Condensation risk: comparison of steady-state and transient methods

D Mumovic, I Ridley, T Oreszczyn and M Davies

BUILDING SERV ENG RES TECHNOL 2006 27: 219

DOI: 10.1191/0143624406bse163oa

Building Serv. Eng. Res. Technol. 27,3 (2006) pp. 219–233

Condensation risk: comparison of steady-state and transient methods

D Mumovic Dipl Ing MSc(Dist) PhD MInstP, **I Ridley** BSc MSc PhD, **T Oreszczyn** BSc PhD CEng CPhys MCIBSE MIntE MInstP and **M Davies** BSc PhD
The Bartlett School of Graduate Studies, University College London, London, UK

Accurate assessment of both surface and interstitial condensation risk is important not only to reduce the damaging effect of moisture within the structure of buildings, but also to provide a healthy environment free from mould growth. The current British Standard (BS EN ISO 13788: 2002) contains an assessment procedure based on the assumption of a steady-state heat flow through the building envelope, neglecting the transient nature of the problem. This paper compares and evaluates numerical results of the condensation risk calculation under both steady-state and transient conditions using the existing numerical codes. Significant differences are apparent between the predictions of the simple (steady-state) and complex (transient) methods for all construction details modelled.

Practical application: The current British Standard (BS EN ISO 13788: 2002) gives calculation methods for determining the internal surface temperature of a building component or building element below which mould growth is likely, given the internal temperature and relative humidity—the method can also be used to assess the risk of other surface condensation problems. The calculation methods in the Standard are steady-state. The paper concludes that for cases where the steady-state method predicts that surface RH values will remain below the key value of 80%, a transient method can predict surface RH values to be *above* 80% for several hours. The practical implications of this work then are that transient calculation methods may be necessary under certain circumstances. This is particularly relevant given that the issue of a time period of a few hours is now more pertinent as it relates to a new *transient* performance standard in the new draft Approved Document F (Building Regulations—England and Wales).

1 Introduction

Moisture transport through building components is of great importance due to the damaging effects moisture can cause to a building envelope. In addition, the 'English House Condition Survey 1996 Energy Report' indicates that a higher percentage of respiratory problems occur in cases where moderate and severe mould is present.[1] Mould growth is reported in 14.6% of the total housing stock in England.[2] This is not only a health hazard but also a major source of distress for householders. Woolliscroft[3] stated that the high level of condensation and mould in the UK is the consequence of the small size of dwellings, low temperatures, high humidity of the incoming air, and the high occupancy of dwellings.

The calculation methods currently used in the UK to assess the risk of surface and interstitial condensation and mould growth

Address for correspondence: D Mumovic, The Bartlett School of Graduate Studies, University College London, 1-19 Torrington Place, London WC1E 6BT, UK. E-mail: d.mumovic@ucl.ac.uk

10.1191/0143624406bse163oa

are specified in the following standard—BS EN ISO 13788: 2002: 'Hygrothermal performance of building components and building elements—Internal surface temperature to avoid critical surface humidity and interstitial condensation methods'.[4] Although recently revised, it is recognized that the new Standard contains limitations.[5] This paper highlights the limitations of the Standard which have arisen from the assumption of simplified and non-transient heat and moisture transport through building envelopes.

Under steady-state conditions, the internal surface temperature of a construction detail is a function of the surface thermal resistances, the thermo-physical characteristics of the materials used, and the internal and external temperatures. The values of the external and internal surface thermal resistances which should be used to assess the risk of condensation and mould growth are defined in the Standard. The risk of mould could be significantly underestimated by neglecting the diurnal fluctuations of the external and internal environmental conditions and the transient response of the construction. For example, surface temperatures may lag behind internal ones, leading to the possibility of condensation problems occurring when steady-state modelling suggests there may be none. In general, 'heavyweight' construction details are more prone to the occurrence of condensation than 'lightweight', especially when large quantities of water vapour are generated as soon as the heating starts as may be the case in intermittently heated bathrooms and showers.

Mould will often first occur at the site of thermal bridges ie, areas of the building envelope where heat flows are higher than through the rest of the building due to both the geometry of the construction and the thermal properties of materials used.[6] This is because the internal surface temperatures will be lower, and hence relative humidity (RH) higher, on surfaces with higher heat flows. Unlike condensation, mould growth may occur below 100% RH. For example, mould is likely on wallpaper if RH is maintained above 80% hence imposing stricter thermal quality criteria to building envelopes.

This paper quantifies the difference in modelled surface and interstitial relative humidity for a number of typical construction thermal bridge details using both simple steady-state and complex transient models and therefore provides a quantitative indication of the types of uncertainties which simple steady-state modelling may introduce.

2 Methodology

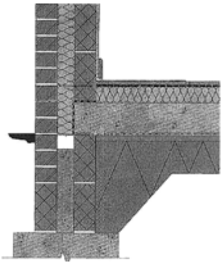
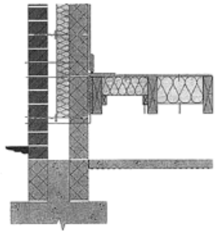
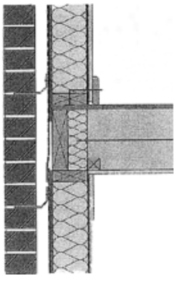
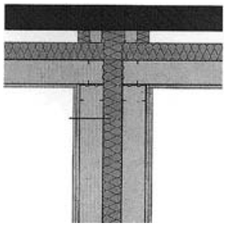
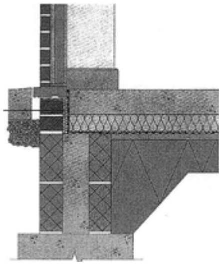
To prevent condensation occurring on new constructions where heat loss is controlled by the Building Regulations of England and Wales, the Government has published guidance on limiting thermal bridging.[7] This 'Robust Detail' document is aimed at helping the construction industry to meet the new performance standards for thermal resistance and airtightness. The construction details contained in the document have been rigorously analysed to confirm that they are robust if constructed with reasonable attention to workmanship and supervision.

The Robust Construction Details (RCD) selected for analysis in this paper (see Table 1) are those which have been identified[8] as being particularly prone to difficulties in construction on site.

The severity of the thermal bridges presented in Table 1 is characterized using the surface temperature factor (f), a dimensionless coefficient between 0 and 1:[9]

$$f = \frac{\text{Internal surface temperature} - \text{External air temperature}}{\text{Internal air temperature} - \text{External air temperature}}$$

Table 1 RCDs Modelled

Geometry	DTLR[7]	Description	f [–]
	3.16.	Masonry. Suspended ground floor slab with insulation above slab. Ground floor/external wall junctions.	0.815
	4.19.	Masonry. Timber suspended ground floor.	0.790
	6.18.	Timber frame, timber intermediate floor.	0.875
	7.12.	Steel frame. Separating wall	0.980
	8.06	Level door threshold. Insulation below slab.	0.775

The value of f is close to 1.0 for a well insulated structure, but will fall below 0.5 for severe thermal bridges. Generally, a surface temperature factor of 0.75 is considered to be sufficient to avoid mould growth in UK dwellings.[9] All the modelled details satisfy this criterion.

2.1 Surface condensation risk

To assess the risk of surface condensation and mould growth in dwellings using the simple steady-state method of calculation defined in the BS EN ISO 13788: 2002, the thermal analysis model TRISCO[10] was used. This is a steady-state heat transfer tool based on the finite difference method. A detailed account of the model is given in the user manual.

Quality assurance was undertaken to test the performance of the model as required for 'high precision calculation methods' according to Annexe A of BS EN ISO 10211-1:1996 (EN ISO 10211-1:1995).[9] In order to be classified as a steady-state 'high precision' model, the results have to satisfy the following requirements: (a) the difference between the temperatures calculated and listed in the standard shall not exceed 0.1 K; (b) the difference between the heat flow calculated and listed shall not exceeded 0.1 W/m; and c) grid independence criteria: difference between refined and coarse grid shall not exceed 2%. Test reference cases were modelled and the relevant requirements were met.

For the transient analysis VOLTRA as developed by Physibel[11] was used. VOLTRA is a transient version of TRISCO, the software used for the steady-state method—the two models are otherwise identical. A detailed account of VOLTRA is again given in the user manual.

2.2 Interstitial condensation risk

To assess the risk of interstitial condensation and mould growth in dwellings two methods were used: (1) the 'Glaser Method' (using the GLASTA[12] software package), commonly used to simulate vapour diffusion and condensation in building envelopes, as prescribed by the current Standard—BS EN ISO 13788: 2002; and (2) a more advanced calculation model based on transient moisture and heat transport through walls—WUFI.[13]

GLASTA as developed by Physibel was used to calculate the temperature, saturation vapour pressure and the vapour pressure in each interface for each period of time as prescribed by the British Standard. The Glaser method simplifies the physics of moisture and heat transport through the building envelope by assuming the following:

a) condensation only occurs at the interface between material layers and remains at that interface;
b) thermal conductivity is independent of the moisture content of the material;
c) capillary suction and liquid moisture transfer does not occur in the building fabric;
d) there is no moisture transfer by convection within the structure of the detail;
e) monthly averaged boundary conditions are only used, whereas the real boundary conditions are not constant over a period of a month;
f) only one dimensional heat and moisture transfer is modelled;
g) no solar radiation or driving rain.

A detailed account of the model is given in the user manual. Quality assurance was also undertaken to assess the performance of GLASTA—the test reference cases were modelled and the relevant requirements met.

The WUFI software package, as developed by IBP[13] addresses all of the limitations of the Glaser method but one ie, moisture transfer by convection in the structure. A detailed account of the model is given in the user manual.

To summarize, the surface and interstitial condensation risks are assessed using both the simple and complex calculations. Whilst the simple calculation methods are based on the assumption of a steady-state heat transfer, the complex calculation methods assume transient heat and moisture flow. In the case of the interstitial condensation risk solar radiation and driving rain are considered. The methodology applied in this paper is summarized in Table 2.

3 Description of numerical model

The assessment of condensation risk and mould growth using the standard and more complex calculation methods was performed for all the RCDs listed in Table 1. However, for clarity, only the numerical results for RCD 6.18 are shown in detail in this paper. Summary results for the other details are however discussed in Section 4.

3.1 Surface condensation risk

Figure 1 shows the detailed geometry of RCD 6.18. The three locations on the surface at which temperatures and RHs are reported are: (a) wall, (b) floor, and (c) corner. The locations chosen are 1 m away from the central element. A non-uniform Cartesian coordinate system was set using 34 200 nodes. All results satisfy the validation criteria given in Annexe A of BS EN ISO 10211-1:1996 including the grid independence criteria. The detail was modelled in 2D for clarity.

An internal surface thermal resistance of 0.25 m^2K/W, and external of 0.04 m^2K/W were used for each surface as recommended in the Standard.[4] Additionally, the Standard assumes that the internal, T_i, and external, T_e, temperatures are kept constant and in this study they were set at 20°C and 0°C. Note that comparability of the simple and transient boundary conditions has been achieved by averaging transient vapour pressure excesses (note that vapour pressure excess is defined as the difference between the internal and outdoor vapour pressure due to moisture load) over a modelled period of time. Therefore, the internal RH in the case of the steady-state modelling relates to the assumed transient internal RH conditions and is adjusted accordingly.

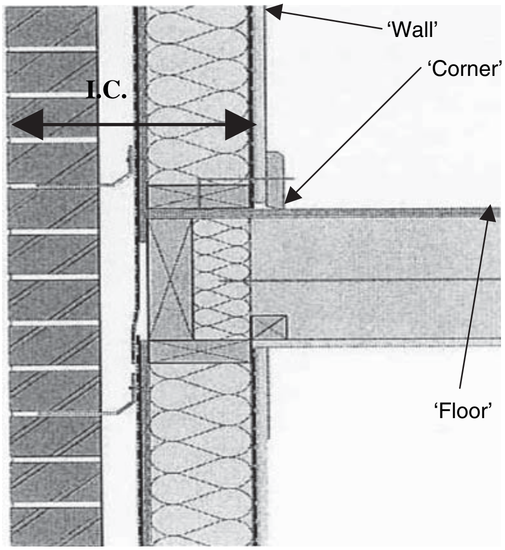


Figure 1 RCD 6.18. Note that IC refers to the cross-section where risk of interstitial condensation risk was modelled in one dimension

A 'heavy-weight' version and a 'light-weight' version of the construction were modelled. Typical thermal and physical properties of the relevant materials were selected (Table 3). Different materials were used for the modelling of the two versions of the construction to simulate different degrees of thermal mass.

Table 2 Summary of the methodology

Condensation	Simple	Complex
Surface	TRISCO: steady-state heat transfer	VOLTRA: transient heat transfer
Interstitial	GLASTA: steady-state model based on Glaser method	WUFI: transient heat and moisture transport with solar radiation and driving rain considered

Table 3 Thermo-physical properties of materials

Material	Heavy-weight			Light-weight		
	Density ρ [kg/m³]	Thermal conductivity λ [W/mK]	Specific heat capacity c [J/kgK]	Density ρ [kg/m³]	Thermal conductivity λ [W/mK]	Specific heat capacity c [J/kgK]
Brickwork	1800	0.9	850	1200	0.45	850
Cellular concrete	600	0.2	1010	480	0.17	1060
Cement and sand	1800	1	1000	1800	1	1000
Clay or silt	1500	2	2100	1500	2	2100
Concrete	2400	2.5	1000	2300	2.3	1000
Reinforced gypsum board	700	0.5	930	700	0.5	930
Plywood	1000	0.24	1600	300	0.09	1600
Rockwool	40	0.037	840	40	0.037	840
Sand and gravel	1950	2	1050	1950	2	1050
Stainless steel	7850	25	480	7850	25	480
Steel	7800	50	450	7800	50	450
Wood	700	0.17	2070	700	0.17	2070

For the transient modelling of surface conditions, a transient temperature profile was assumed which would mimic a family coming home to a cold property and turning on the heating, resulting in a rapid air temperature change from 13 to 20°C over 1 h. During this temperature rise the surface RH was calculated for different vapour pressure excess profiles.

The vapour pressure excess profiles have been developed based on daily moisture generation rates for a family of three (according to the National Census 2001 the average number of occupants per dwelling is 2.4) living in a two bedroom property with a volume $V = 200\ m^3$. BS 5250:2002[9] defines three different levels of moisture occupancy as a function of moisture generation rate, G [kg/day]:

a) dry occupancy ($G = 4$ kg/day) is characterized with a proper use of ventilation and results in an internal vapour pressure excess of up to 300 Pa; in this study it has been assumed that 90% of moisture generated in a kitchen and bathroom is extracted by either extract fans or openable windows.
b) moist occupancy ($G = 9$ kg/day); internal vapour pressure excess between 300 and 600 Pa; a moisture extraction rate of 50% is assumed.
c) wet occupancy ($G = 12$ kg/day); internal vapour pressure excess greater than 600 Pa; ventilation hardly ever used (ie, only 10% moisture extraction rate is assumed).

To calculate the internal vapour pressure excess, Δp_v, the following equation has been applied:[4]

$$\Delta p_v = \frac{G}{nV} R_v (T_i + T_e)/2 \qquad (1)$$

where R_v [Pam^3/Kkg] is the water vapour gas constant, T_i [K] and T_e [K] are internal and external temperatures respectively, and n [ac/h] is the ventilation rate. The internal vapour pressure excess (VPX) calculated for different moisture generation rates is shown in Figure 2.

For transient models the assumed time-step can result in significant errors. Recently, in an inter-model comparison Ben-Nakhi[14] compared the newly developed three-dimensional transient heat conduction module, which was integrated into the ESP-r software package with results from VOLTRA. He reported that for a 10-minute time step, the oscillations of

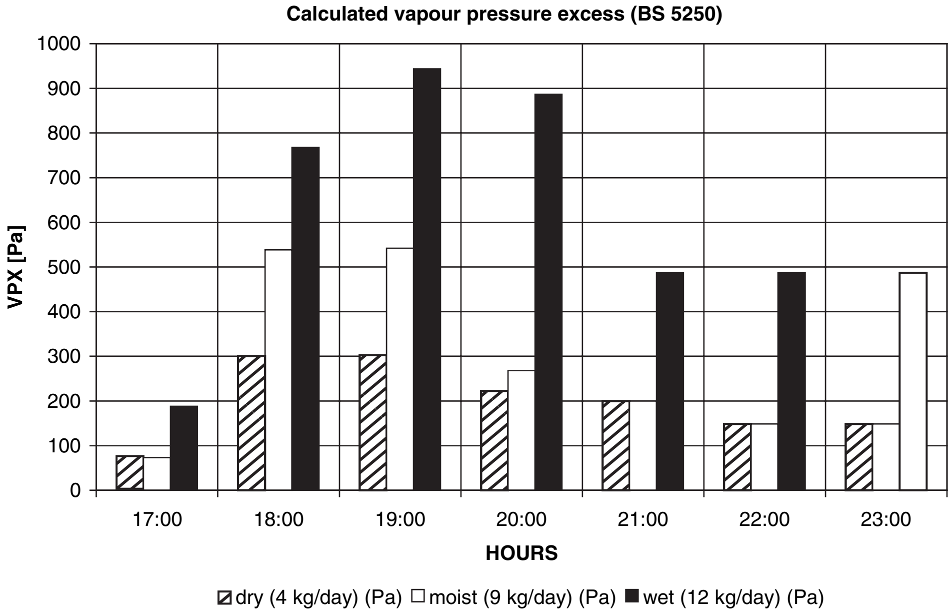


Figure 2 Calculated internal vapour pressure excess (VPX) for dry, moist and wet occupancy

the VOLTRA results, due to the nature of stability error associated with the Crank-Nicholson discretization method, were significantly dampened, which is of significant importance for convergence of numerical results. To determine an appropriate time-step for this paper, an additional test, using the above construction detail, was performed to assess the numerical sensitivity of VOLTRA to the different time-steps, namely 1, 5 and 10 min. The results were identical for all three time steps. Hence, the following results were obtained using a time-step of 10 min over a 6 h period (17:00–23:00).

3.2 Interstitial condensation risk

Analyses were performed using both the simple and complex calculation methods on a one-dimensional cross-section through the external wall section of RCD 6.18. A cross-section of the detail modelled is shown in Figure 1, and marked as IC.

Although the complex method does not suffer from all of the simplifications and limitations of the simple method, its increased complexity requires more thermo-physical material data and transient boundary conditions.

Apart from the thermo-physical properties defined in Table 3. additional properties are needed for the complex calculation method: (a) dependence of the vapour resistance factor on relative humidity, μ [$-$]; (b) liquid transport coefficient for suction, D_{ws} [m^2/s], and redistribution, D_{ww} [m^2/s], which are normally strongly dependent on the moisture content; (c) moisture dependent heat conductivity, λ [W/mK]; and (d) sorption isotherm, which represents change in moisture content of material as a function of relative humidity at the same temperature. All values used in this study were taken from the WUFI material database.[13]

Transient (hourly) boundary conditions are defined using the following parameters: (a) outdoor and indoor temperature, θ [°C]; (b) outdoor and indoor relative humidity, RH [%]; (c) vertical incident of rain load on the exterior surface, often referred to as 'driving rain' [l/m^{2}h]; and (d) incident solar radiation on a vertical exterior surface [W/m^2]. Since barometric pressure has only a minor effect on the calculation, the specification of a mean barometric pressure is sufficient.[13]

External boundary conditions for the transient complex analysis were determined from a meteorological Test Reference Year for Kew (west of London, UK) because no Moisture Design Reference Year is available for the UK. Hourly internal boundary conditions were generated using the building simulation software Energy Plus[15] with the monthly average values being equal to those in the standard BS 5250: Code of practice for control of condensation in buildings,[9] and used in the steady-state, GLASTA simulation.

4 Results and discussion

4.1 Surface condensation risk

The surface temperatures at the three locations (wall, corner and floor) marked on Figure 1 and predicted by the steady-state TRISCO model range from 17.5°C at the corner, to 20°C at the floor end (Table 4). The 'simple' steady-state calculated RH is well below 80% for the three locations, therefore for these boundary conditions, the simple method predicts no risk of mould growth.

In order to assess the effect of the thermo-physical properties on the thermal response of the chosen RCD, different types of masonry and sheathing boards were modelled (Table 3). Similar steady-state results were obtained for the 'heavy-weight' and 'light-weight' constructions, see Table 4.

Figures 3 and 4 show the effect of thermal mass on calculated internal surface temperatures during a ramped change in internal temperature. As expected the internal surfaces of the RCD 6.18 respond slowly to fluctuations of internal temperature. The calculated relative humidity for both the 'heavy-weight' and 'light-weight' version of the RCD is shown in Figures 5 and 6. The calculated relative humidity at the corner starts at 58% and rises rapidly to 95% compared to the lightweight of 52% and 84%. It remains above the threshold value of 80% for 2 h for the 'heavy-weight' case. This is a significant issue as the impact of having surface RHs above 80% for several hours is potentially important for mould growth. This statement is based on a new criterion for mould growth given in the Review of approved document F—Ventilation,[16] which defines a period of 2 h in any 12 h of the RH (air) being above 70% as a critical performance standard for the new Part F.

Figure 7 shows the effect of moisture generation on the predicted surface humidity results for the RCD 6.18. Whilst in the case of moist and dry occupancy no condensation is predicted at the corner of the detail, in the case of wet occupancy the surface humidity reaches 100% for a period of a few hours. Note that in the case of moist occupancy RH exceeds 80% for approximately 2 h.

Table 4 Calculated surface RH using the simple and complex calculation methods for RCD 6.18

Surface	Simple				Complex	
	Heavy		Light		Heavy	Light
	T[°C]	RH[%]	T[°C]	RH[%]	Time (h) (RH >80%)	Time (h) (RH >80%)
Wall	18.8	43.0	18.9	42.7	0.3	0.2
Corner	17.5	46.5	17.8	45.7	1.9	0.7
Floor	20.0	40.0	20.0	40.0	0.0	0.0

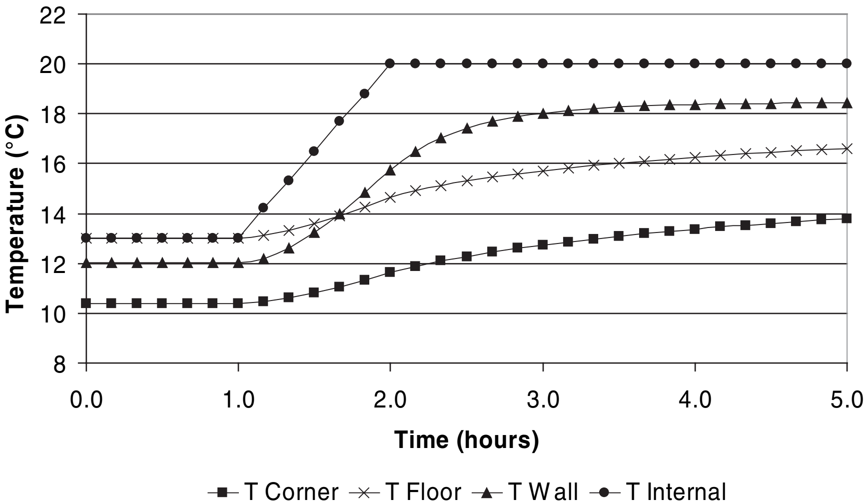


Figure 3 Calculated temperatures at three different locations after a step change in internal temperature for the 'heavy-weight' version of construction detail

The effect of the ventilation rate on the predicted surface relative humidity is shown in Figure 8. Three different ventilation rates were used: (1) 0.5 ac/h for a modern well-insulated, sheltered dwelling, (2) 0.65 ac/h as the average ventilation rate in the UK, and (3) 0.9 ac/h a modelled air ventilation rate at which the predicted surface relative humidity does not exceed 80% at anytime. Note that all the Figure 8 results assume wet occupancy.

In order to cover a wider range of different construction types, the same methodology has been applied for another four RCDs. A

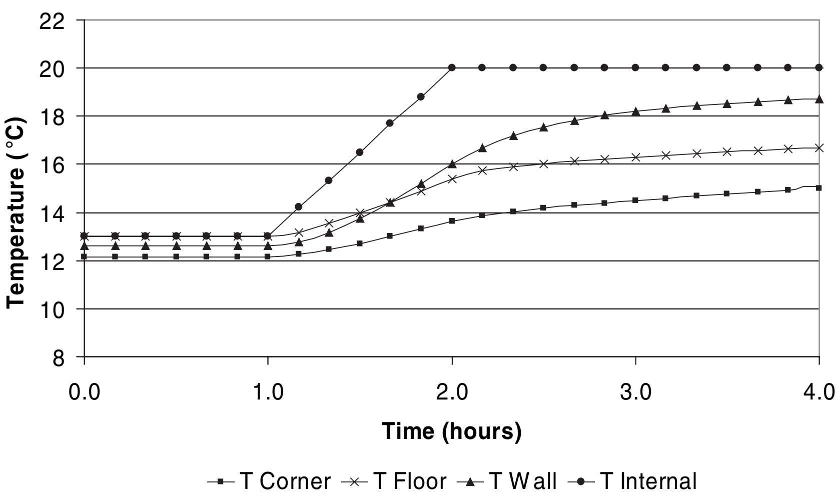


Figure 4 Calculated temperatures at three different locations after a step change in internal temperature for the 'light-weight' version of construction detail

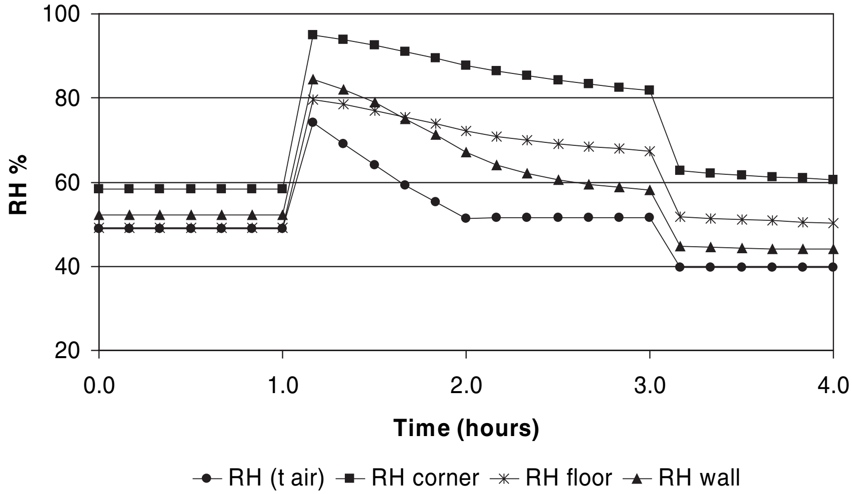


Figure 5 Calculated relative humidity at three different locations after a step change in internal temperature for the 'heavy-weight' version of construction detail

summary of calculated temperatures and RHs using the simple and complex calculation methods for two different thermal masses ('heavy weight' and 'light weight') is given in Table 5. For all the modelled RCDs the complex calculation method predicts up to 2 h above 80% RH at several points on the internal surface of the RCD, whilst the simple method predicts that surface RH values are all significantly below 80%.

Note that in the case of the detail 8.06, not only does the RH exceed 80% but condensation is predicted for 40 min for both 'heavy-weight' and 'light-weight' construction.

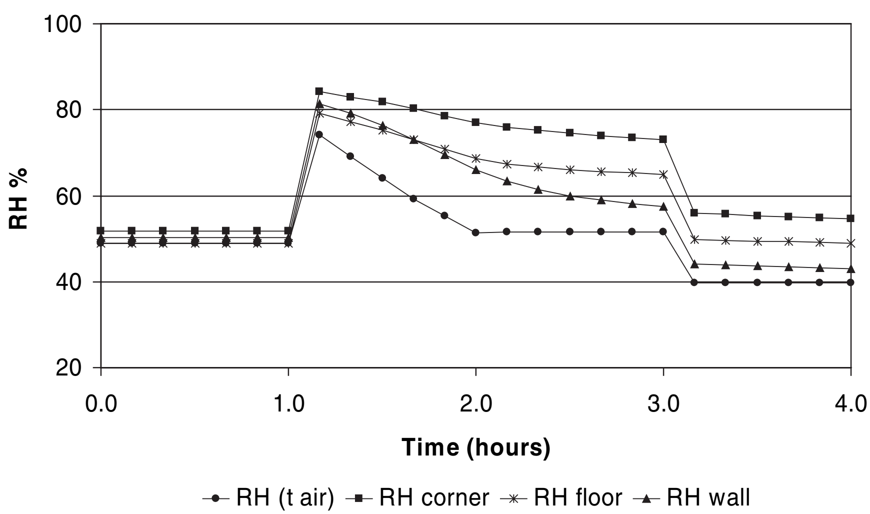


Figure 6 Calculated relative humidity at three different locations after a step change in internal temperature for the 'light-weight' version of construction detail

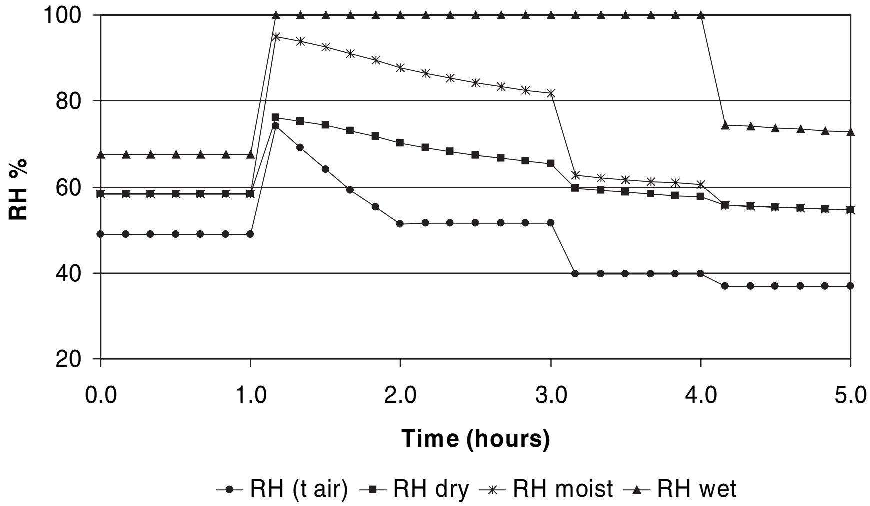


Figure 7 Calculated relative humidity for the 'heavy-weight' version of construction detail after a step change in internal temperature for dry, moist and wet occupancy (0.5 ac/h)

4.2 Interstitial condensation risk

There is a risk of interstitial condensation risk at the junction between the sheathing and the insulation for RCD 6.18 (Figure 1). Condensation formation starts in October, reaches a peak in March, but then has all evaporated by June (Figure 9). The calculated quantity of condensation exceeds the allowed water content for cellulose fibre materials with no waterproof glues (A: 0.05 kg/m^2).[13]

A complex WUFI simulation was also carried out on the same element, using a transient external weather file and internal conditions. The results of the simulation considering driving rain differ from those without driving rain. In the latter case no

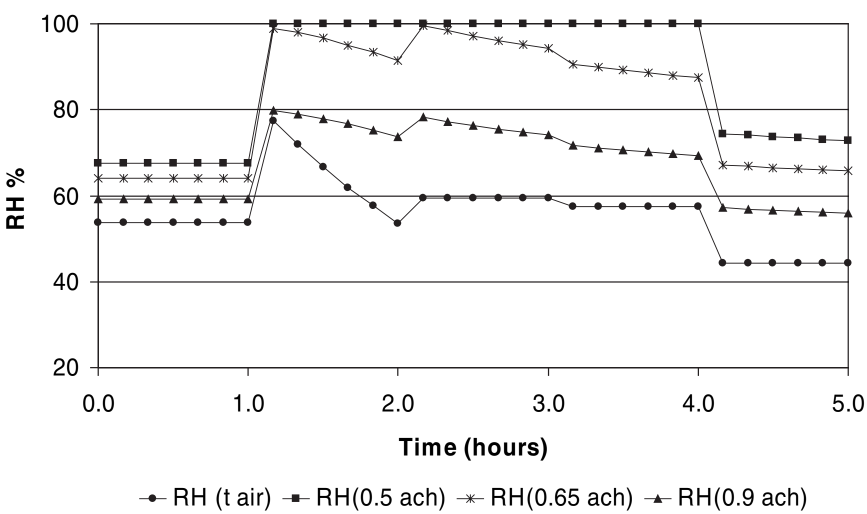


Figure 8 Calculated relative humidity for the 'heavy-weight' version of construction detail after a step change in internal temperature for different air infiltration rates (wet occupancy)

Table 5 Summary of calculated temperatures and RHs at the corner, for selected construction details, using the simple and complex calculation methods

Robust detail	Simple				Complex	
	Heavy		Light		Heavy	Light
	T[°C]	RH[%]	T[°C]	RH[%]	Time (h) (RH >80%)	Time (h) (RH >80%)
Boundary conditions	$T_{ext}=0°C$; $T_{int}=20°C$; $RH_{int}=40\%$				$T_{ext}=0°C$; $T_{int}=$a step change from 10 to 20°C; $RH_{int}=$moist	
3.16	16.3	50.0	16.5	49.5	1.5	1.4
4.19	15.8	51.6	16.2	50.4	2.0	1.5
7.12[a]	19.6	41.0	19.8	40.5	0.3	0.3
8.06[b]	15.5	52.6	15.6	52.3	2.0	2.0

[a]Note that modelled cross-section represents the worst case scenario ie, includes metal bars.
[b]Note that modelled cross-section includes the door frame only.

condensation formation is predicted at the interface of the vapour control layer and the insulation.

The difference in results, between simple and complex methods, was expected as the complex model includes the moisture sorption of the hygroscopic materials and moisture redistribution due to liquid transfer. The moisture content of the RCD 6.18 is shown in Figure 10. Note that the highest values of moisture content were predicted in the sheathing board, whilst the lowest was predicted in the insulation.

Both methods were applied to all the RCDs listed in Table 1. A summary and comparison of the results obtained using the simple and complex calculation methods are shown in Table 6. Note that the RCD

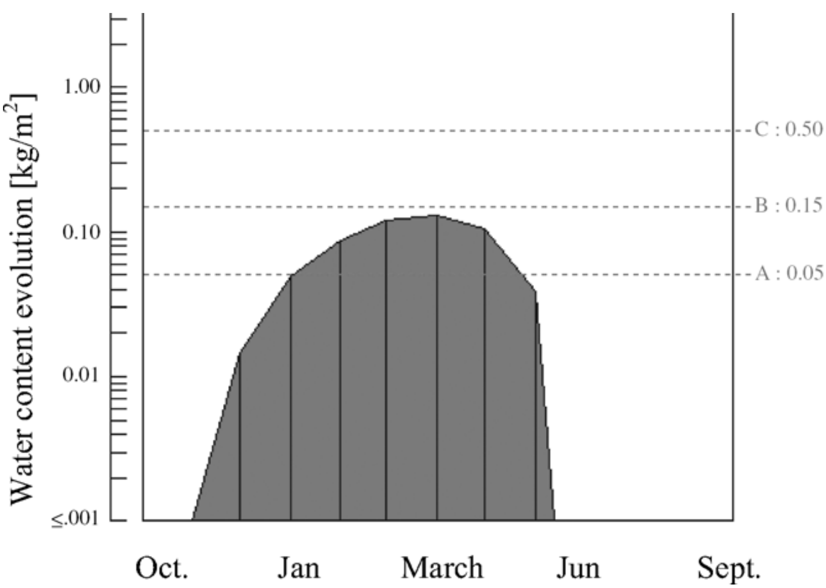


Figure 9 Logarithmic plot of water content at the interface of sheathing board and insulation for RCD 6.18

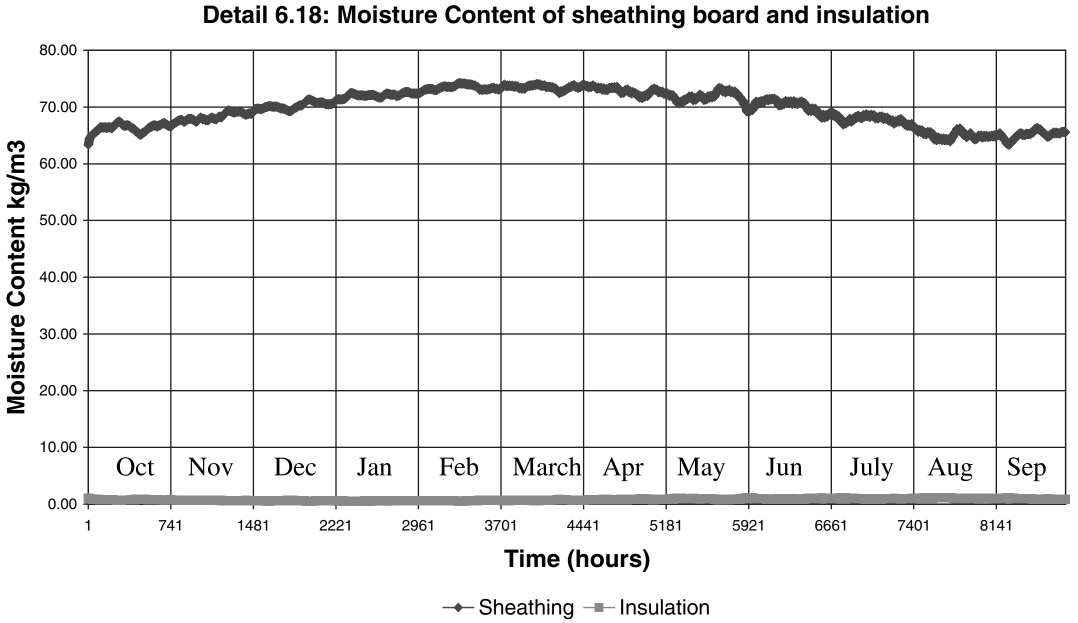


Figure 10 Moisture content of sheathing board and insulation of RCD 6.18

8.06 was not modelled because it is predominantly made up of a door frame which is not of particular interest in terms of interstitial analysis.

Differences are apparent between the predictions of the simple and complex methods for all details when driving rain is considered in the complex model. Moisture accumulation

Table 6 Summary of results obtained using both simple and complex calculations

RCD	GLASTA	WUFI driving rain considered	WUFI driving rain not considered
3.16	Interstitial condensation predicted at the interface of brickwork and insulation. Condensation forms November to March. Condensation all evaporated by August	Moisture accumulates in the brickwork and insulation all year and does not return to initial levels. RH in the brickwork and insulation approaches 100%.	Moisture accumulates in the insulation and brickwork from October to March and then reduces to initial levels. Maximum RH at brick/insulation interface = 95% in March
4.19	Interstitial condensation predicted at the interface of brickwork and air cavity. Condensation forms November to March. Condensation all evaporated by July	Moisture accumulates in the brickwork all year and does not return to initial levels. RH in the brickwork approaches 100%. There is a slight annual increase in moisture content of the insulation layer. The moisture content of the air cavity has a net annual increase.	Moisture accumulates in the brickwork, air cavity and to a lesser extent in the insulation from October to March. The brickwork does not return to its initial condition with a net annual gain of moisture taking place. The moisture level in the air cavity and insulation return to initial levels by September. RH approaches 100% in the air cavity.
7.12	No Condensation	Moisture accumulates in the brickwork. There is no significant moisture accumulation in the other layers.	No condensation predicted at the steel/insulation interface. Moisture accumulation in brickwork during winter, but returns to initial levels.

is predicted in the external brickwork layer and often in the air cavity. The predictions of the simple and complex methods are in agreement when driving rain is not considered in the complex model.

5 Conclusions

The current Standard used for the assessment of condensation risk and mould growth is based on the assumption of steady-state conditions inside and outside of buildings neglecting the fluctuation of environmental conditions on a daily basis.

In the case of surface condensation, potentially significant differences are apparent between the predictions of the simple and complex methods for the particular boundary conditions applied to all RCDs modelled. The complex method tends to predict a few hours above 80% RH (depending on the assumed moisture generation and ventilation rates) at several locations on the internal surface of the robust details, mostly corners and lower areas of external walls and doors, whilst the simple method tends to predict that surface RH values are all significantly below 80%. The issue of the time period of a few hours is now more pertinent as it relates to a new transient performance standard given in the new Approved Part F Document—Ventilation.[16]

Future work would be helpful in order to further test the new performance criteria. In addition to experimental work conducted in controlled environmental chambers, further work should also include detailed analysis of mould growth in relation to RH in *real* dwellings.

In the case of interstitial condensation it was shown that the two calculation methods can provide different results in the prediction of risk of interstitial condensation, when driving rain is considered in the complex method.

Further work is needed to develop a set of adequate Moisture Design Reference Years for the UK.

This study is being extended to examine the surface and interstitial condensation risk of actual construction details as found on site thereby addressing the possible influence of workmanship on the moisture performance of the RCDs.

Acknowledgements

This research was undertaken as part of a research project to support the development of the Building Regulation, entitled: *Condensation Risk—Impact of Improvements to Part L and Robust Details on Part C (Project Reference Number: CI/71/6/1 BD2414)* funded under the Office of the Deputy Prime Minister Building Operational Performance Programme. The views expressed in this paper however, are those of the authors only.

References

1 DETR. *English House Condition Survey 1996*, *Energy Report*. Department of Environment, Transport and Regions, London, UK, 2000.
2 DETR. *English House Condition Survey 1996*. Department of Environment, Transport and Regions, London, UK, 1996.
3 Woolliscroft M. *Residential ventilation in the United Kingdom: an overview*. ASHRAE Transactions: Symposia PH-97-8-3, 1997.
4 BSI. *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*. BSI, London, 2002.
5 Sanders C. *Advanced calculations of moisture in structures cc2073*. Building Research Establishment, East Kilbride, Scotland, 2003.
6 DoE. *Good Practice Guide 174: Minimising thermal bridging in new dwellings*. Best Practice Programme, Department of Environment, London, 1996.

7 DTLR. *Limiting thermal bridging and air leakage: Robust construction details for dwellings and similar buildings*. Norwich, TSO, 2002.

8 Oreszczyn T, Mumovic D, Davies M, Ridley I, Bell M, Smith M, Miles-Shenton D. *Condensation risk—impact of improvements to Part L and robust details on Part C—final report*. Office of the Deputy Prime Minister Building Regulations Division Under the Building Operational Performance Framework. Project Reference Number CI 71/6/16 (BD2414), 2005.

9 BSI. *BS 5250: 2002 Code of practice for control of condensation in buildings*. BSI, London, 2002.

10 PHYSIBEl. *TRISCO Version 10.0w*. http://www.physibel.be/v0n2tr.htm Physibel Software, Belgium [last accessed 26 February 2004].

11 PHYSIBEL. *VOLTRA Version 4.0w*. http://www.physibel.be/v0n2vo.htm Physibel Software, Belgium [last accessed 26 February 2004].

12 PHYSIBEL. *GLASTA Version 5.0w*. http://www.physibel.be/v0n2gl.htm Physibel Software, Heirweg 21, B-9990 Maldegem, Belgium [last accessed 26 February 2004].

13 IBP. *WUFI Version 2.2*. http://www.hoki.ibp.fhg.de/wufi/intro_e.html Wufi Fraunhofer Institute of Building Physics, Germany [last accessed 26 February 2004].

14 Ben-Nakhi AE. Development of an integrated dynamic thermal bridging assessment environment. *Energy and Buildings* 2003; 35: 375–82.

15 US DoE. *Energy Plus*. http://www.eere.energy.gov/buildings/energyplus US Department of Energy [last accessed 26 February 2004].

16 ODPM. *Approved Document F—Ventilation (interim edition)*. Office of the Deputy Prime Minister, Building Regulations Office, 2005.