumed that, because of convection, the permeability of the air in cavities and at the surfaces of building structures is effectively infinite, ie the resistance is zero.

European standards (including BS EN ISO 13788:2002) and manufacturers' data sheets commonly quote vapour resistivities or resistances in the form of the water vapour resistance factor, μ, or the equivalent air layer thickness, s_d. These are defined as:

$\mu = \delta_a/\delta$ and
$s_d = \mu d$

where: δ_a = vapour permeability of still air
δ = vapour permeability of the material
d = thickness of a sample of material (m)

The permeability of air, δ_a, varies with temperature and atmospheric pressure (see BS EN ISO 12572:2001). However, a value of 0.2 g·m/MN·s should be taken as typical of UK conditions. Therefore to convert a μ-value to a vapour resistivity in the units given in BS 5250:2002, MN·s/g·m, divide by 0.2. Similarly, to convert an s_d value into a vapour resistance in MN·s/g, divide by 0.2.

Measured data are available from manufacturers, BS 5250, EN 12524 and in references 5, 8, 9, 10 and 11.

Data needed for advanced calculations

Information on many more parameters, as well as the thermal conductivity and vapour permeability described above, is needed for more advanced calculations.

Density

Density, ρ (kg/m^3), is available for most materials and is measured by the methods specified in BS EN 1602:1997.

Measured data are available from manufacturers and in references 5, 7, 8 and 9.

Specific heat capacity

Specific heat capacity, C (J/kgK), is so widely available that there is no demand for a standard method for its measurement.

Measured data are available from manufacturers and in references 5, 7, 8 and 9.

Porosity

Porosity, ξ, is defined as the total volume of the voids within a porous medium divided by the total volume of the medium.

Details and requirements for porosimetry measurements are given in BS 7591 Parts 1, 2 and 4.

Porosity is relevant only to materials such as plastics foams, masonry, mortars and plaster, that have a regular pore structure. Some data are available from manufacturers for individual products, but there is no general catalogue of data.

Water sorption coefficient

The water sorption coefficient, A (kg/(m^2·s$^{1/2}$), describes the rate of moisture uptake by a surface of a given material.

A number of product standards that cover specific materials have been available for some time. These have been superseded by BS EN ISO 15148:2001 which covers all materials.

Few measurements of the water sorption coefficient are available. Measurements are generally carried out when they are required.

Sorption isotherm

The sorption isotherm defines the relationship between the moisture content of a hygroscopic material and the relative humidity of the air surrounding it. It is usually expressed as a graph of moisture content versus humidity, or a functional relationship between them.

A number of product standards that cover specific materials have been available for some time. These have been superseded by BS EN ISO 12571:2000 which covers all materials.

Two comprehensive catalogues of sorption isotherms that cover most common materials are available[10,12].

Liquid water diffusivity

Liquid water diffusivity, D_w (m/s), is mainly used to describe moisture transfer in the liquid phase. It relates the movement of liquid water through the pores of a material to the moisture content gradient and is one of the most important parameters for full modelling of the hygrothermal performance of materials and structures. Unfortunately it is also one of the most difficult properties to measure and there are no standard methods available and no data available except in research reports[9].

Emissivity

The emissivity, ε, of a surface represents the amount of thermal radiation it will emit compared with an ideal 'black body'. Most materials have emissivities of between 0.9 and 1.0. However, values for polished metal surfaces may fall as low as 0.1 or less. As the emissivity also determines the amount of incoming radiation reflected by a surface (reflectivity = 1 – emissivity), it determines the response of a building to solar radiation during the day and long-wave radiation loss at night.

There is no current standard for measurement of emissivity, but some data are available in reference 5.

Boundary conditions

To calculate the risk of condensation or the movement of moisture in any structure it is necessary to assume appropriate internal and external environmental conditions.

Internal conditions

The difference between the vapour pressures inside a building and that outside provides the driving force for interstitial condensation. As the external vapour pressure is a given factor of the outside environment, the critical parameter is the internal vapour pressure, which depends primarily on the moisture generated by the activities within the building and its ventilation rate. Vapour pressures within a dry goods warehouse will be much less than those in a laundry or swimming pool. Internal temperatures are also relevant for two reasons: a higher temperature will support a higher vapour pressure at the same relative humidity, and a high temperature difference between inside and outside creates stack pressure differences that drive air carrying water vapour through the air-permeable structures. This effect can be greatly exacerbated in those buildings such as operating theatres or clean rooms which are operated at an over-pressure to avoid ingress of contaminants.

The only relevant internal climate parameters are, therefore, the air temperature and relative humidity or vapour pressure, except in buildings that operate at an over-pressure, where total pressure also has to be taken into account.

The approach adopted in BS EN ISO 13788:2002 and quoted in BS 5250:2002 is based on the 'Climate Class' methodology developed in the Netherlands in the 1980s and used in Dutch and Belgian standards ever since. This assumes the following:

- Buildings are heated to a constant internal temperature of 20 °C all year
- The moisture generated within the building depends on the building use
- The vapour pressure inside the building depends on the outside value plus a vapour load which is determined by the moisture generation rate and the ventilation rate
- Ventilation rates are high in the summer, when windows are open more often, and fall in the winter, when they are kept closed

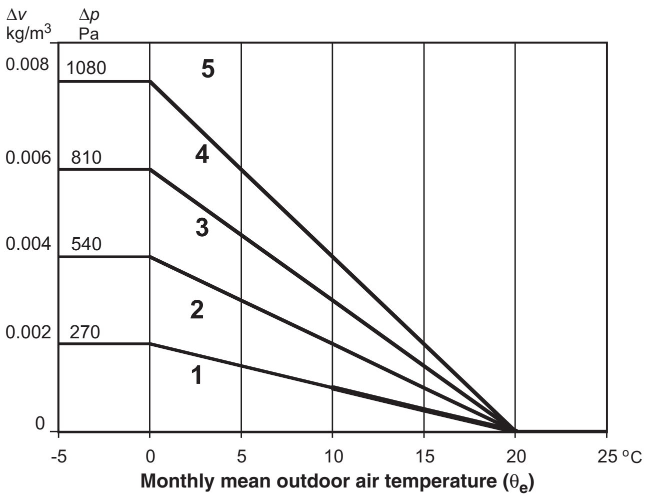

Figure 4 Variation of internal humidity classes with external temperature for five different types of building occupancy

These assumptions produce the distribution of vapour load, Δp, against outside temperature shown in Figure 4, for five different types of building occupancy.

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

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

The calculations specified in BS EN ISO 13788:2002 are carried out using monthly mean air temperature and relative humidity

Table 1 Internal humidity classes: building types and limiting relative humidities at T_e = 0 °C

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	Dwellings with high occupancy, 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

representative of the use of the building. Generally a constant internal temperature of 20 °C is assumed and the internal humidity calculated assuming a moisture load in one of the five classes shown in Table 1.

While MATCH can be run using an input file of hourly values of internal temperature and humidity, the difficulty of obtaining these for almost all buildings means that it is more common to use monthly means. The MATCH calculations for this paper have used the same internal data as used in the BS EN ISO 13788 calculations.

External conditions

Relevant parameters

External air temperature is the most important parameter in all construction types as it determines the temperature in the zone outside the insulation, where condensation is most likely. This can be modified by the effects of radiative cooling and heating in some construction types.

The loss of long-wave radiation to a clear night sky can cool the external surface of a building to several degrees below the air temperature, significantly increasing the rate of condensation. This effect is most important for flat roofs, becoming less significant as the pitch of a roof increases; it can, however, still be an important effect in vertical walls. Lightweight structures, such as sheeted metal roofs and walls, are much more affected than massive structures, which have sufficient thermal inertia to maintain their temperature during one cold night.

Conversely, solar radiation warms the external surface and can aid the evaporation of condensation that has occurred in colder periods. In some constructions, however, especially those containing elements that can store significant amounts of moisture, solar radiation can drive moisture in and cause condensation on an impermeable inner lining. Flat roofs and south-facing pitched roofs and walls are most affected; however, even north-facing walls receive some solar input in the summer. As with cooling from radiation loss, lightweight structures are more strongly affected than massive ones. Figures 5 and 6 show the external air temperature and the surface temperature of a flat roof, calculated by MATCH, on three winter and three summer days. The effect of radiation causing sub-cooling overnight, even in the summer, and over-heating by day, even in the winter, can be clearly seen.

External vapour pressure is strongly linked to external temperature, and is, in any case, of secondary importance in systems with impermeable outer layers. It can, however, play an important role in structures, such as cold roofs and some cladding systems, that rely on a ventilated cavity for successful performance.

Wind speed can be relevant in a number of complex ways: it provides the main driving force for ventilation in ventilated systems; by creating negative pressures over, for example, the ridge of a roof it can draw warm humid air out of a building through air permeable systems, greatly increasing the risk of interstitial condensation; and wind drives rain against the façade of a building increasing the moisture content of external elements.

Rain falling on roofs, or being driven by the wind against walls, increases the moisture content of components. This moisture may then move under humidity and, especially, temperature gradients, into areas where it may cause problems.

Parameters used by the models

The BS 5250:1989 and EN 13788 methods both use only temperature and relative humidity as the external boundary conditions. The BS 5250:1989 method uses 60 days of winter weather, generally the mean January and February conditions. The EN 13788 method uses a year of 12 monthly mean values. These monthly means are freely available for many locations in the UK and Europe.

MATCH uses years of hourly values of temperature, relative humidity, wind speed and various solar radiation parameters. Other advanced programs can take rainfall rates and total pressure. The need for hourly values severely limits the availability of data. All meteorological

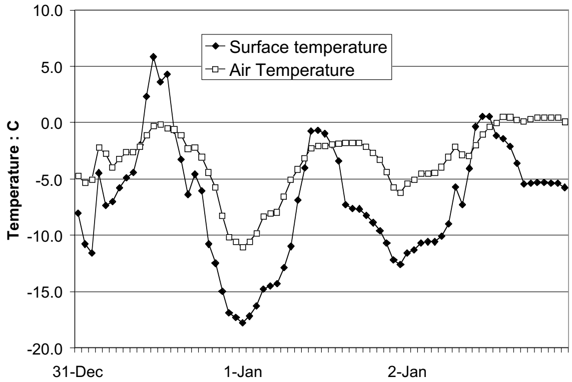

Figure 5 Air and surface temperatures during three winter days

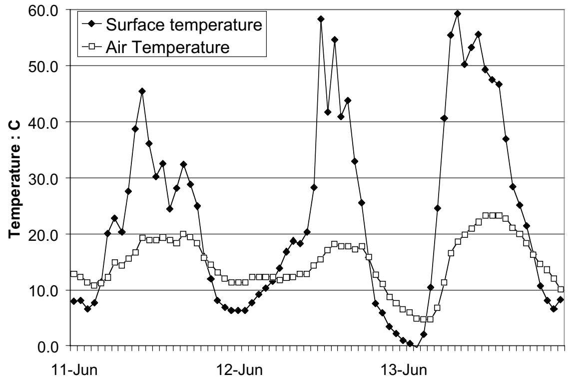

Figure 6 Air and surface temperatures during three summer days

services charge for the supply of this information; in the UK, for example, the Met Office charges several thousand pounds for a year of hourly values of the required parameters. Software exists that can be used to construct artificial years of hourly values from monthly means. It has been developed for solar applications, where it has proved successful, but it is less reliable in moisture applications.

The most commonly used source of data for running MATCH and other similar software, is the EC Test Reference Years (TRYs). These were constructed in the 1970s, by assembling typical months from 20 years of data, to produce a year that would be typical of long-term average conditions at each locality, for calculations of energy use. They are freely available for 27 locations in Europe, including four in the UK: Kew in south-west London, Aberporth on the west coast of Wales, Eskdalemuir in the Southern Uplands of Scotland, and Lerwick in the Shetland Isles.

Appropriate external data

Monthly mean temperature data are available for many locations relatively easily. However, vapour pressure data are rather more difficult to obtain. The only useful source is the CD-ROM *International Station Meteorological Climate Summary, Version 3.0* available from the US National Climate Data Centre, which contains information for 43 UK stations and many more around the world. Table 2 summarises the mean temperatures and relative humidities, calculated from the mean temperature and vapour pressure, for London, Manchester and Edinburgh.

The data in Table 2 are derived from long-term means and can be used for calculating parameters such as the long-term energy performance of a building, but are less appropriate for calculating the potential damage due to condensation. Any construction that just passes the BS EN ISO 13788 criteria, using these external climates, will fail in half the years. It is more satisfactory to use the climate, which is more severe in condensation risk terms, that may recur once in *N* years, where *N* is a number appropriate to the likely consequences of condensation occurring. In most buildings a once-in-ten-year risk might be adequate. However, in particularly sensitive buildings (eg computer centres, etc) once-in-50-years might be more appropriate.

Condensation risk years with various return periods can be constructed by changing the monthly temperatures and relative humidities from a mean year with the corrections shown in Table 3.

Table 3 Corrections to monthly mean temperatures and relative humidities from a mean year to achieve condensation risk years with various return periods

Risk	Temperature (°C)	Relative humidity (%)
1 in 5	–1	+2
1 in 10	–1	+4
1 in 20	–2	+4

In the analysis for this paper, the MATCH calculations have used the hourly values from the Eskdalemuir TRY which is considerably colder than a cold year in southern England and the Midlands. These data therefore represent the most severe conditions likely to be experienced by UK housing. The monthly mean values from Eskdalemuir were used for the ICOND calculations.

Table 2 Monthly mean temperature and relative humidity for interstitial condensation calculations

	Heathrow (London)		Ringway (Manchester)		Turnhouse (Edinburgh)	
Month	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)
Jan	4.9	84	4.2	83	3.5	83
Feb	4.7	82	4.1	80	3.7	81
Mar	6.9	77	5.8	76	5.3	78
Apr	8.8	71	7.8	71	7.0	75
May	12.6	69	11.3	68	9.9	75
Jun	15.7	69	14.1	71	12.8	75
Jul	17.9	68	16.1	72	14.7	76
Aug	17.6	70	15.8	74	14.4	78
Sep	14.9	75	13.3	77	12.1	80
Oct	11.2	81	10.3	81	9.2	82
Nov	7.6	84	6.7	82	5.8	83
Dec	5.9	86	5.2	84	4.3	84

The appropriate model for different construction types

The following sections summarise, for a range of different construction types, the findings of the most appropriate analysis methods that should be used to predict interstitial condensation.

Externally insulated solid masonry wall
Air infiltration from the inside and ventilation of cavities are not relevant. EN 13788 calculations suggest that there may be a small amount of condensation behind the external surface in the winter that will not affect the performance. Analysis with MATCH, including the liquid water transport, suggests that there will be a steady, if slow, accumulation of water within the wall causing a slow deterioration in performance over time.

Masonry cavity wall with full fill insulation
Air infiltration from the inside and ventilation of cavities are not relevant. EN 13788 calculations suggest that this construction, which is widely used without apparently giving any problems, will suffer from severe condensation on the outer leaf, which will promote frost damage and render the insulation ineffective. MATCH calculations, including liquid water transport, show that the condensed water will move into the brickwork, and never raise the moisture content high enough to cause any problems.

Masonry wall with partial cavity fill
Air infiltration from the inside is not relevant but ventilation of the cavity will affect the incidence of condensation. Both the EN 13788 and MATCH calculations agree that only minor condensation will occur in the outer leaf, which will not affect the performance of the wall. Even a minimal amount of ventilation to the wall cavity will eliminate any condensation.

Masonry cavity wall with internal insulation
Air infiltration from the inside is not relevant but ventilation of the cavity will affect the incidence of condensation. EN 13788 calculations predict severe condensation on the inner face of the internal leaf, which will affect the performance of the wall even though it will all evaporate in the summer. Ventilating the cavity between the masonry leaves will have little effect on this. MATCH calculations with liquid transport included confirm this finding.

Timber framed wall
Both air infiltration from the inside of the building into the wall and ventilation of a cavity may affect the risk of condensation. EN 13788 calculations show that there will be severe condensation on the plywood sheathing that will cause structural problems within a few years. This is confirmed by MATCH calculations. Ventilating the cavity outside the sheathing plywood has little effect. Air infiltration into the structure from inside will increase the risk of condensation. There is at present no method of assessing the effect of air infiltration on performance, except to assume that it will make condensation problems worse.

Timber flat roof
Both air infiltration from the inside of the building into the roof and ventilation of a cavity may affect the risk of condensation. EN13788 calculations show that there will be severe condensation on the plywood deck that will cause structural problems within a few years. This is confirmed by MATCH calculations. Ventilating the cavity inside the plywood deck plywood eliminates the risk of condensation, but may be difficult to achieve in practice. Air infiltration into the structure from inside will increase the risk of condensation. There is at present no method of assessing the effect of air infiltration on performance, except to assume that it will make condensation problems worse.

Concrete flat roof
Air infiltration from the inside and ventilation of cavities are not relevant. EN 13788 calculations suggest that water will accumulate within the insulation, adversely affecting the thermal performance. A full MATCH calculation suggests that the moisture capacity of the concrete will act as a buffer and limit the amount of winter condensation to acceptable levels.

Domestic pitched roof
As the risks of condensation are dominated by air flows from the house to the roof and ventilation of the loft, neither EN 13788 models nor MATCH are relevant. A dedicated model has been developed to predict condensation in pitched roofs.

Built-up sheeted metal roofs
As air flows and quality of workmanship dominate the risks of condensation, neither Glaser models nor MATCH are relevant.

Conclusions

A number of more general conclusions can be drawn from the construction types outlined above.

- Ventilating a cavity within the structure that is on the warm side of the area in which condensation is taking place, will reduce and usually eliminate the condensation. Ventilating a cavity on the cold side of the condensation area will make little or no difference.
- Air infiltrating the structure from within the building can increase the condensation rate greatly. Except in the special case of domestic pitched roofs, neither the models nor the flow rate data necessary to quantify this effect are available.
- In lightweight structures with little capacity for storing water in materials, such as timber framed walls and timber flat roofs, Glaser models give similar predictions to the advanced MATCH calculations and can therefore be used to give robust advice.
- In massive structures with the capacity to store water in the materials, Glaser calculations will generally overestimate the risk of problems in those cases where the materials are starting dry. Glaser calculations will therefore fail safe, but may be unnecessarily restrictive.
- In massive structures with the capacity to store water in the materials, Glaser calculations will not deal with situations where the materials may have started wet because of built-in construction water or rain impact during construction before a weatherproof layer was complete. In these circumstances, advanced calculations using MATCH, or a similar program, are advisable.

Controlling interstitial condensation

To minimise interstitial condensation, it is necessary to do one or more of the following.

- Obtain low vapour pressures by ventilation or reduced moisture input to the building, or both
- Use materials of high vapour resistance near to the warmer side of the construction
- Use materials of low vapour resistance, or provide ventilated cavities, near the colder side of the construction
- Use materials of low thermal resistance near to the warmer side of the construction
- Use materials of high thermal resistance near to the colder side of the construction

If that condensation is judged to be harmful, take steps to limit the amount of moisture reaching the colder elements by using vapour control layers or inner layers of relatively high vapour resistance or by the inclusion of a ventilated air space between the insulation and the outer elements.

Vapour control layers

Where a vapour control layer is specified, it should be of appropriate vapour resistance and should be situated on the warm side of the insulation. A vapour control layer placed within the insulation will be colder and be a possible site for condensation in a high humidity environment.

It is difficult to construct an impervious layer in practice. For example, a vapour control layer laid above a roof deck can be constructed to have a high vapour resistance, but if the same material is fixed to the soffit, it will be much more difficult to achieve the same resistance. The performance of a vapour control layer depends upon the design life of the building, the material selected, workmanship and buildability. Any holes, fixings, pipes or electrical fittings will downgrade performance and should be considered in the design.

Lap joints in a flexible sheet vapour control layer to a minimum of 50 mm and seal with an appropriate sealant, and make the joint over a solid backing member or substrate. Similarly, repair tears and splits using an overlay of the same material, jointed as above. If polyethylene sheeting is used, protect it from heat and sunlight to reduce the risk of degradation.

Where a vapour control layer is incorporated in or on a rigid board or profiled metal liner sheet, seal joints between adjacent boards with an appropriate sealant or tape, or cover or otherwise close the joints to avoid mass transfer of water vapour due to air leakage.

Extend the vapour control layer over the whole of the internal roof and wall areas. Keep side and end joints to a minimum. Carefully consider at the design stage this requirement to achieve a functional vapour control layer. Attach great care and importance to the design of different construction elements and the connections required between different materials. Integrate vapour control layers with and seal them to other building elements such as masonry, upstands and glazing systems.

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