Condensation Risk and Improved Thermal Performance of Housing

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Summary

This paper considers the likely impact of alternative conservation measures on the incidence of surface and interstitial condensation on or within the elements of the building fabric. It concentrates specifically on domestic buildings in temperate climates, e.g. UK and Ireland. After outlining the mechanism whereby condensation occurs and some of the shortcomings of treating the phenomenon from a static point of view, the paper goes on to consider energy conservation measures under three broad headings, i.e. reduction of heating levels, reduction of ventilation and increase in insulation. It establishes the need for special precautions to prevent condensation and mould growth problems where average ventilation rates of less than one air-change per hour are envisaged. The paper also shows that insulated constructions reduce the incidence of surface condensation. However, special precautions may be required to prevent harmful interstitial condensation.

Les Risques de Condensation et l'Amélioration de la Performance Thermique de l'Habitat

Ce rapport examine l'effet probable de diverses mesures de conservation sur l'incidence de condensation de surface et interstitielle sur ou dans les éléments de la charpente. Il se penche spécifiquement sur l'habitat dans un climat tempéré tel que celui du Royaume Uni et de l'Irlande. Après un aperçu du mécanisme de formation de la condensation et de quelques désavantages résultant d'un traitement statique de ce phénomène, le rapport examine trois grandes catégories de mesures de conservation de l'énergie: réduction du niveau de chauffage, réduction de la ventilation et augmentation de l'isolation. Il établit la nécessité de prendre des précautions spéciales pour empêcher les problèmes de condensation et de moisissure lorsque l'on envisage des taux moyens de ventilation entraînant moins d'un changement d'air par heure. Le rapport démontre aussi que l'isolation des bâtiments réduit l'incidence de condensation des surfaces. Toutefois des précautions spéciales contre la condensation interstitielle nuisible peuvent être nécessaires.

Introduction

This paper considers the likely impact of alternative energy conservation measures on the incidence of surface and interstitial condensation on or within the elements of the building fabric. It concentrates specifically on domestic buildings in temperate climates, e.g. United Kingdom and Ireland, since condensation has long been a problem in this situation, and in recent years its incidence appears to have increased rather than decreased. The traditionally recommended measures to prevent condensation are heating, ventilation and insulation, i.e. an increase in the level of one or all of these should prevent condensation.

Clearly increased heating and ventilation levels are not to be recommended from the energy conservation point of view - in fact the opposite may be desirable. Thus, there is an apparent conflict between the objectives of energy conservation and prevention of condensation as far as these are concerned. Both objectives, however, imply an improvement in insulation levels. Yet, even here, conflicts can arise, since increased insulation levels can reduce the temperature within the building's external elements and, therefore, increase the likelihood of interstitial condensation. This depends on where the insulation is placed and the arrangements made to prevent moisture ingress into the structure.

Condensation in Buildings

Before considering the impact of energy conservation measures in this context, it is desirable to refer to the basic mechanism by which condensation occurs, and some limitations of the simple steady-state condensation risk analysis method (or the dew-point method) as applied to building design. Condensation will occur at any point within a building where the partial water vapour pressure reaches saturation vapour pressure at that point. Saturation vapour pressure is directly related to temperature. The actual vapour pressure is directly related to the moisture content of the air. The relative humidity, i.e. actual vapour pressure expressed as a percentage of saturation vapour pressure, is therefore dependent on both temperature and moisture content. These relationships are usually presented in the form of a psychrometric chart.

In buildings, both temperature and moisture content in the enclosed air vary. Thus, it is possible that temperature and moisture content combinations will occur which make condensation inevitable. The likelihood of these occurring depends on a number of factors, e.g. the temperature pattern maintained within the building, the rate of moisture production within

the building, the basic moisture content of the external air and any arrangements for removing excess moisture content. Since, in general, the temperature of the surfaces of at least some of the enclosing elements will be lower than the room air temperature, condensation will occur initially on the surfaces rather than as a mist internally in the building. In addition to internal surface condensation, condensation can also occur within the external fabric elements of the building, i.e. within cavities or in the pores or interstices of porous materials. Since temperatures and water vapour pressures on both faces of any fabric element differ, there is a temperature gradient and water vapour pressure gradient through the element connecting internal and external temperatures and pressures respectively. If a long-term steady state existed with respect to internal and external temperatures and vapour pressures, the slopes of these gradients would depend on the thermal conductivity and vapour diffusivity of the elements' surfaces and materials respectively, and could easily be calculated.

A gradient of saturation vapour pressure corresponding to the temperature gradient can also be calculated, and by comparison with the vapour pressure gradient, the likelihood of condensation in these conditions established. This forms the basis of the widely used condensation risk analysis technique employed by designers to assess the likelihood of condensation occurring in particular constructions (1).

However, the steady state model outlined above bears little relationship to what normally occurs in real buildings. Internal and external temperatures and vapour pressures are continually changing in practice. The thermal gradient, saturation vapour pressure gradient and actual vapour pressure gradient in the element, tend to follow these changes, but considerable time lags can be involved before steady state conditions within the element are reached. The extent of the time lags depends on the thermal admittance of the structure for the thermal gradient and saturation vapour pressure gradient and on the absorptivity and moisture content of the materials for the actual vapour pressure gradient. Other factors, such as the existence of cold bridges on the one hand, or holes in wall linings and vapour barriers on the other, also affect the time lags involved. Time lags of several hours have been found in some recent research work, e.g. Rodwell (2) found time lags of the order of seven hours in the response of the vapour pressure in the cavity behind a plasterboard lining to sudden changes in vapour pressure on the other side.

The steady state condensation risk analysis is also limited by the fact that it indicates only that the risk of condensation exists. It does not indicate the point in the structure where condensation will first occur, or the mechanisms involved in determining the build-up of condensate within the structure. Considerable research work has been done on this aspect, e.g. the work of Vos and Tammes (3) and Hens (4), but further work needs to be done before there is a full understanding of the mechanisms involved in the various types of fabric elements, and a method of taking account of these at the design stage established.

Steady state condensation risk analysis is basically useful, therefore, in signalling the risk of long-term interstitial condensation, but not of short-term condensation in response to fluctuations of internal or external temperatures or moisture contents. Long-term average internal and external climatic data should be used in the calculations.

The buildings most at risk from condensation are those with a very high level of moisture production, e.g. swimming pools, laundries, and those where temperatures, moisture production and moisture removal are largely in the control of individual users and not determined by considerations of optimum comfort and relative humidity. Individual dwellings are the main building type in this latter category. Condensation control in the former category has always been a problem and is not closely related to energy conservation. Individual dwellings, however, represent a building type where it is felt that large energy savings can be made, and where certain measures aimed at achieving these savings can significantly affect the risk of condensation. This paper, therefore, concentrates on this building type.

Condensation has always been a problem in housing in Ireland and the United Kingdom. This is not surprising when one considers the climate - high relative humidity and moderate temperatures in winter - and the average temperature maintained in houses. There is little enough information on this latter, but both measured and calculated data suggest an average internal/external difference of 6 - 8°C during the heating season (5). For example, the average external temperature in Ireland for the months October - May is 7°C and the average relative humidity is about 80%. This permits an average internal/external difference of 3 mbar in vapour pressure or 2g/kg in moisture content for an average 14°C internal temperature and 70% relative humidity. The moisture production rate within dwellings is not known to any high degree of accuracy, but average production rates are suggested to lie between 7.2 kg and 14.4 kg per day (6). The lower of these, in association with an air change rate of one air change per hour, would give the above internal/external vapour pressure and moisture content differences.

Energy Conservation and Condensation

The energy conservation methods which have direct impact on the likely incidence of condensation, either surface or interstitial, fall into three broad categories:

(a) reduction of heating levels, i.e. reduced average temperatures
(b) reduction in air infiltration, i.e. reduced average rates of air change
(c) increase in insulation, i.e. increased average U values of the fabric external elements.

Air Infiltration and Temperature Control

Employment of either method (a) or (b) on its own, or both methods together will always increase the likelihood of surface condensation. This does not mean that these measures should never be adopted on their own. In situations where humidities are relatively low and temperatures or air change rates excessively high, then a reduction in temperature or air change rates or both, may be desirable. Such action will result in an increase in average relative humidity which must be kept below 70% for the prevention of mould growth. Moreover, Loudon's (7) work suggests that the relationship between internal relative humidity, heat input and air change rates is such that the gross heat input required to maintain internal relative humidity below 70% is at a minimum at between one and two air changes per hour, and increases for both lower and higher rates of air exchange. Table 1 shows this for a typical centre terrace house at different insulation levels and external temperatures. This assumes that the rate of moisture input within the house does not vary with air change rates - a reasonable assumption. Thus, where maintenance of relative humidity below 70% becomes the determining factor on temperatures and energy requirements, there is no energy saving to be made by increasing air change rates above approximately one air change per hour. In this situation there is a definite advantage in terms of comfort in keeping air change rates down to this level. There is, therefore, an optimum air change rate in terms of energy requirements for the prevention of condensation. This is about one air change per hour, and varies little with external conditions. There is some variation with the insulation level of the building - the optimum level tending to be lower for well-insulated buildings than for poorly insulated ones. For a moisture production rate of 7.2 kg/day, this air change rate implies, in Irish climatic conditions, an internal temperature 7 - 8°C above the external temperature for much of the heating season, which is close to the typical temperature currently achieved. For average daily external temperatures of 7°C or greater (which occur for approximately half of the heating season) it is not desirable to increase this temperature difference, and therefore, a rate of air exchange of one air change per hour is required. For periods when average daily external temperatures are less than 7°C a larger temperature differential is desirable, and thus a lower rate of air exchange required for optimum energy conservation. However, if houses are constructed with typical air change rates of the order of 0.6 per hour, designers must ensure that levels of one air change per hour can be easily achieved without associated problems such as draughts from open windows. This implies either mechanical ventilation or arrangements for moisture removal at source together with better controlled arrangements for natural ventilation than has been the case in the past. Indeed, given the tradition of partial and intermittent heating, with energy consumption apparently governed by economic rather than environmental determinants, there is a question mark over the desirability of attempting to attain low air infiltration rates.

Insulation and Surface Condensation

Insulation has the apparent dual advantage of reducing the risk of condensation and conserving energy. As far as surface condensation is concerned, its main impact is to increase the surface temperature of the fabric elements. This increases the dew point or saturation vapour pressure and, therefore, reduces the likelihood of condensation. Table 2 gives the internal temperature/surface temperature differences to be expected for different insulation levels and internal/external temperature difference. From this the significant impact of changing from single to double glazing or from 2.1 W/m² °C to 0.6 W/m² °C for wall U values can be seen. The virtual impossibility of avoiding condensation on single-glazing is obvious. This clearly shows the necessity of providing drainage channels and weep-holes in single glazed frames - a practice which has been generally discontinued in recent years.

In addition to the increase in surface temperatures outlined above, field studies have shown that typically higher internal temperatures are maintained in insulated houses compared with uninsulated houses (8). This arises partly from the way temperatures are determined in a partially and intermittently heated house using heating systems with limited controls and partly from consumer choice, i.e. choosing higher temperatures instead of energy savings per se. This reduces the cost-effectiveness of insulation when energy savings alone are taken into account. However, there are many other benefits from insulation, not least being the reduced risk of conden-

sation. This is particularly significant since the greatest increase in temperatures are likely to occur in those houses with the lower internal temperatures and therefore, the higher condensation risk. Generally, wall surfaces in insulated houses should be 3°C warmer than similar uninsulated ones.

As well as surface condensation associated with average levels of internal moisture content, surface condensation can also occur due to rapid changes in either the moisture content or the temperature of the air. Whilst both these may be caused by climatic factors, the more critical changes in internal temperatures are associated with occupancy factors. The trend towards intermittent occupancy and heating are both considered to be significant contributory factors determining the incidence of condensation. Intermittency implies that both heat and moisture inputs to the dwelling are concentrated in morning and evening periods - generally not exceeding three and six hours respectively. Thus, whilst air temperature and moisture content may rise rapidly in the early morning and early evening, the rise in the fabric's average and surface temperature will lag behind making condensation more likely. The extent of the lag depends on the thermal mass and insulation characteristics of the structure.

Billington (9) suggests that condensation due to intermittent heating will not occur if the following inequality is observed:

$$2U + U_s \leq P_o (2Y + Y_s)$$

Where

U = average U value of external elements (W/m² °C)

U_s = U value of element at risk (W/m² °C)

Y = average admittance value of building (W/m² °C)

Y_s = admittance of element at risk (W/m² °C)

$$P_o = \frac{\sum AU + C_v}{\sum AY + C_v}$$

C_v = heat loss due to air infiltration (W/°C)

This inequality is based on the criterion that the surface temperature should never be lower than the minimum air temperature. For this criterion to ensure that surface condensation does not occur, the rate of moisture production must be constant (which is generally not the case with intermittent occupancy) or the materials forming the wall surfaces must be such as to absorb and give up any excess moisture over a 24 hour cycle. Thus, the likelihood of surface condensation due to these causes can be seen to be a function not only of the fabric insulation level but also the location of the insulation (since this determines the admittance value) and the nature of the surface finishes. This is a possible area for further research.

Insulation and Interstitial Condensation

Thermal insulation materials, in general, have a low resistance to vapour diffusion. Thus, the addition of a layer of thermal insulation to a structure will, in general, have a marked impact on the temperatures through the structure - reducing those on the cold side and increasing those on the warm side. At the same time it will have little or no direct effect on the vapour pressure gradient. Together with the drop in temperature across the insulation material, there will be an equivalent drop in saturation vapour pressure. Therefore, there is generally a much increased risk of condensation on the cold side of the layer of insulation. This may be such as to require action to reduce the vapour pressure in this area - generally by the introduction of a vapour barrier or vapour check on the warm side of the insulation.

The degree of damage that can be caused by interstitial condensation depends on the amount and location of the condensate. One can identify a number of different situations in this context:

1. Situations where condensation at any time and in any quantity is undesirable, e.g. flat timber roofs where any condensation is likely to drop onto the ceiling underneath and, at least, cause staining problems.
2. Situations where long-term condensation - even if in small quantities - is undesirable, e.g. at the location of materials of high thermal resistance, since the thermal resistance qualities of materials are impaired when moist or wet. The joint between materials bonded with adhesives which are broken down by long-term dampness also falls into this category. Parts of the fabric containing timber, steel or other materials of which the tendency to rot or corrode is enhanced in a damp environment, also fall in this category.
3. Situations where long-term condensation causing a large volume of building fabric to become saturated occurs. This will happen if material has not got the opportunity to dry out either because of the particular construction arrangements used, or because sufficient time does not exist between one period of condensation occurrence and the next. These situations are generally to be avoided.

Provided precautions are taken to ensure that moisture is not trapped within the structure, category three above is unlikely to occur in dwellings in normal use. For dwellings, therefore, likely interstitial condensa-

tion problems are those of category one and two. This paper does not propose to deal in detail with design solutions for all such problems. This is covered in some detail elsewhere (10). Rather is it the intention to highlight specific problems that may be associated with particular measures or constructions adopted for energy conservation purposes.

(a) Pitched Domestic Roofs: The typical roof to domestic buildings in the United Kingdom and Ireland consists of tiles or slates on battens on rafters with an underlay of bitumen felt to the tiles or slates. The pitch of the rafters is generally between 20° and 35° although lesser and greater pitches are used. The ceiling is generally plasterboard fixed to timber ceiling joists. Traditionally no insulation was used, but now 50 to 100 mm fibreglass or equivalent is generally used, laid between the joists at ceiling level. It has been suggested that the addition of insulation was a major reason for an increase in incidence of condensation in these roofs in the recent past. Work at the BRE Scottish Laboratory (11) suggests, however, that whilst it may have been a contributory factor, the major factor was climatic. Other changes in construction and materials also contributed, e.g. an increased use of plastic sheeting as underlay instead of the traditional felt meant that when condensation occurred it was more likely to form droplets. In addition - and this has some basis in energy conservation - the tendency to seal houses more tightly has been carried over to roofs where tight sealing is not desirable. The reduction of air infiltration through the external fabric has meant that a higher proportion of the house ventilation took place by way of the attic bringing moisture from the house with it. Effective ventilation of the roof space, sealing of air paths from the house to attic and, for pitches less than 20°, where ventilation is not likely to be so effective, a vapour barrier underneath the insulation are recommended.

(b) Walls: In Ireland the majority of domestic external walls in the recent past were constructed of either single leaf 225 mm hollow blockwork, or two leaves 100 mm blockwork internal leaf, 50 mm cavity and 100 mm brick or blockwork external leaf. Such walls were generally rendered externally (except where brickwork was used) and plastered or lined with plasterboard internally. To improve their insulation characteristics insulation is employed either in conjunction with an internal lining, or in the cavity. Cavity insulation may or may not fill the cavity completely. Long-term condensation occurring at the insulation location may damage the insulation or be detrimental to the timber or metal fixings of the internal linings. A steady state condensation risk analysis will generally show if these dangers exist. In general, cavity insulation will give some risk of condensation in the outer leaf, but it can safely be assumed that if it occurs it will evaporate to the outside. Insulation at, or near, the internal surface however, generally gives a risk of condensation at the junction of insulation and the external wall element. Because of the location of the condensation, this will have more difficulty in drying out and is more likely to be harmful. A vapour barrier is, therefore, recommended on the warm side of this insulation, i.e. just behind the drylining.

In addition to the general risk of condensation associated with insulated walls, particular attention must be paid to cold bridges since the local lowering of temperature is likely to have more extreme effects when the rest of the element is well insulated.

(c) Vapour Barriers: The addition of insulation to traditional constructions will require, in some cases, the incorporation of a vapour barrier or vapour check on the warm side of the insulation to prevent harmful interstitial condensation. Whilst its theoretical effectiveness in eliminating the risk of interstitial condensation can easily be shown, doubt has been cast on the performance of vapour barriers in practice. There are generally two reasons given for this doubt:

(i) Even with good workmanship it is extremely difficult to achieve a true vapour barrier, and

(ii) the lack of tradition in this type of work, and the general level of quality control enforced in domestic construction, mean that a true vapour barrier would generally not be achieved in practice.

Both of these reasons carry some weight and, without getting involved in a broader topic at this point, it seems fair to say that there is an urgent need for the education of operatives and practitioners at all levels in the industry on the need for care in the design and installation of constructions incorporating insulation layers and vapour barriers. At the design level, detailing should be such as to avoid as far as possible the necessity to penetrate vapour barriers with water pipes, electric conduits, etc. At site level care must be taken to avoid damage to vapour barriers before, during, and after placement, to ensure proper detailing at joints in vapour barrier material, and to seal any punctures which do occur in the vapour barrier. In addition, constructions should generally be such as to allow the escape of any moisture which does penetrate past the vapour barrier rather than depend solely on the vapour barrier to prevent moisture ingress.

The impact of perforations, tears and holes on the performance of vapour

barriers is an area where further research is required. Seiffert (12) has reported that, for aluminium sheet, perforations equivalent to 0.22% of area reduce its vapour resistance from 6,000 MNs/g to 1.4 MNs/g. Rodwell (13) reports reductions of a similar order for polythene sheets 0.022 to 0.04 mm and 0.10 mm thick. However, Rodwell further reports that damage to barriers attached to board material is not so disastrous. For example, foil-backed and polythene-backed plasterboard, with holes equivalent to 2.37% of their area, whilst their performances were reduced by factors of 24 and 12 respectively, were still ten times more effective as vapour barriers than undamaged plain plasterboard. These experiments were in situations where moisture passing through the vapour barriers was free to diffuse outwards from the construction. Clearly, further information is required about the performance of vapour barriers in practice.

Conclusion

This paper suggests that, in certain situations, there is conflict between the objectives of energy conservation and prevention of harmful condensation. However, careful design and construction should overcome these problems. In particular, reduced average ventilation rates (below one air change per hour) require positive means of removing moisture at source. Insulated external elements should always be checked for the likelihood of harmful long-term interstitial condensation, and, where necessary, steps taken to prevent this. In general, higher insulation levels should greatly reduce the risk of surface condensation and mould growth through increased surface temperatures and probably increased air temperatures. Two areas for further research are the short-term response of fabric temperature and vapour pressure to fluctuations in internal and external air temperatures and vapour pressures and the performance of vapour barriers in practice.

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Air Change Rates (Volumes/hr)	Internal Moisture Content (g/kg dry air)		Internal Temperature (°C)		Useful Energy Required (kWh) Insulation A		Insulation B		Insulation C	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
0.3	7.6	9.6	15.3	19.0	2445	1918				
0.6	5.5	7.5	10.3	15.0	1850	1437	1438	1117	2468	1917
1.0	4.65	6.65	8.0	13.3	1648	1298	1328	1046	2128	1676
1.4	4.3	6.3	6.8	12.4	1580	1255	1308	1039	1988	1579
2.0	4.0	6.0	5.9	11.7	1604	1278	1369	1090	1959	1560
3.0	3.8	5.8	5.0	11.3	1690	1453	1490	1281	1990	1711
4.0	3.7	5.7	4.7	11.0	1899	1616	1711	1456	2181	1856

Table 1. Energy and internal temperature requirements to maintain 70% average relative humidity in typical centre terrace house

Note: (a) : External temperature = 0°C r.h. = 90%
(b) : External temperature = 7°C r.h. = 90%
Insulation A : Average fabric U value = 1 W/m² °C
Insulation B : Average fabric U value = 0.7 W/m² °C
Insulation C : Average fabric U value = 1.4 W/m² °C

Internal/External Temperature Difference (°C)	Fabric U value (W/m² °C) 5.6	4.7	3.4	2.7	2.1	1.7	1.1	0.6	0.4
4	2.8	2.3	1.7	1.3	1.0	0.8	0.5	0.3	0.2
8	5.5	4.6	3.3	2.7	2.1	1.7	1.1	0.6	0.4
12	8.3	6.9	5.0	4.0	3.1	2.5	1.6	0.9	0.6
16	11.0	9.2	6.7	5.3	4.1	3.3	2.2	1.2	0.8
20	13.8	11.6	8.4	6.6	5.2	4.2	2.7	1.5	1.0

Table 2. Difference between room and fabric surface temperatures