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Hygrothermal Modelling of Shrewsbury Flaxmill Maltings

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HYGROTHERMAL MODELLING OF SHREWSBURY FLAX MILL MALTINGS

SHREWSBURY, SHROPSHIRE

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SUMMARY

The report describes hygrothermal simulations of the second floor of the South Engine House at Shrewsbury Flaxmill Maltings to predict the impact of a range of internal wall insulation systems over a period of thirty years. Simulation results using WUFI indicate that 1-D modelling is generally satisfactory for a range of scenarios. Uncertainty will result from using alternative material data from the WUFI database compared with the actual material in the Flaxmill case. Thirty year simulations indicate that insulation systems which are hygroscopic with some vapour resistance are possibly the best option to reduce risk of moisture problems in internal wall insulation, whereas materials unable to buffer moisture or having a high vapour resistance may, in the worst case, allow a long term build-up of moisture. WUFI is a useful tool which can be used to assess options for upgrading the thermal performance of traditional buildings, provided we know the material properties of our traditional materials. However, as the simulations results reported show, unknown boundary conditions such as absorption of driving rain may produce a high level of uncertainty.

CONTRIBUTORS

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2015

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CONTENTS

FIGURES & TABLES

FOREWORD

Shrewsbury Flaxmill Maltings is listed at Grade I and is of international importance. It was designed by Charles Bage and built in 1797 for John Marshall of Leeds and the Benyon brothers.. The Main Mill is the earliest iron-framed building in the world. The design used a fireproof combination of cast iron columns and cast iron beams, a system which later developed into the modern steel frame, and led to the development of the skyscraper.

This report presents hygrothermal simulations by Dr. Paul Baker, from Glasgow Caledonian University, to predict the impact of a range of internal wall insulation systems on the performance of the solid brick walls over a period of thirty years in the South Engine House of the Flax Mill. The key objectives of the simulations have been to improve modelling by considering how 1 D and 2 D simulations compare and the effect of modelling different materials and designs from the WUFI software database when actual material properties are unknown. The study also compares these results with using known material properties from Shrewsbury Flaxmill Maltings and the influence of driving rain on the modelling.

Hygrothermal modelling simulateses the movement of heat and moisture through buildings. It is often used by building professionals to predict their hygrothermal performance to manage risk and to prevent the degradation of the building fabric after the application of insulation systems.

Energy efficiency measures improve thermal performance but this can affect the moisture behaviour of the building fabric. Inappropriate retrofit can dramatically affect internal conditions. In particular, exposure to cold and wet climates or high internal moisture loading may increase risk of moisture accumulation in the fabric and at the interface of internal wall insulation and the wall. This can affect the performance of the insulation and the long-term durability of the building envelope.

Accurate prediction of the hygrothermal behaviour of solid walls is an important factor in managing the health of the building. However, one of the principal shortcomings of hygrothermal modelling is the lack of data on traditional building materials in England. The study compares the behaviour of the walls as predicted by the WUFI 1D software using its ‘library’ data and the behaviour of the walls modelled using actual values gathered from laboratory tests of the bricks used at Shrewsbury Flaxmill Maltings.

The results from the study will be combined with data gathered from *in-situ* monitoring and climate data from the site to help guide the future proposals for the rehabilitation of Shrewsbury Flaxmill Maltings. It may also help with future guidance on energy efficiency upgrades and moisture risk assessment for similar constructions.

This work is part of a wider programme of research by the Building Conservation & Research Team at Historic England which is investigating the moisture behaviour of solid walls following the installation of internal wall insulation. Laboratory studies and fieldwork in Flaxmill Maltings and New Bolsover are in progress to determine whether the modelled behaviour of the walls reflects actual performance. The work is being accompanied by a sensitivity analysis of hygrothermal models to assess the critical parameters of the simulations and a study to validate the models using measured data.

This report is based on the software program, WUFI 1D, developed by the Fraunhofer Institute in Germany. The results are not an endorsement by Historic England of the programme nor of any of the insulation materials included in the study.

Soki Rhee-Duverne

1. INTRODUCTION

This report presents the results of modelling of the walls of the South Engine House at Shrewsbury Flaxmill Maltings, near Shrewsbury, using WUFI software, which models the heat and moisture transfer through building envelope components. The aim of the study was to assess the hygrothermal performance of the walls of the original construction (bricks and mortar) and refurbishment options with internal wall insulation.

An interim report was submitted to Historic England using available materials property data from the WUFI database in order to assess the possible variation in predicted behaviour due to material choice. This would be the case where the actual material properties of the building material properties are unknown. ‘Historic’ and ‘Hand formed’ bricks were selected from the WUFI database as being possible options to represent the bricks in the South Engine House.

Following this report, Glasgow Caledonian University measured the hygrothermal properties of a sample of bricks from Shrewsbury Flaxmill Maltings and included the data in the WUFI database. Further WUFI simulations using the Flaxmill brick properties were performed and compared the results with those from simulations using the Historic and Hand formed bricks.

An alternative to WUFI Pro 5, which models 1-dimensional heat and moisture transfer, is to use the 2-D version, which allows a more detailed simulation of, for example, a wall with a series of brick courses including horizontal mortar joints. However when using the latter program, computational times are considerably longer (days rather than less than an hour). Therefore, a comparison was made of the 1-D and 2-D results from modelling a wall with and without internal wall insulation, to see whether 1D modelling could give a good approximation of 2D solutions, and thereby reduce computation times. This would enable more constructional variations to be modelled. Simulations of internal wall insulation options were carried out.

In addition, the impact of driving rain was assessed for the wall of the upper floor of the east elevation. WUFI employs an adherence or rain reduction factor which allows for the fact that some rain water hitting an inclined surface splashes off on impact or cannot be absorbed by the surface and is therefore not available for capillary suction. A range of adherence factors from 0.01 to 1 (all driving rain absorbed by surface) were used.

2. WUFI

WUFI (Wärme und Feuchte instationär - Transient Heat and Moisture) has been developed by the German Fraunhofer IBP. WUFI complies with BS EN 15026:2007 which provides minimum criteria for simulation software used to predict one-dimensional transient heat and moisture transfer in multi-layer building components exposed to transient climate conditions on both sides. A 2-dimensional version is also available.

WUFI considers the following properties for each material in its database:

- Moisture content as a function of relative humidity (RH): sorption isotherm.
- Liquid transport.
- Water vapour diffusion resistance factor (as a function of RH).
- Thermal conductivity (as a function of moisture content and temperature).
- Thermal capacity.
- Porosity.
- Density.

The drawback of WUFI is that there are effectively no UK traditional materials in the database. As an initial study it was proposed that the Flaxmill walls were modelled using 'hand formed brick' and 'historical brick' from the WUFI database. There are also suitable lime mortars in the database.

WUFI can model a construction using dynamic indoor and climate conditions and is also able to model the impact of driving rain. The initial conditions, the temperature and moisture contents of each layer in the construction, must be specified.

WUFI 1-D outputs: it is possible to 'monitor' temperatures, relative humidity, moisture content and heat and moisture fluxes through the construction at any position (see Figure 1) with time: this data can be exported to a text file for further processing, for example, using Excel. The monitor positions are selected by the user. An animated film which represents the changes in temperature, RH and moisture through the construction as the simulation progresses can also be produced.

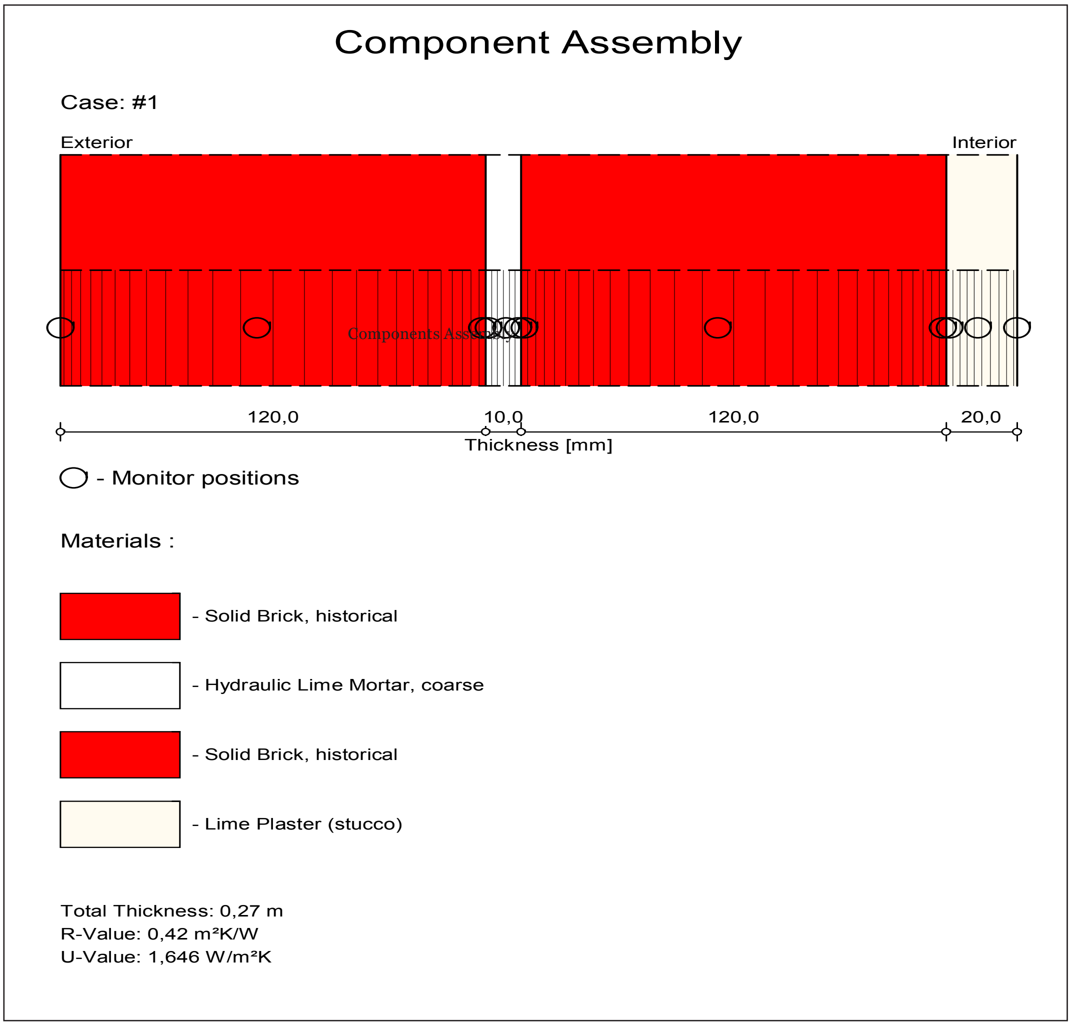


Figure 1: WUFI 1-D construction with monitoring positions

With WUFI 2-D, there is a graphical interface which enables the user to select an element, area or profile from the results file (Figure 2). These results are then processed as spatial averages for each time-step of the simulation.

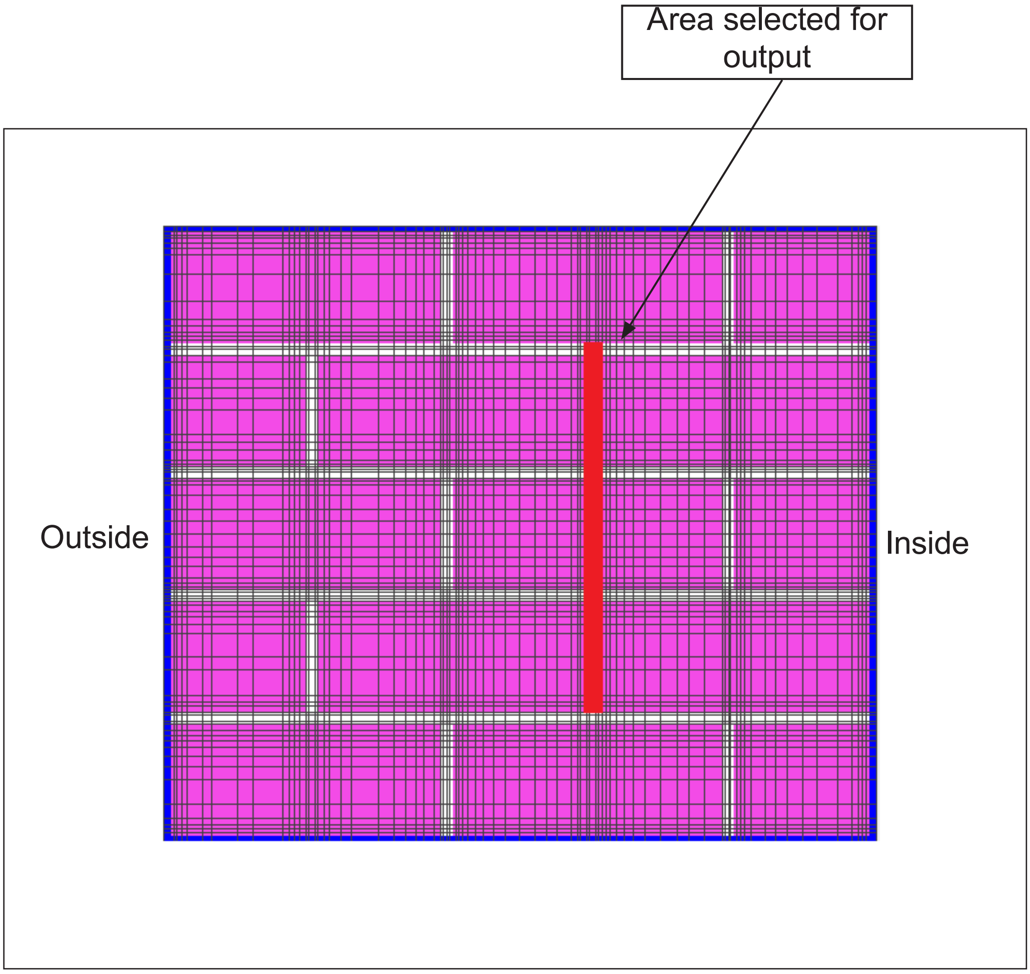


Figure 2: WUFI 2-D – an element, area or profile can be selected for output over the period of simulation

3. MODELLING THE SOUTH ENGINE HOUSE

The South Engine House consists of five floors. Figure 3 shows the construction of the walls on each floor. For the modelling exercise the ground floor construction (2½ bricks thick) and the 3rd and 4th floor construction (1½ bricks thick) were chosen, shown in beige in Figure 3. Historic England has measured the moisture contents on both east and west elevations of the building: these measurements were used as initial moisture contents in the simulations.

Figure 3: Wall construction of the five floors of Shrewsbury Flaxmill Maltings, showing 1-D simulation profiles in beige

4. BRICK PROPERTIES

The properties of the Flaxmill brick were measured and entered into the WUFI database. The main properties are compared with the Historic and Hand Formed bricks in the database in Table 1. The moisture storage functions (absorption curves) are shown in Figure 4 as functions of relative humidity. A capillary-active material in contact with water will take up water until it reaches its free saturation: in the WUFI database free saturation moisture contents of the bricks correspond to the values at 100%RH in Figure 4. Because of air pockets trapped in the pore structure, however, the free saturation is less than the maximum water content which is determined by the porosity.

Table 1: Main properties of the three bricks

	Density (kg/m^3)	Thermal Conductivity (W/mK)	Diffusion Resistance Factor (-)
Historic	1800	0.6	15
Hand Formed	1725	0.6	17
Flaxmill	1789	0.6	19.5

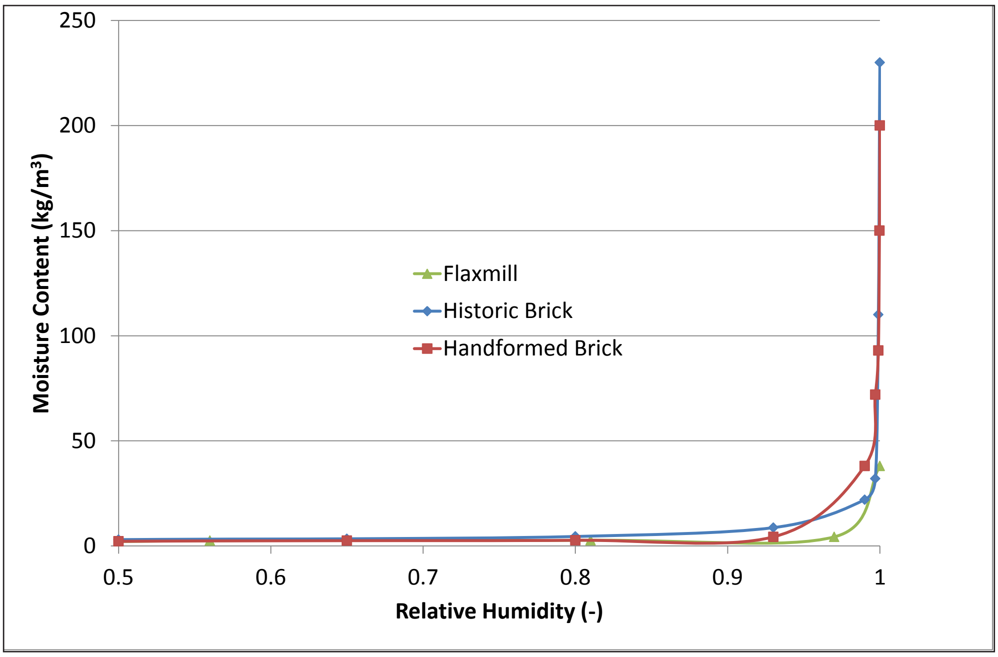


Figure 4: Moisture absorption curves of the three bricks

The Flaxmill brick has a similar thermal conductivity to the Historic and Hand Formed bricks and the Diffusion Resistance Factor is higher. Figure 4 indicates that the Flaxmill brick has generally lower moisture absorption.

5. CLIMATE

Suitable climate data from a nearby location (52.32°N, 2.70°W; 30 miles south of Shrewsbury Flaxmill Maltings at 52.72°N, 2.74°W.) was sourced from the database of the European FP7 project 'Climate for Culture' for the period 1960-1990. Usage of this data should enable a realistic assessment of whether there is a build-up of moisture within the construction over time or a dynamic equilibrium is achieved. The climate data includes temperature, relative humidity, wind speed and direction, rainfall and solar radiation.

Wind driven rain estimates were calculated for the east and west elevations by applying BS EN ISO 15927-3:2009. From images of the building and its surroundings it was assumed that the west elevation was more sheltered: Figure 5 shows that there are more high driving rain events on the east elevation than the west. However the total wind driven rain on the west elevation is 6% higher than that on the east elevation. In the WUFI model it is assumed that all the driving rain is absorbed by the wall surface, however this 'adherence factor' can be changed in the model and results of some simulation changing this factor are also reported. Solar radiation is 21% higher on the west elevation than on the east elevation.

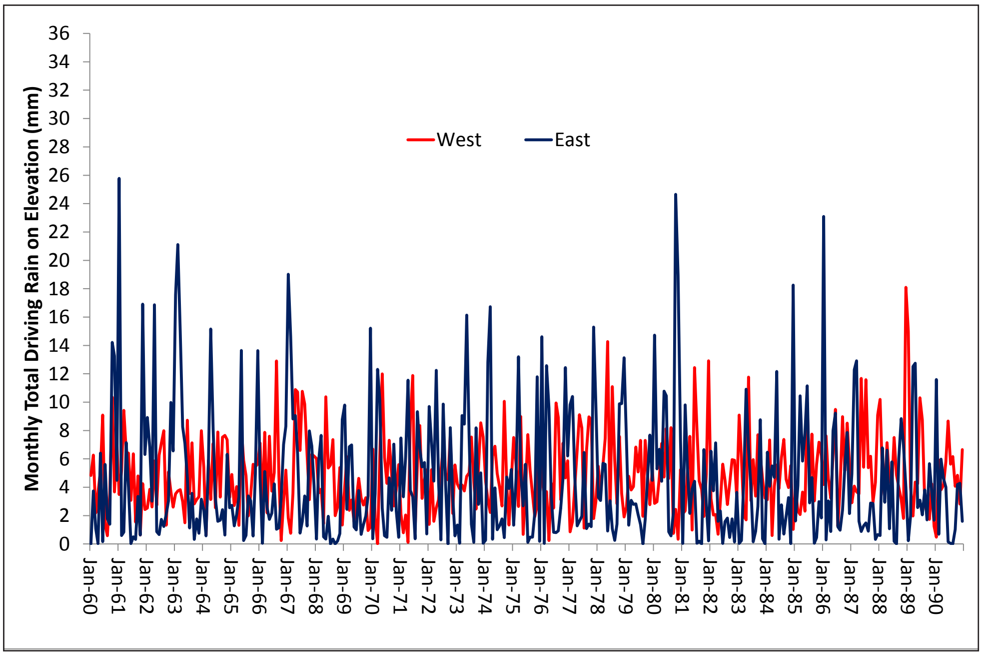


Figure 5: Monthly totals of driving rain calculated for each elevation

The internal climate chosen assumes a set point temperature of 20°C, however when the external temperature exceeds 10°C, the room temperature is allowed to rise to a maximum of 25°C for an external temperature of 20°C or greater (Figure 6). Similarly the indoor relative humidity is also calculated from the external temperature (Figure 7).

The monthly average internal and external temperature and relative humidities are shown in Figures 8 and 9.

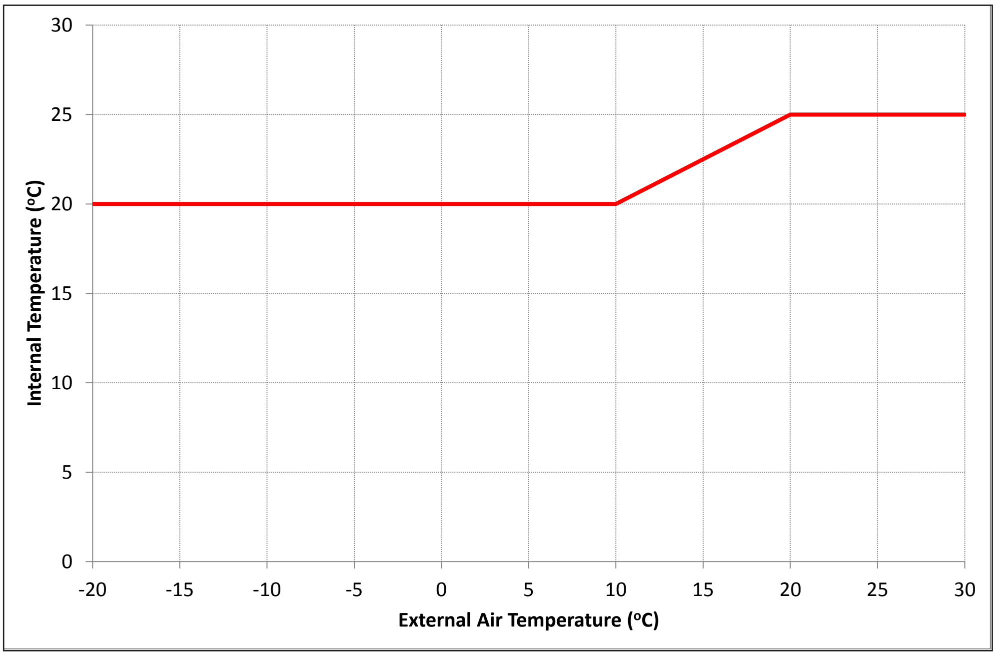


Figure 6: Variation of internal temperature with external temperature

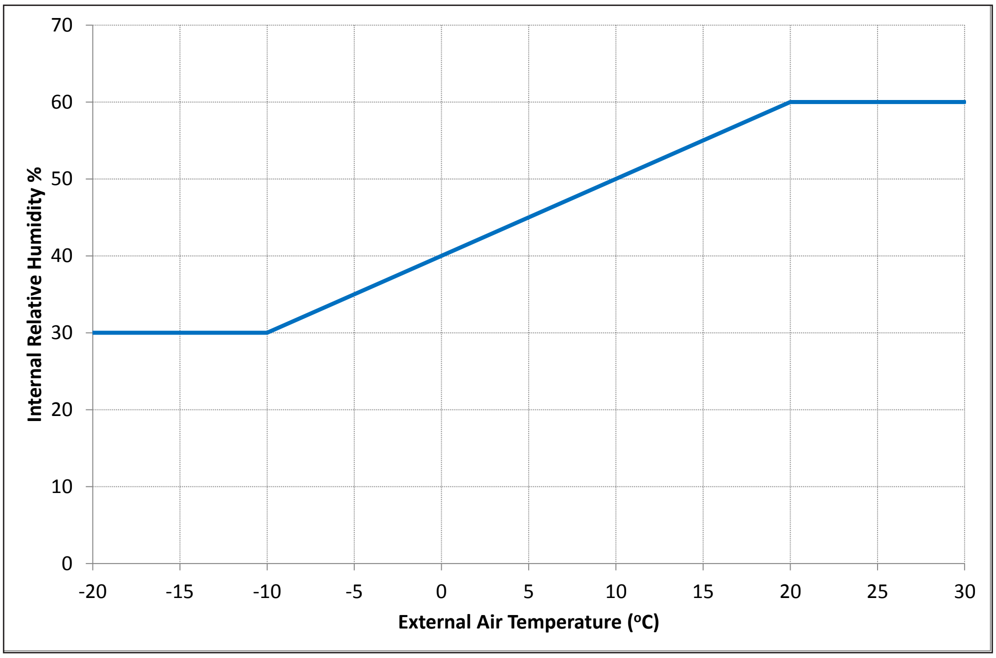


Figure 7: Variation of internal relative humidity with external temperature

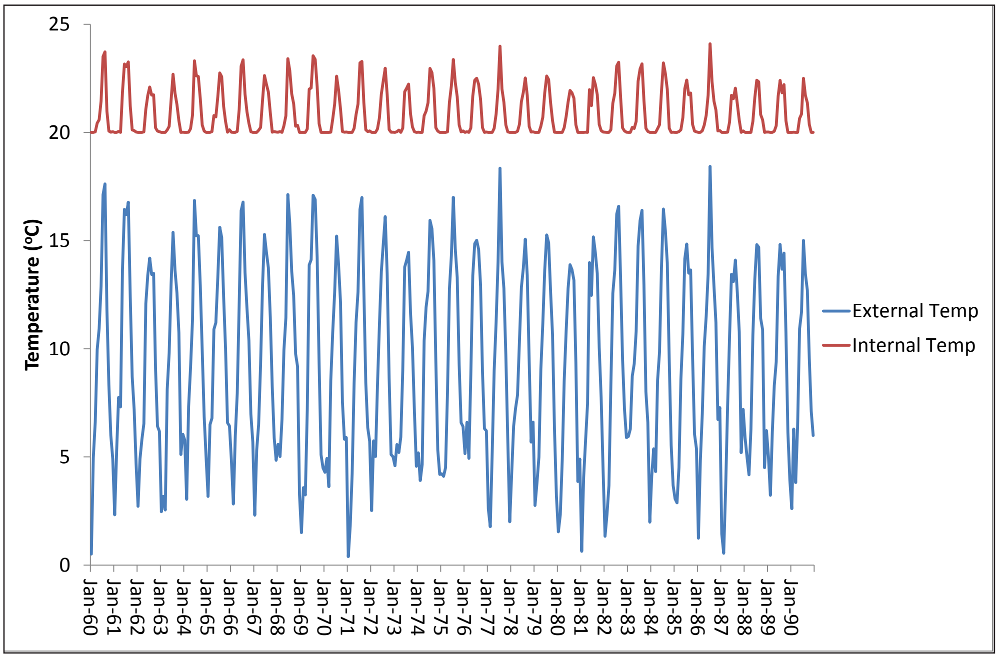


Figure 8: Monthly average internal and external temperatures

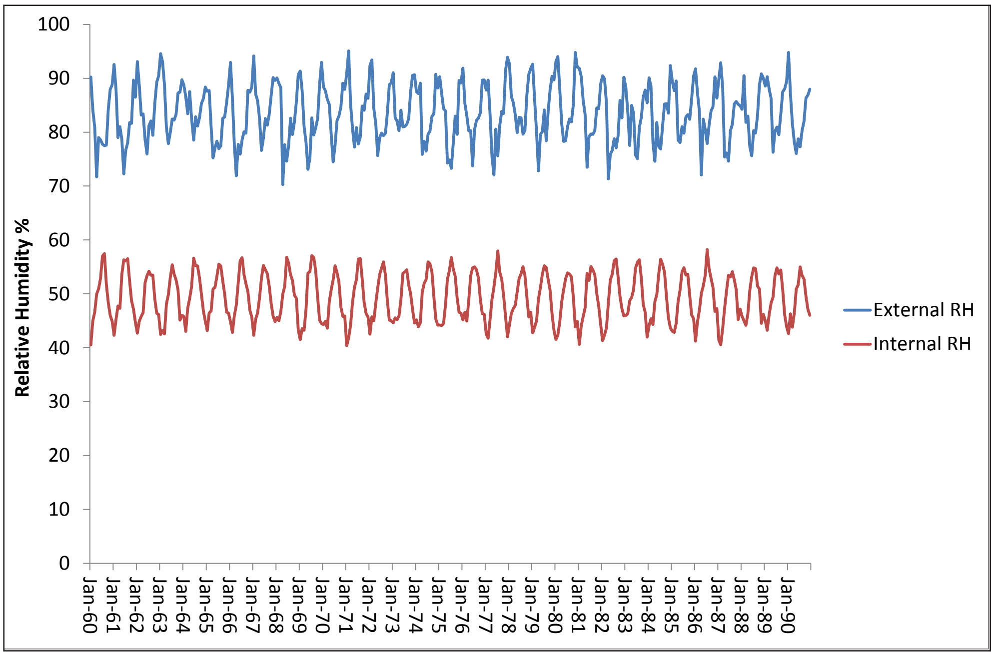


Figure 9: Monthly average internal and external relative humidities

6. SIMULATION RESULTS

6.1. A comparison of WUFI 2-D and WUFI 1-D

Simulations were run using the 1-D and 2-D software with the same boundary conditions, initial moisture contents of the materials and temperature through the construction. The first 10 years of the 1960-1990 climate data described above, were chosen to reduce computation times using the 2-D software.

Two example constructions were used:
Case 1 Ground floor, east elevation with Flaxmill brick only;
Case 2 Ground floor, east elevation with Flaxmill brick and 75mm PIR internal wall insulation.

The 1-D and 2-D models for the latter case are shown in Figure 10. In the 2-D version five brick courses were modelled.

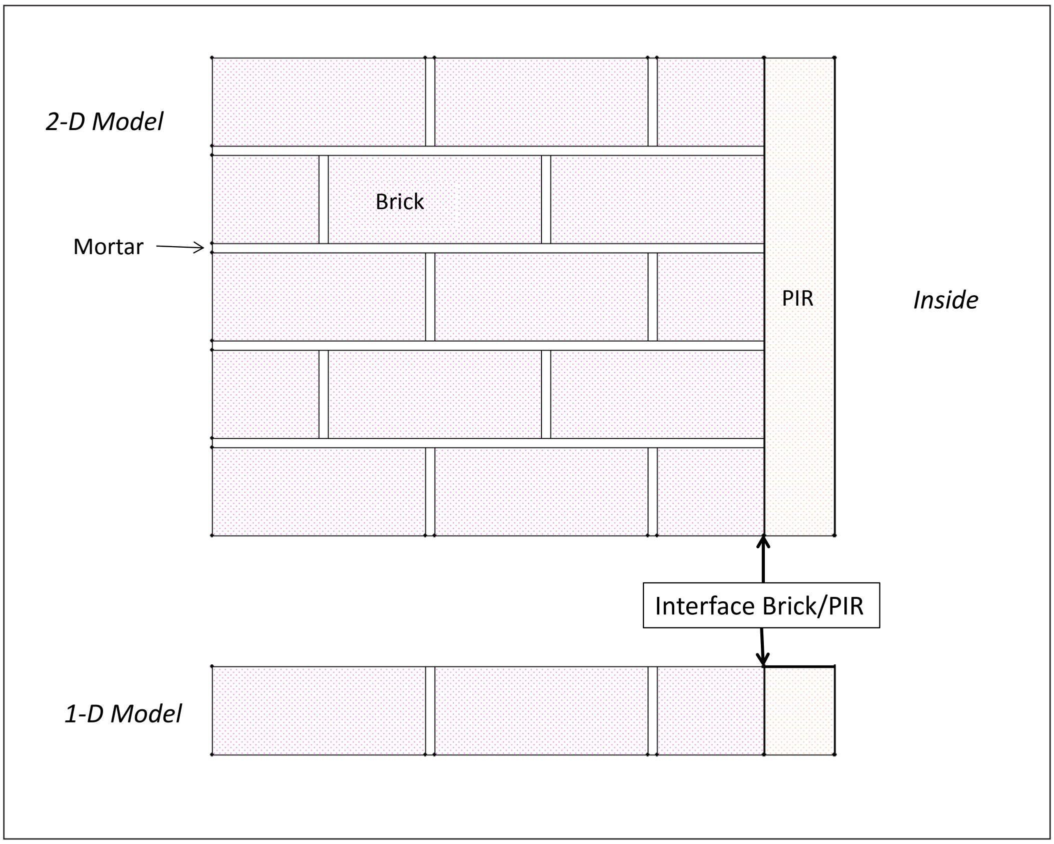


Figure 10: 1-D and 2-D models with PIR internal wall insulation

In terms of modelling, the conditions near to the inside of the construction are most important in terms of assessing potential risk, particularly at the interface between the masonry and insulation. Figure 11 shows the relative humidity at the first vertical mortar towards the inside of the brick wall without insulation (Location A). Figure 12 shows the relative humidity at the brick/PIR interface. In both cases there is good agreement between the 1-D and 2-D solutions. The moisture content of the brick adjacent to the PIR insulation is shown in Figure 13; again there is good agreement between the 1-D and 2-D models.

The results indicate that the 1-D program performs adequately for the purpose of predicting risk for walls with internal wall insulation. The program also complies with BS EN 15026 (BSI: 2007), which provides minimum criteria for simulation software used to predict one-dimensional transient heat and moisture transfer in multi-layer building components exposed to transient climate conditions on both sides. The main disadvantage of the 2-D version is the long computational times. Therefore WUFI 1-D was selected for the further simulations for comparison of brick types and internal wall insulation systems, and driving rain.

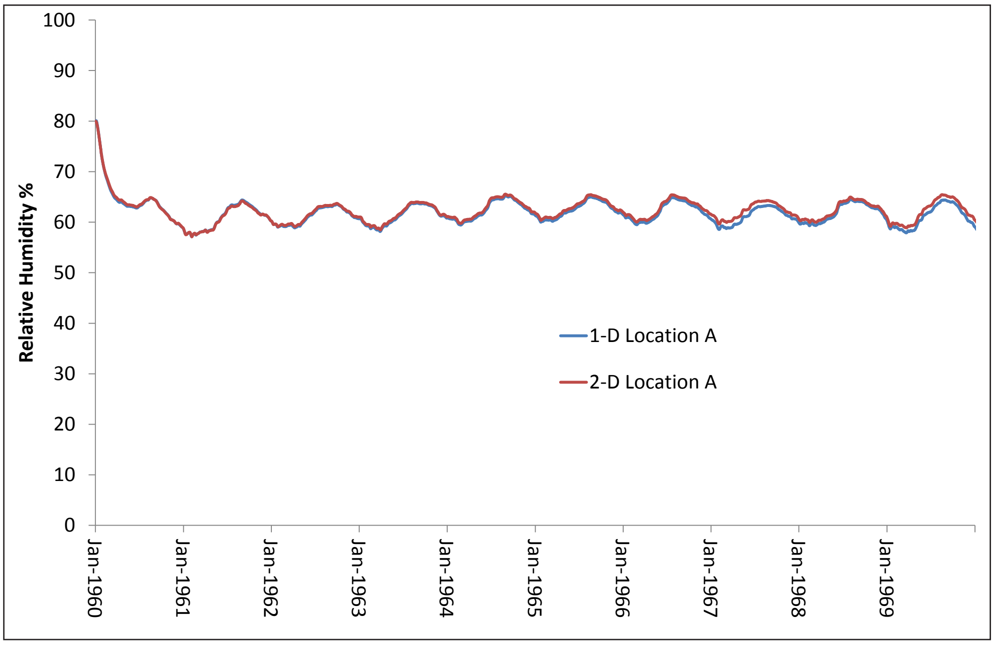


Figure 11: Comparison of 1-D and 2-D simulations of case 1 brick wall only

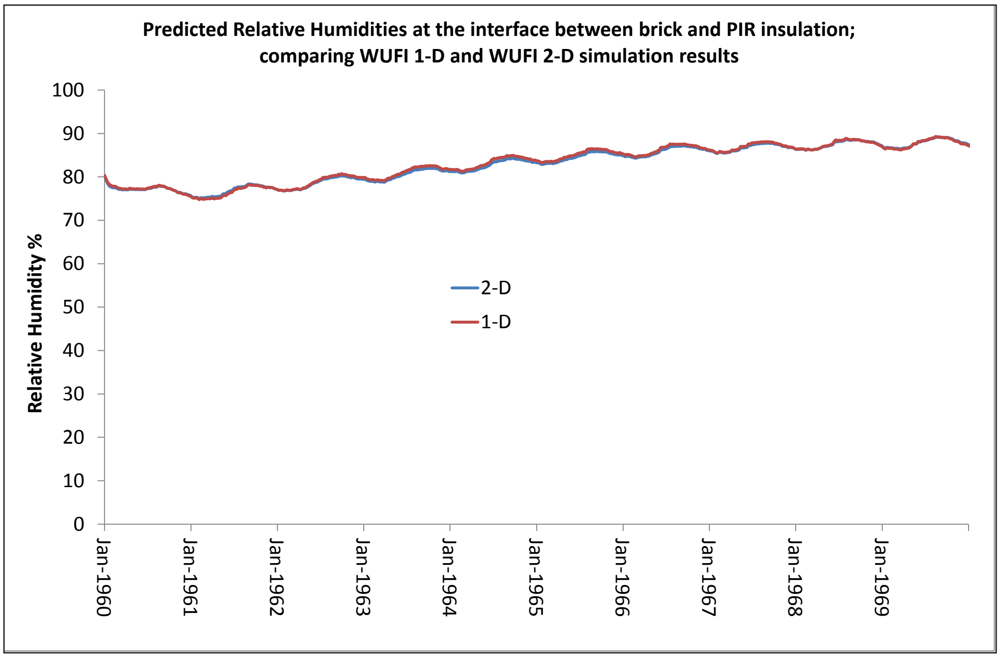


Figure 12: Comparison of 1-D and 2-D simulations of case 2 brick wall with PIR insulation

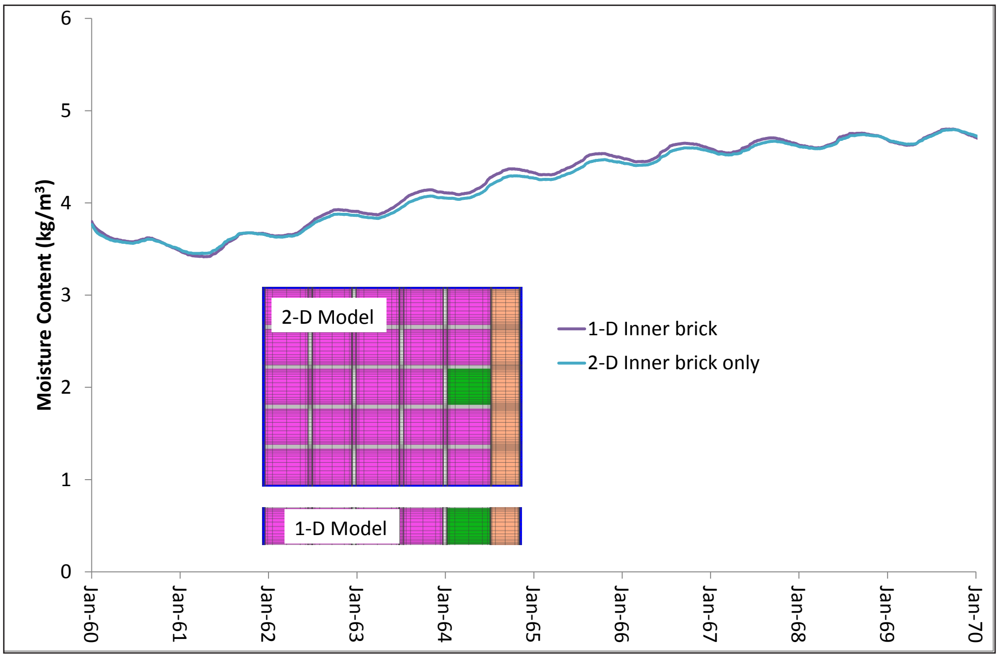


Figure 13: Comparison of 1-D and 2-D simulations of case 2 brick wall with PIR insulation: inner brick moisture content

6.2 Comparison of simulations with Flaxmill brick and ‘Historic’ and ‘Hand- Formed’ bricks from WUFI database.

The wall constructions (with and without PIR insulation) were modelled for both east and west elevations for both the ground floor and upper floor.
Figure 14 shows an extract from the WUFI data input summary showing the construction dimensions (width), materials and ‘monitoring’ positions for output data, using the Historic Brick case with PIR as an example.

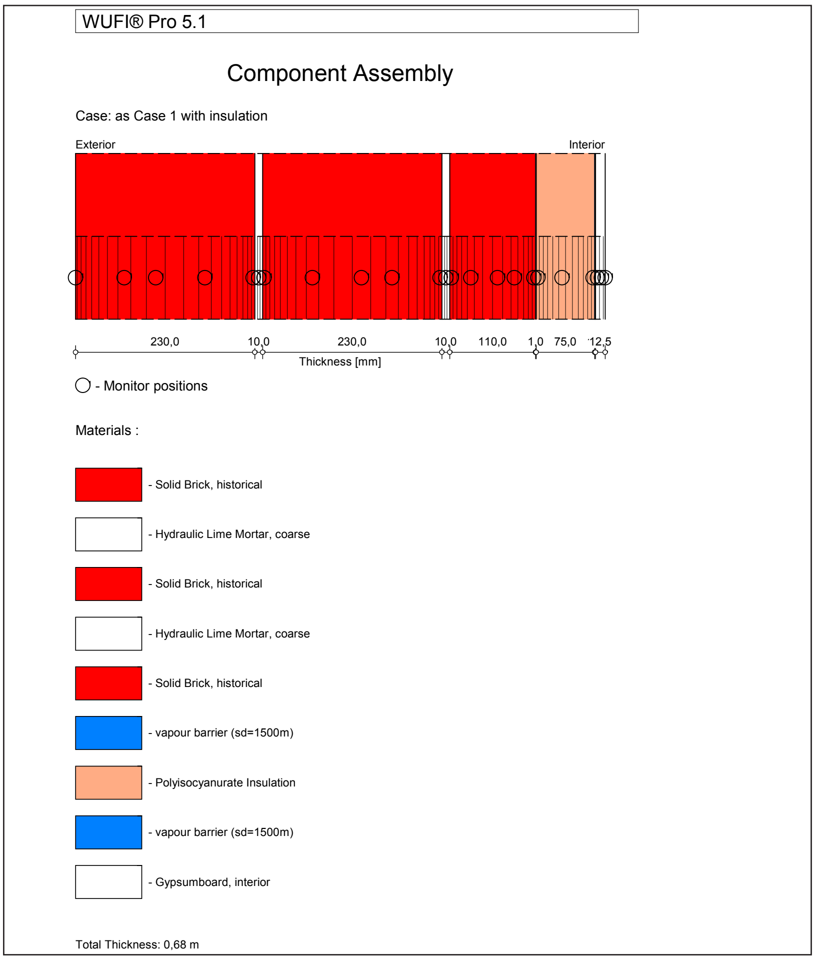


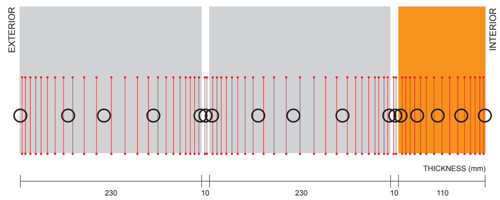
Figure 14: WUFI input for case with insulation (PIR) and vapour barriers on both faces of insulation

To initialise each model, a preliminary simulation was run for the first five years with starting conditions of 80% Relative Humidity and 15°C through the construction. The moisture content and temperature profiles at the end of this five year period were then used to re-initialise the model and the simulation re-run for the period 1960-1990. The aim of this approach was to start the simulations with more realistic conditions for each construction, taking account of wall orientation and floor level.

The inner brick moisture contents and average relative humidities of the walls without insulation are compared for the three different bricks in Figures 15-22.

For the wall constructions with PIR insulation, Figures 23-30 show the inner brick moisture contents and relative humidities at the interface between the inner brick and the PIR, which is considered the most critical location for assessing risk to the construction with internal wall insulation.

All the results are displayed as monthly averages for clarity.



Ground floor; Brick without insulation

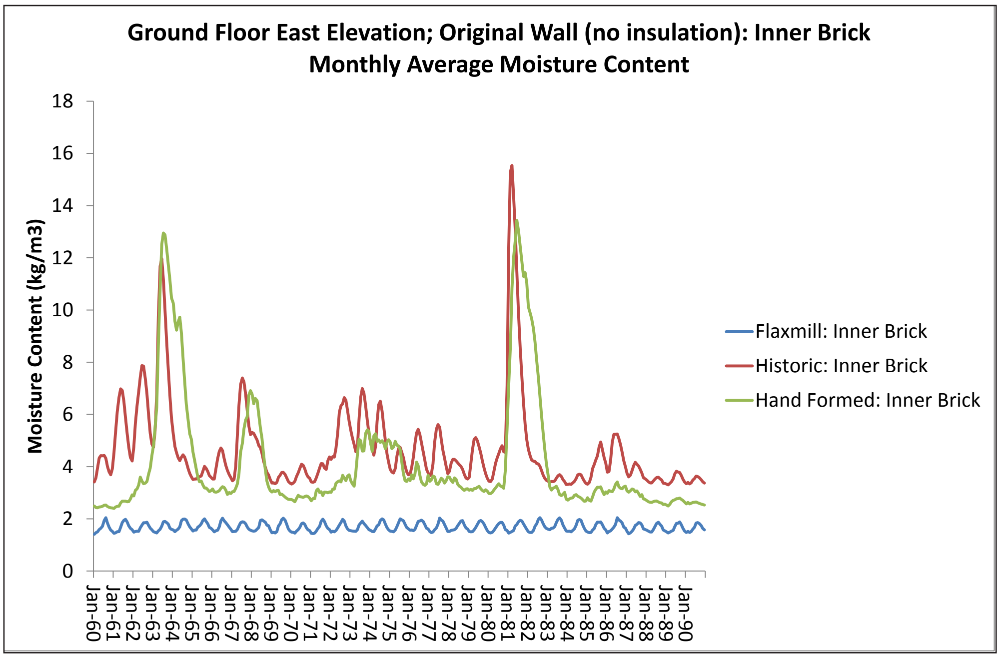


Figure 15: Ground Floor East Elevation; original wall without insulation; inner brick monthly average moisture content

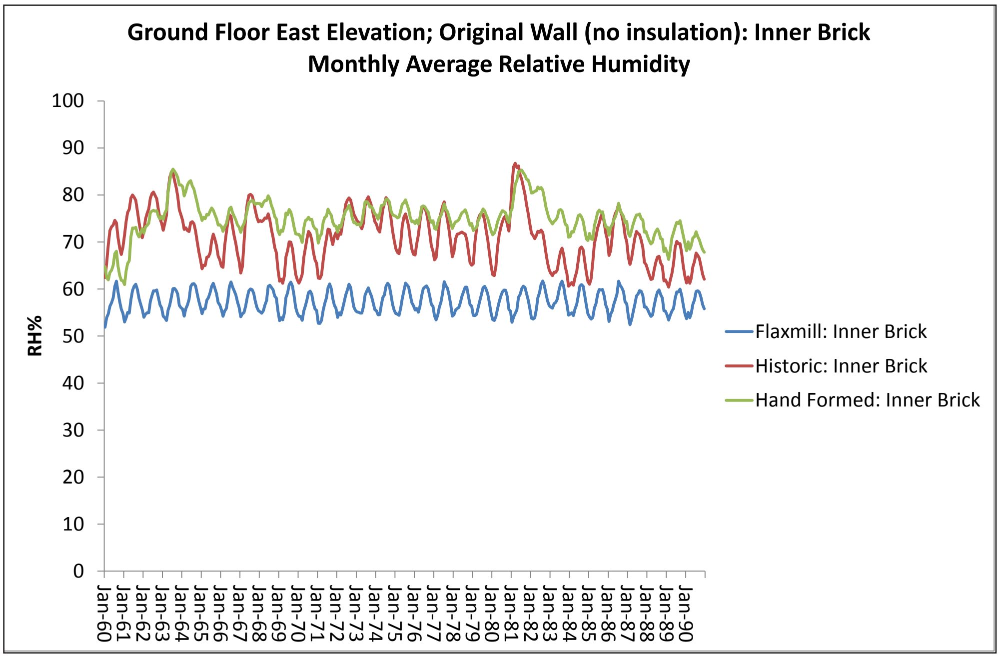


Figure 16: Ground Floor East Elevation; original wall without insulation; inner brick monthly average relative humidity

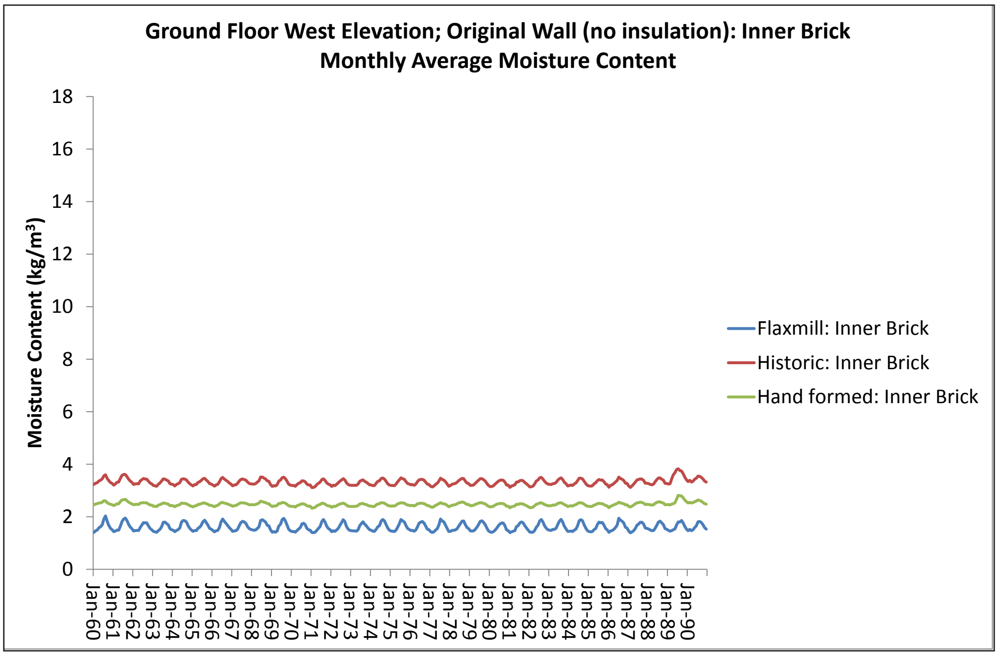


Figure 17: Ground Floor West Elevation; original wall without insulation; inner brick monthly average moisture content

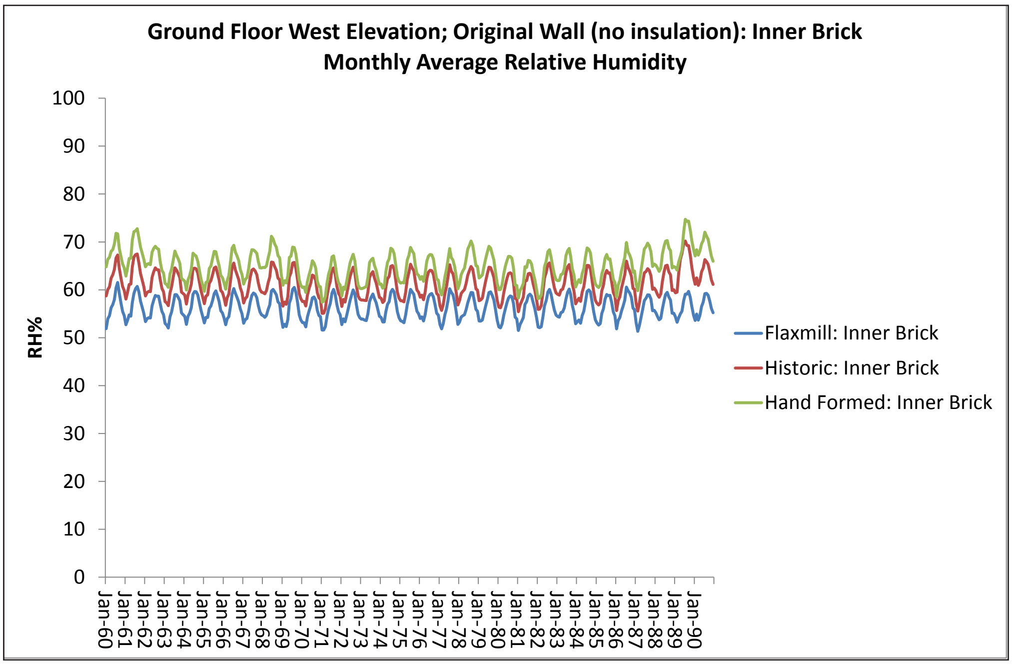
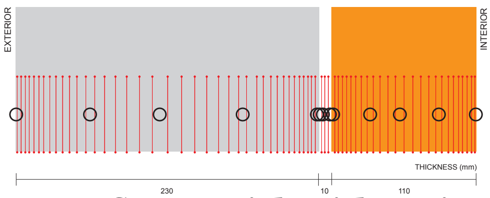


Figure 18: Ground Floor West Elevation; original wall without insulation; inner brick monthly average relative humidity



Upper floor; Brick without insulation

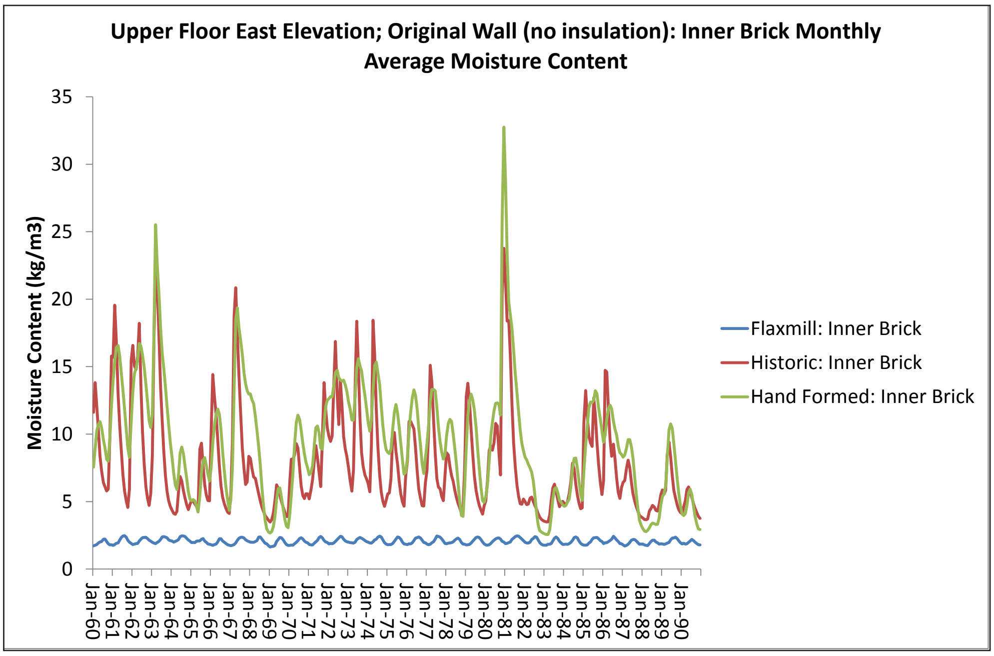


Figure 19: Upper Floor East Elevation; original wall without insulation; inner brick monthly average moisture content

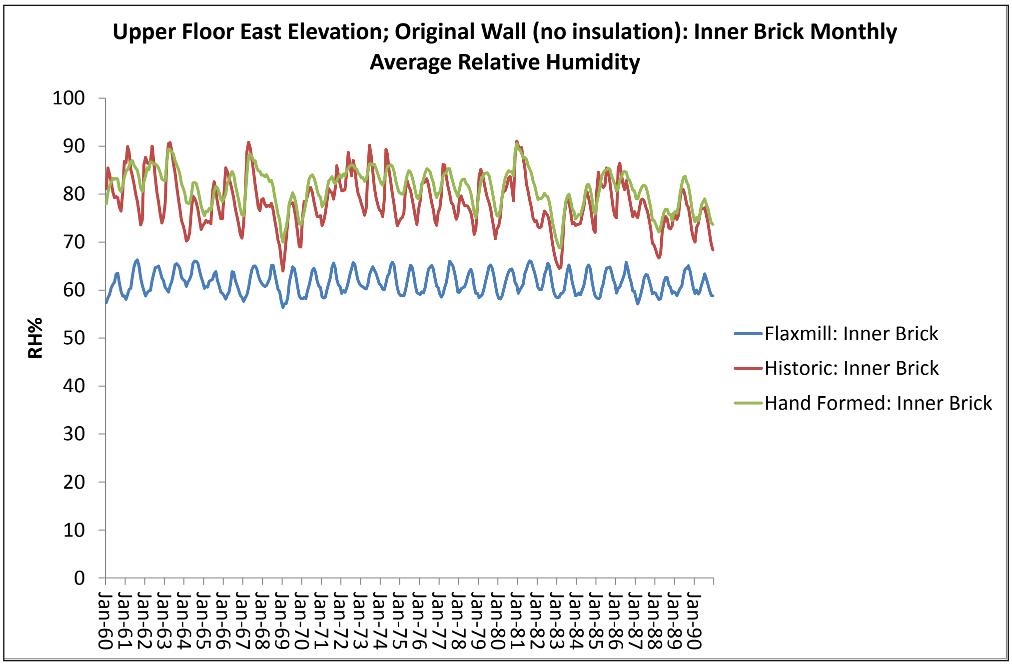


Figure 20: Upper Floor East Elevation; original wall without insulation; inner brick monthly average relative humidity

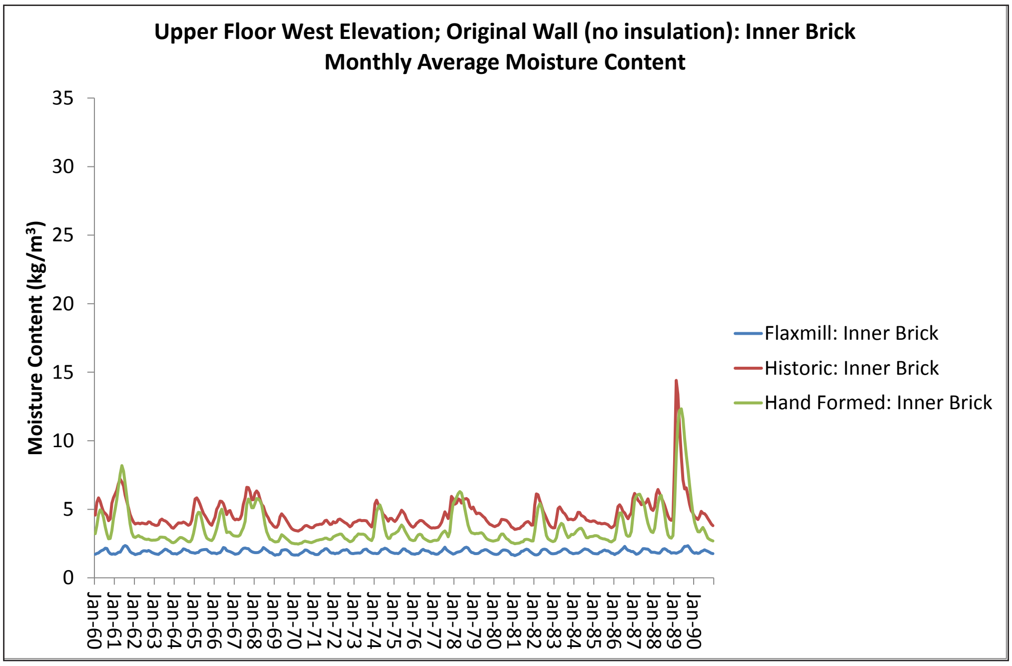


Figure 21: Upper Floor West Elevation; original wall without insulation; inner brick monthly average moisture content

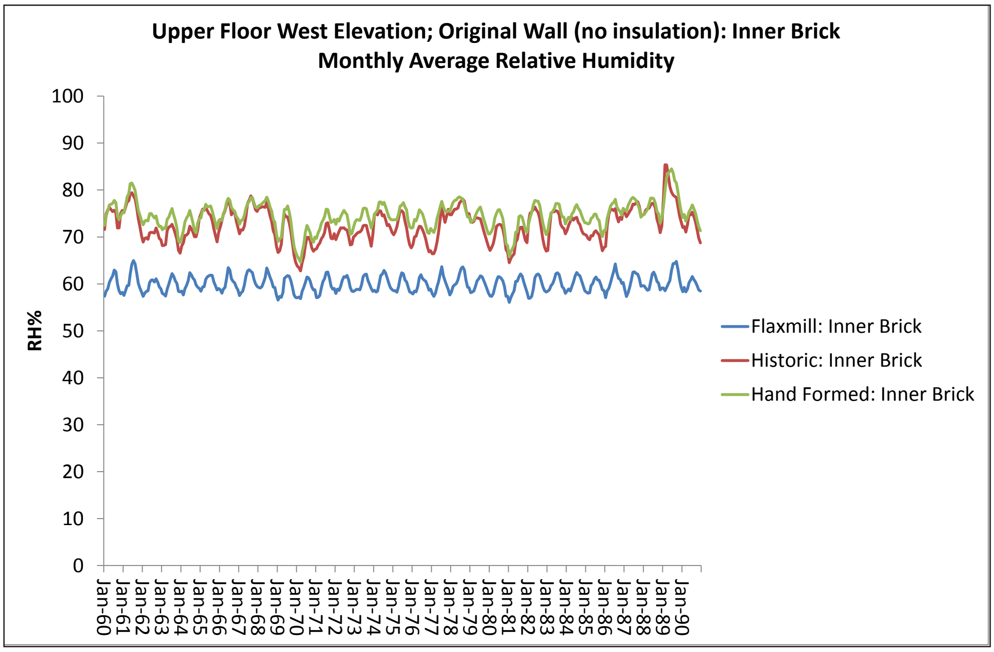
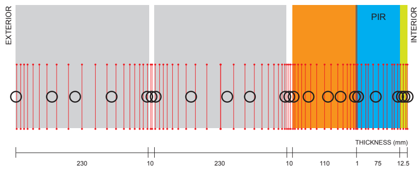


Figure 22: Upper Floor West Elevation; original wall without insulation; inner brick monthly average relative humidity



Ground Floor, wall with PIR insulation

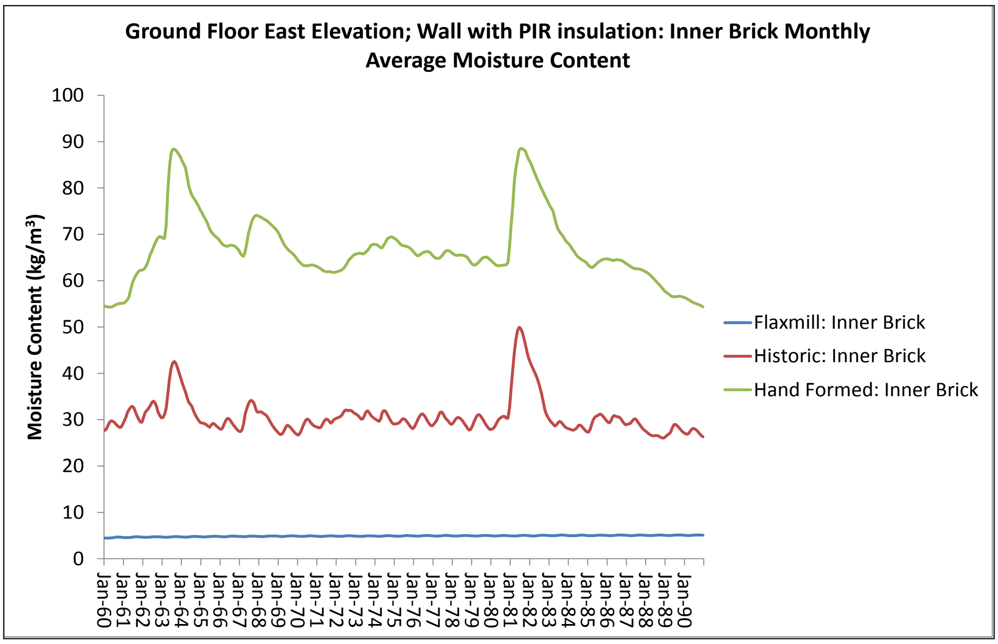


Figure 23: Ground Floor East Elevation; wall with PIR insulation: inner brick monthly average moisture content

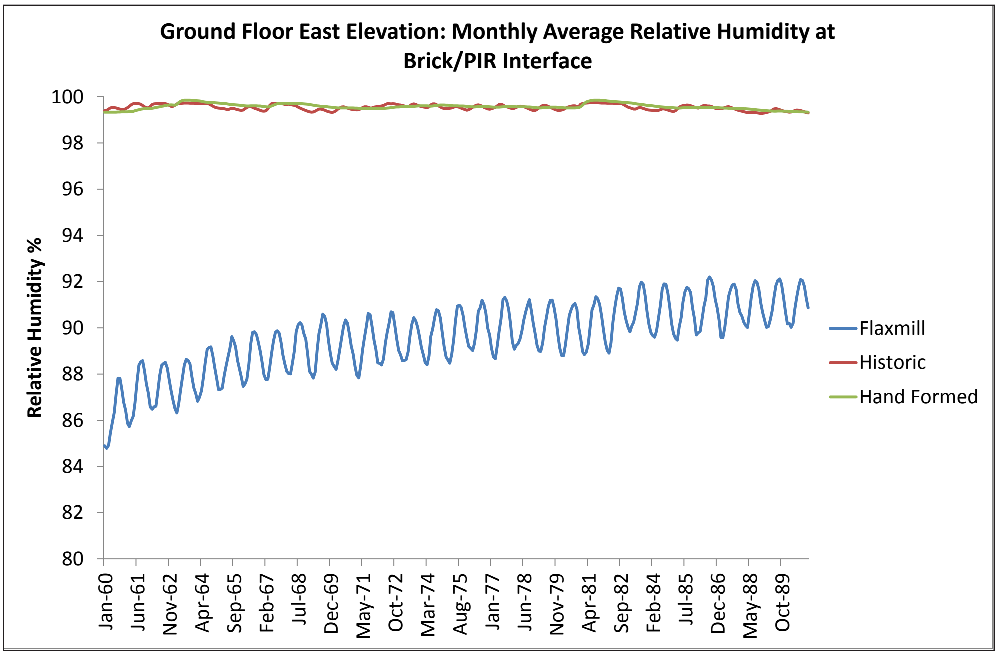


Figure 24: Ground Floor East Elevation: monthly average relative humidity at brick/PIR interface

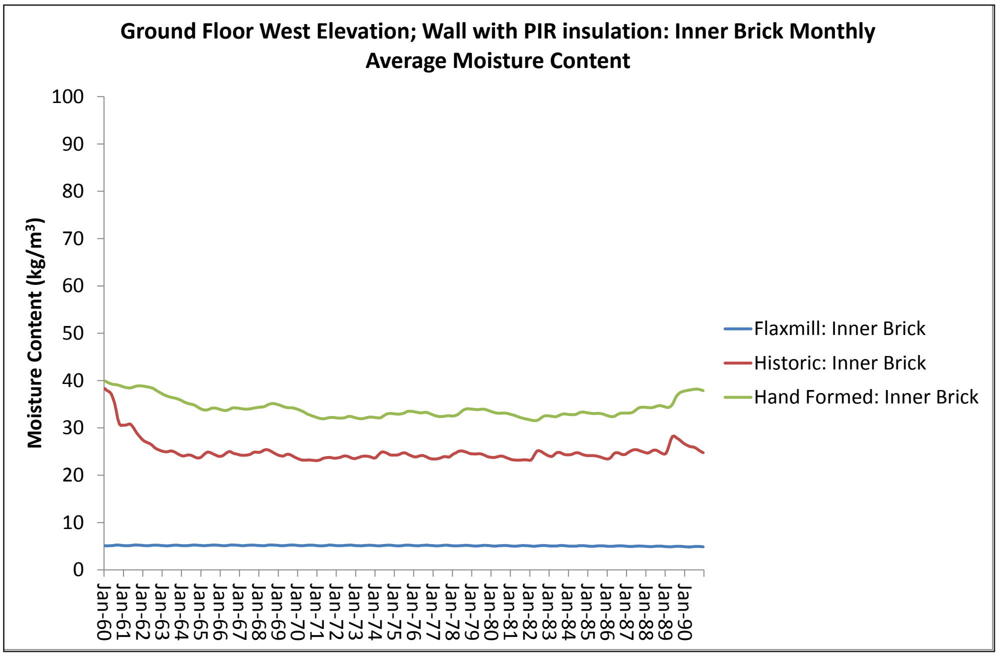


Figure 25: Ground Floor West Elevation; wall with PIR insulation; inner brick monthly average moisture content

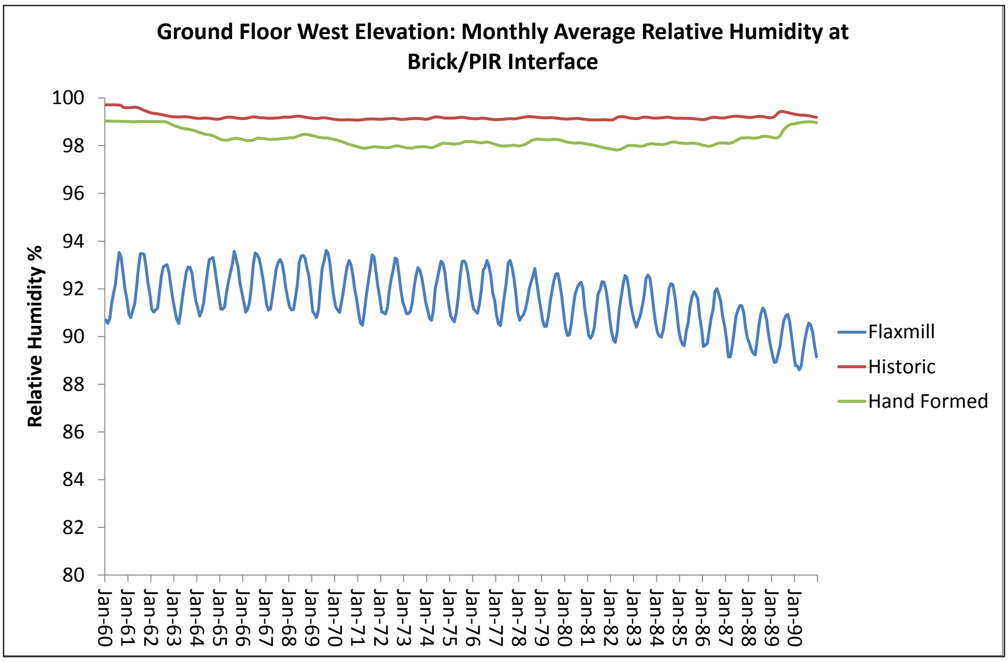
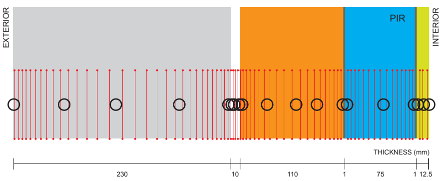


Figure 26: Ground Floor West Elevation; monthly average relative humidity at brick/PIR interface



Upper Floor; wall with PIR insulation

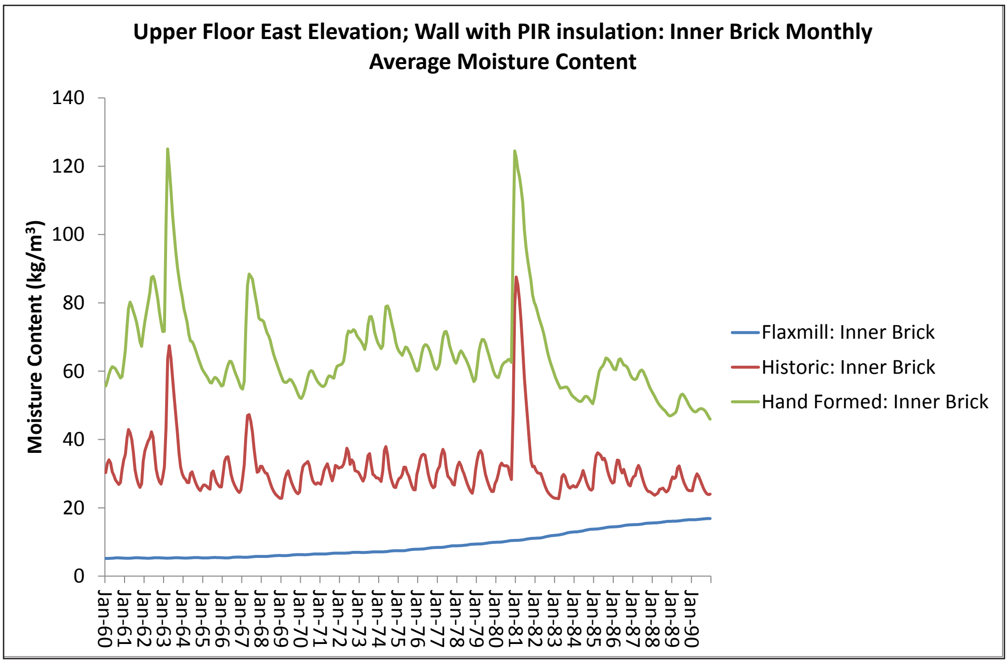


Figure 27: Upper Floor East Elevation; wall with PIR insulation; inner brick monthly average moisture content

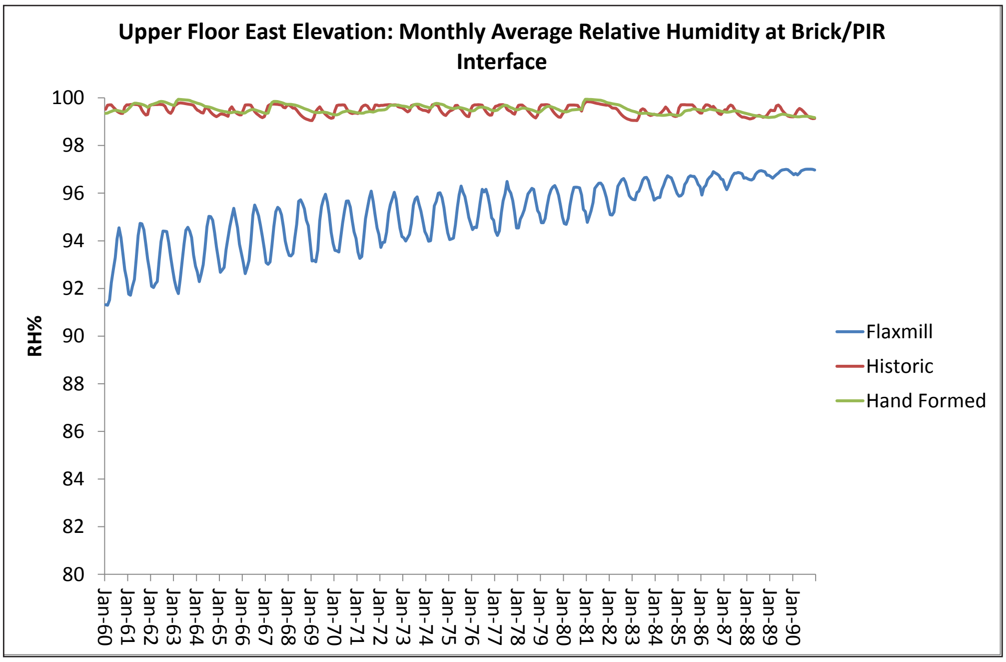


Figure 28: Upper Floor East Elevation; monthly average relative humidity at brick/PIR interface

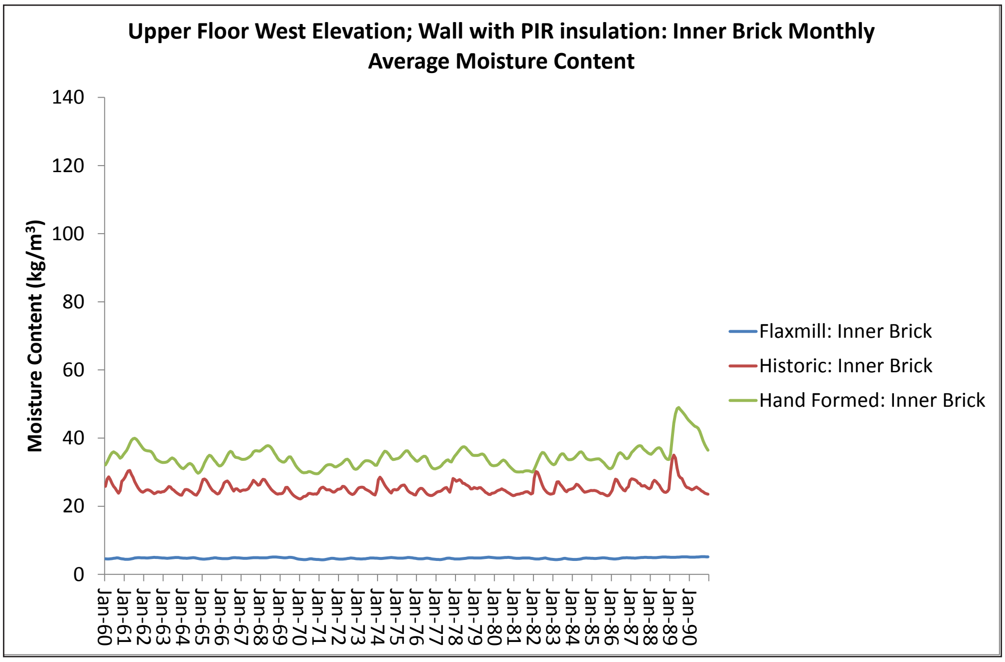


Figure 29: Upper Floor West Elevation; wall with PIR insulation; inner brick monthly average moisture content

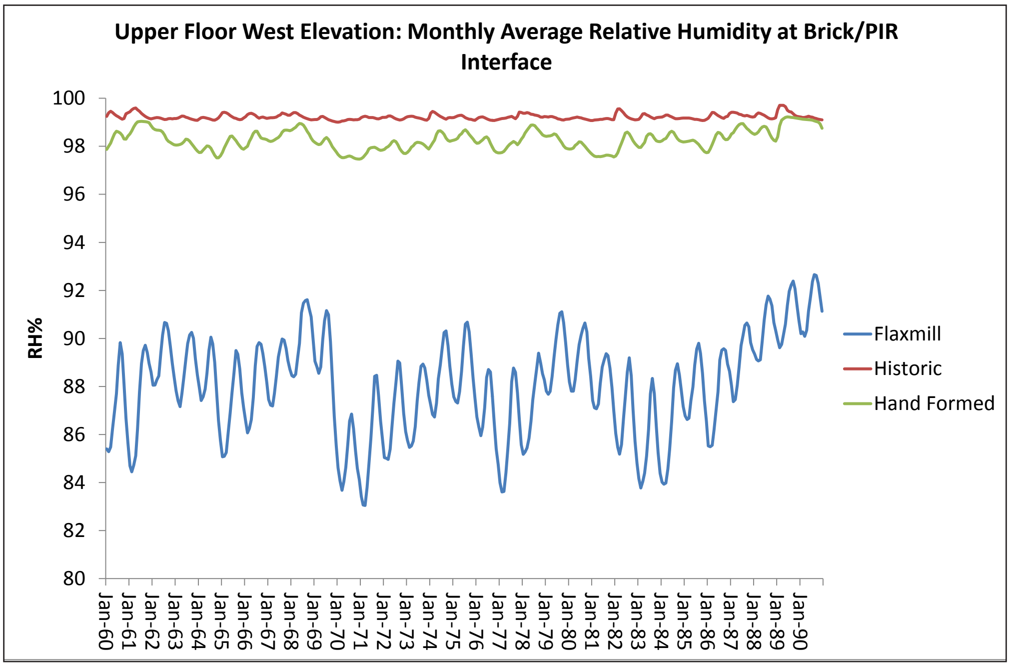


Figure 30: Upper Floor West Elevation; monthly average relative humidity at brick/PIR interface

The results show varying behaviour depending on brick type, elevation and floor level. In general, for the uninsulated brick walls, the moisture contents and relative humidities of the inner brick are lower for the west elevation than the east. The peaks in moisture content for the east elevation (Figures 15 & 19) correlate well with the peaks in monthly driven rain (Figure 5). The moisture content and relative humidities are lower for the ground floor construction (2½ bricks thick), Figures 15-18, compared to the upper floor (1½ bricks thick), Figures 19-22. The Flaxmill brick generally gives lower moisture contents and relative humidities than either the Historic or the Hand Formed brick.

Considering the wall with PIR insulation, the results show higher moisture contents than for the cases without insulation and high relative humidities at the brick/PIR interface. The results also reflect differences due to orientation and wall thickness. The Flaxmill brick cases show lower moisture contents and interface humidities than the other bricks, with the Hand Formed brick showing the highest moisture contents.

The difference in the results for the three bricks may be attributed to the differences in moisture absorption, with significantly lower absorption for the Flaxmill brick.

6.3 Comparisons of different insulation systems

A series of simulations was carried out with the following internal wall insulation systems:

- PIR with plasterboard finish (as for section 6.2)
- Mineral Wool with plasterboard finish
- Mineral Wool with vapour barrier and plasterboard finish
- Lime parge coat on internal surface of brick, wood-fibre insulation with ‘functional’ layer and internal lime plaster coat. The 0.75mm functional layer has a diffusion resistance factor of 450 (SD value = 0.034) and is sandwiched between two layers of wood wool fibre insulation.

The ground and upper wall on the east elevation were modelled using Flaxmill brick and the same initialisation and climate period used in section 6.2. The results are shown in Figures 31-34.

In general there is a difference between the performance of the walls comparing the ground and upper floor constructions, with higher moisture contents and humidities in the thinner 1½ brick upper wall. The four systems behave somewhat differently. The mineral wool without a vapour barrier shows a large seasonal range in the relative humidity at the interface between the brick and insulation. SD-value or vapour diffusion thickness of the mineral wool and plasterboard is the lowest of the four systems at 0.14. The mineral wool is also treated as non-hygroscopic. Adding a vapour barrier reduces the seasonal range, but the average interface relative humidity increases and in the case of the upper floor, the moisture content appears to ratchet up year-on-year (Figure 33). The SD-value with a vapour barrier is 1500.

The PIR is the only system with interface relative humidities peaking in summer, indicating that the vapour barrier at the outside face of the PIR is allowing a build-up of moisture, which does not fully disperse in the winter months. This results in the ratcheting up of the interface relative humidity and inner brick moisture content year-on-year over the simulation period. This is most apparent for the upper floor wall construction (Figures 33 & 34). The PIR system has the highest SD-value of 3004.

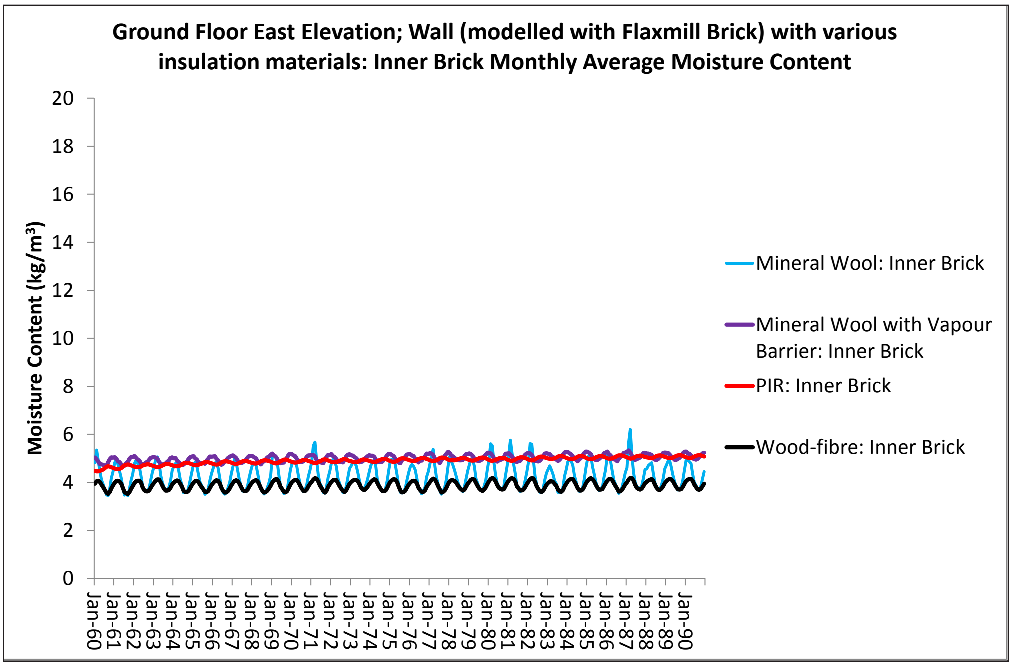


Figure 31: Ground Floor East Elevation; wall (modelled with Flaxmill brick) with various insulation materials: inner brick monthly average moisture content

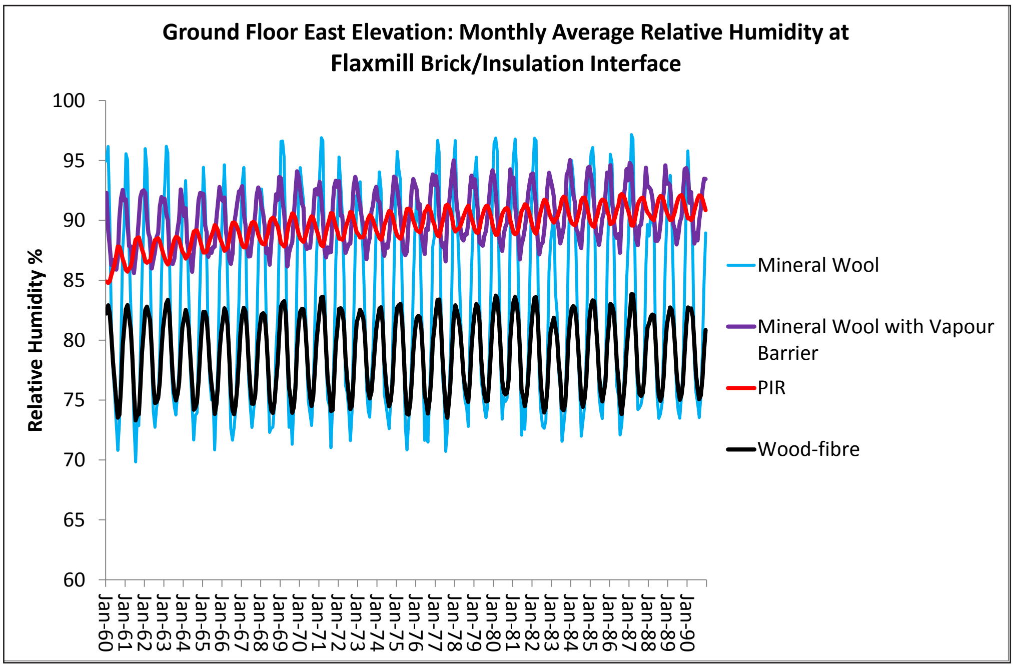


Figure 32: Ground Floor East Elevation: monthly average relative humidity at Flaxmill brick/insulation interface

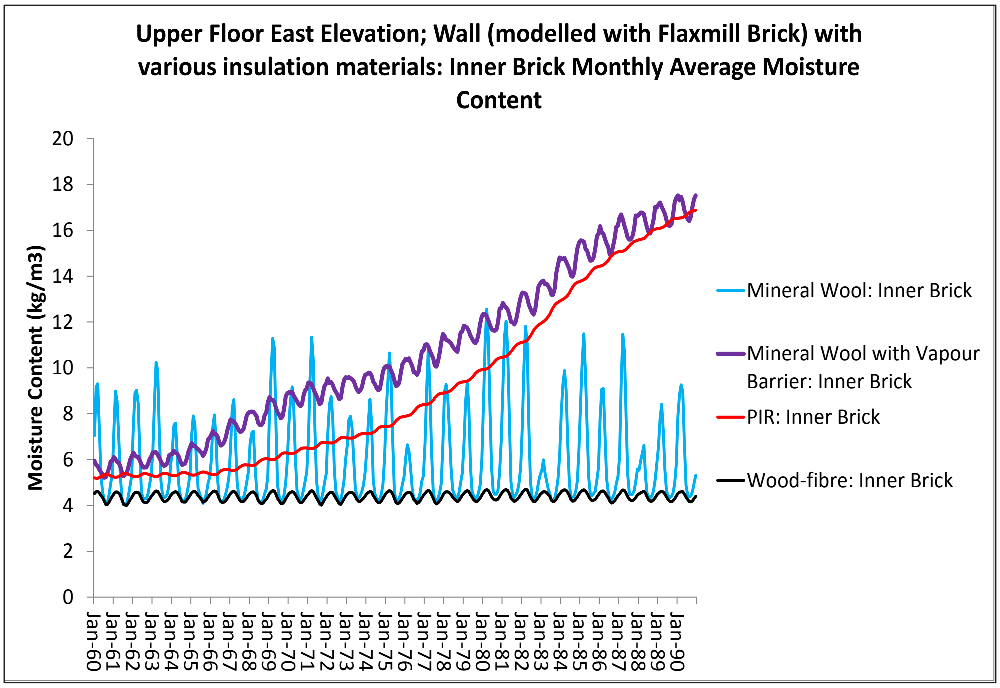


Figure 33: Upper Floor East Elevation; wall (modelled with Flaxmill brick) with various insulation materials: inner brick monthly average moisture content

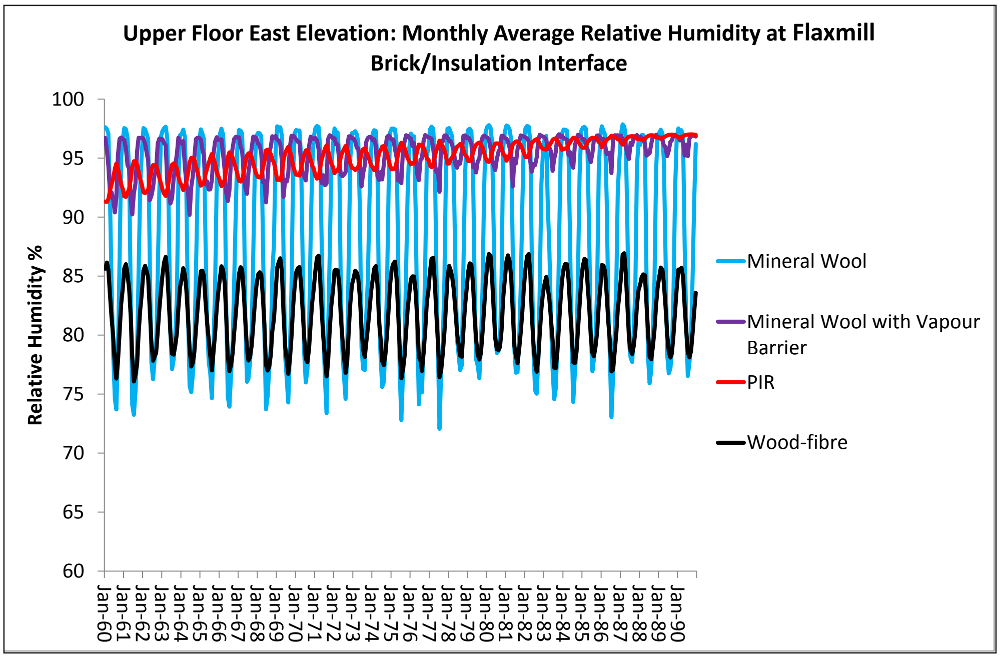


Figure 34: Upper Floor East Elevation: monthly average relative humidity at Flaxmill brick/insulation interface

The wood-fibre insulation system appears to give the best results with average interface relative humidities of around 80%RH and also similar moisture contents in both ground and upper floor constructions throughout the simulation period. The insulation system has a SD-value of 0.9, of which 0.34 is provided by the functional layer. The insulation itself has a moisture content of approximately 17kg/m3 at 80%RH. A simulation was carried out to identify the effect of the functional. Figure 35 shows that removing the functional layer increases the seasonal swings in relative humidity at the interface between the brick and the insulation.

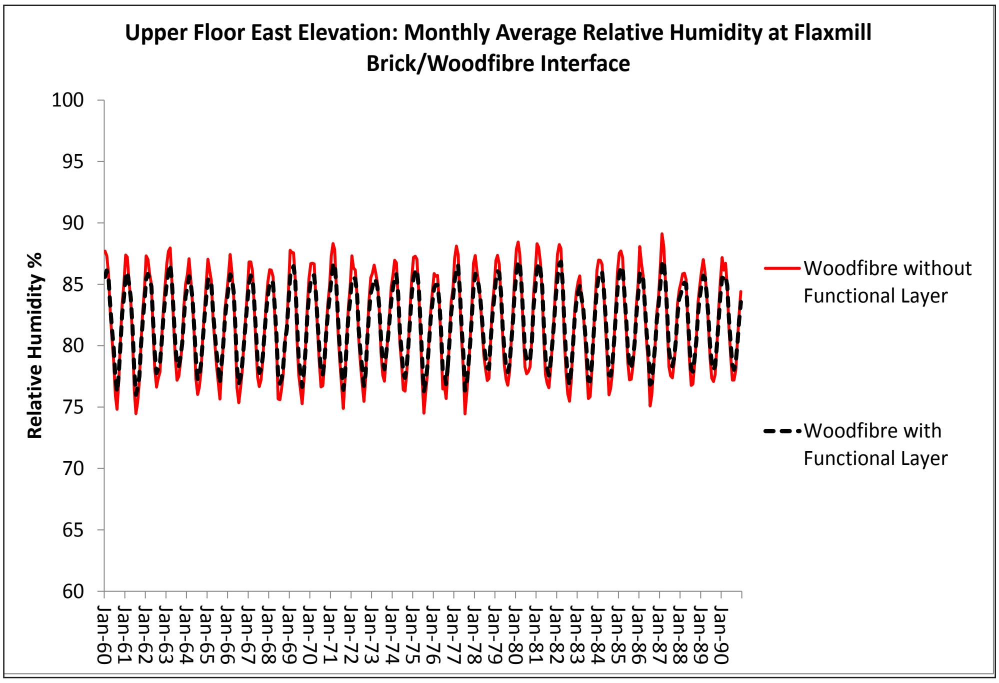


Figure 35: The effect of the functional layer in the wood-fibre insulation system

6.4 Rain adherence factor

As explained above, the rain adherence factor takes into account that some of the rain water hitting the wall surface splashes off on impact and is not available for capillary absorption. Also under heavy driving rain conditions, all the rain impacting on the wall surface may not be absorbed due to the capillarity of the wall material, which results in rain running off the surface (Straube J. 2010).

The above simulations have assumed a rain adherence factor of 1, i.e. 100% of the rain impacting on the surface is absorbed, based on the assumption that the driving rain calculation according to BS EN ISO 15927-3:2009 accounts for this. However, this may not be the case, if the wall surface and capillary moisture transport properties of the wall material should also be considered in determining the amount of rain absorbed. Unfortunately we have no simple means of measuring this in practice.

Simulations were carried out for the 1½ brick upper wall on the east elevation constructed of Flaxmill brick with PIR internal wall insulation and an internal plasterboard lining. Rain adherence factors of 0.01, 0.1, 0.25, 0.5, 0.75 and 1 were applied. The results are shown in Figure 36 for the relative humidity at the brick/PIR interface.

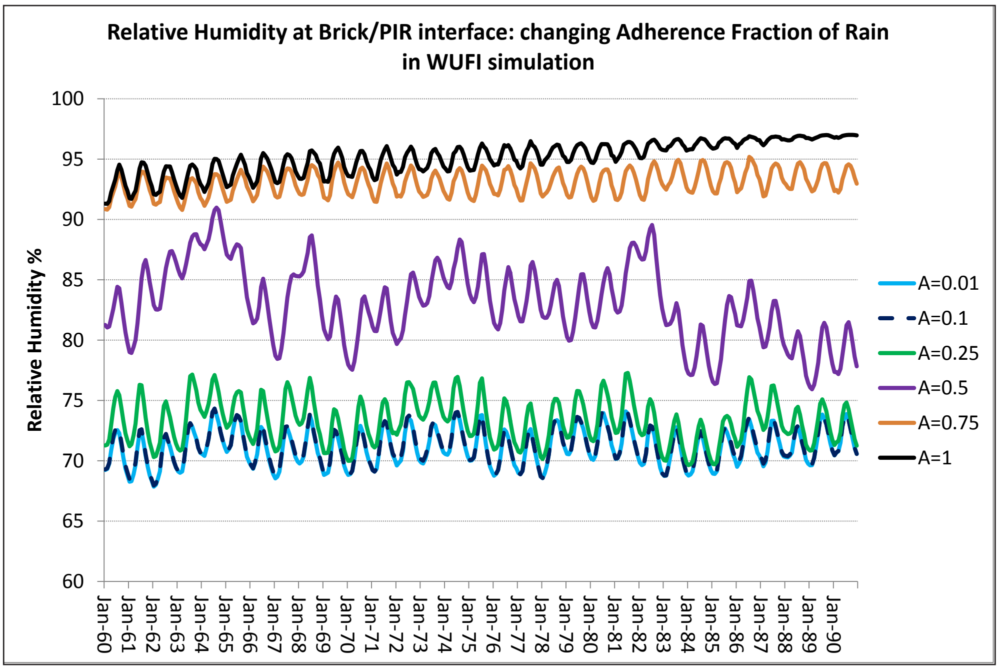


Figure 36: The effect of changing the rain adherence factor on the relative humidity at the brick/PIR interface of the upper wall on the east elevation

Figure 36 indicates that lowering the rain adherence factor has a significant impact on the interface relative humidity. However, the actual adherence factor is unknown and may not be constant in any case, depending on the intensity of the driving rain. Measurements of driving rain on the east and west elevations of the 3rd floor of the South Engine House are currently being made in combination with wall moisture contents. Using these data and measured outdoor climate and internal environmental conditions it should be feasible to 'calibrate' WUFI models of the walls by adjusting the rain adherence factor to produce a good fit of the model to the real data.

7. CONCLUSIONS

Clearly it is better to use the measured properties of traditional materials for hygrothermal simulations. Uncertainty will result from using alternatives from the WUFI database.

For relatively simple constructions such as the walls at Flaxmill, WUFI 1-D is satisfactory for modelling a range of scenarios. The results converge with those from 2-D simulations, which take considerably longer to run. WUFI 2-D is more suitable for complex constructions, such as wall/floor junctions.

The wood-fibre insulation system, which has some vapour resistance and is also hygroscopic, appears to be the best of the four insulation systems. Mineral wool, whilst having a very low vapour resistance, is effectively non-hygroscopic and therefore is unable to buffer moisture.

The insulation systems with high vapour diffusion resistance, PIR and the mineral wool with a vapour barrier, appear to cause a build-up of moisture within the walls in the long term. Changing the rain adherence factor in the modelling has a significant effect on the simulation results. However, the actual adherence factor is unknown and may not be constant in any case depending on the intensity of the driving rain. Current measurements, which are underway at the South Engine House, may be used to 'calibrate' WUFI models of the walls by adjusting the rain adherence factor to produce a good fit of the model to the real data. WUFI is a useful tool which can be used to assess options for upgrading the thermal performance of traditional buildings, provided we have suitable material properties of our traditional materials. However, as the simulations results reported show, the unknown boundary conditions such as absorption of driving rain may produce a high level of uncertainty.

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