Heat and Moisture Transport in Buildings with Retrofitted Insulation: Computer Modelling and Case Studies

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Heat and Moisture Transport in Buildings with Retrofitted Insulation: Computer Modelling and Case Studies

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ABSTRACT

Within areas of temperate climate, like the United Kingdom, retrofitting of existing houses to improve their energy efficiency is becoming common place. Within the UK this has been driven mainly by government directives focused at reducing the CO2 emissions from existing housing stock to meet 2050 Kyoto Protocol targets, but increasingly by home owners who have seen a sharp rise in home heating costs. A key element of this retrofit work is the addition of extra insulation to the building fabric. In some cases this has proved successful and home owners have noted reduced energy costs and increased comfort levels but in other cases problems with mould growth, surface or interstitial condensation and material degradation have been reported. These problems are a result of poor consideration of moisture movement within the building and the build fabric by either poor design, construction or a combination of both.

This paper reviews a building element heat and moisture transport computer modeling tool, WUFI Pro 5.2, which has been developed to assess the hygrothermal performance building elements such as the wall assembly. Tools like this are being increasingly used in the construction industry to mitigate the retrofit issues described previously. The modelled results are compared against the humidity profile obtained using embedded sensors in a internally insulated solid wall properties. The accuracy and suitability of heat and moisture modelling software is discussed along with a review of the hygrothermal performance of the case study buildings.

KEYWORDS: retrofit; hygrothermal modeling; heat and moisture transport; HAM; solid wall insulation; in-situ u value; sensors

1. INTRODUCTION

This research is being driven by industry demand to assess the quality of retrofit measures in regards to their moisture performance. This is particularly important when dealing with the restoration of historic buildings or improving the thermal transmittance (U-Value) of existing structures. Questions around this subject are closely related to the present and future moisture conditions within the structure. It is unpractical to carry out experimental investigations on all new construction types or construction details to test their performance so it is vital that modelling can be carried our accurately. While general wall constructions do not change vastly there can be a large variation in junction detailing in buildings therefore one off designs are often needed.

Building element heat and moisture transport models have been extensively validated for laboratory experiments worldwide with the most notable project being the IEA Annex 24 project (Hens, 1996). Within this exercise models were validated in three ways: Analytical verification; comparison of investigated models results and empirical validation. Each of the methods has numerous benefits and draw back for example analytical solutions only exist for simple cases were material properties are constant but do test accuracy of main algorithms; comparison of predicted results between a variety of models successfully builds an idea of modelling consensus but may miss situations were all models perform poorly and finally experimental data is limited to the accuracy in which heat and moisture phenomenon can be measured. Six case studies were investigated and they still remain as a key standard to which all new models can be calibrated and include the analysis of a concrete flat roof, timber framed wall, block cavity wall, metallic roof, a crawl space and a timber flat roof. The next major project in BEHAM modelling was the HAMSTAD project (Hagentoft et. al., 2004) launched by the EU at the end of 2000, with the aim of calibrating all new models against a set of industry approved experimental data. This benchmark process was designed in a way in which software manufacturers could assess the accuracy of their work and also retain and develop their own program algorithms. Five simulations are presented and include an insulated concrete roof, homogenous wall, lightweight wall, capillary active inside insulation and a render clad block wall. Importantly exact material definitions are provided as well as full detail of boundary conditions for all scenarios. While this level of information is import for validation of model algorithm accuracy the industrial significance of software has not been fully assessed due to the unknown accuracy in commercial situations. The complexity of the models is high with a large variation of input parameters needing to be addressed by the user including climate data, internal conditions, material properties and boundary conditions. This research looks to investigate the accuracy of WUFI Pro 5.2 using common UK retrofit wall assemblies with particular focus on internal insulation of solid wall red brick buildings, a type of wall construction that has posed problems for the industry so far when considering retrofit practises.

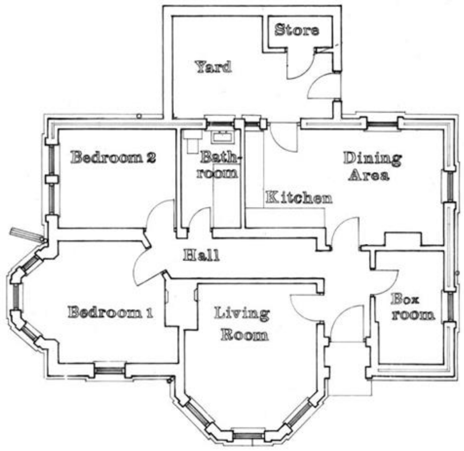
2. CASE STUDY: TWO RETROFITTED SOLID WALL HOUSES

2.1 Specification of Retrofit A and B, Northern Ireland

The first case study house (Retrofit A) is a two bedroom solid wall red brick bungalow built in 1885, 10 miles outside Belfast, Northern Ireland. The structural and insulation levels of the house remained largely unchanged until 2005 when measures to improve the energy efficiency of the home were introduced. These upgrades included the addition of internal insulation, upgrading of loft insulation and the addition of a mechanical ventilation and heat recovery system. The layout of the bungalow can be seen in Figure 1 and an overview of the design specification of the case study house can be seen in Table 1. It is important to note that the building is a Grade II Listed Building (protected historical building) therefore limiting the external work that can be implemented on the house, including the replacement of the single glazed sash windows. This type of building poses a particular problem to designers and the social housing authority that is responsible for it- a balance needs to be found between conservation, CO2 output and occupant running costs. The second property investigated (Retrofit B) is a four bedroom solid wall red brick house built in 1878 and located in central Belfast, Northern Ireland. The building was in a state of disrepair before renovation work was completed in 2007. Walls were internally insulated, double glazing installed, space heating provided by an air source heat pump and ventilation via an MVHR system. Layout and design specifications can be again seen in Figure 1 and Table 1 respectively.

Table 1. Summary of Case Study Houses

	Unit	Retrofit A	Retrofit B
Air-changes per hour (As built value at 50Pa Pressure)	ACH	8.9	11.2
Ground floor (Design value)	W/m^2K	N/A	0.21
Walls (Design value)	W/m^2K	1.05	0.24
Roof (Design value)	W/m^2K	0.19	0.19
Windows (Design value)	W/m^2K	4.8	1.8



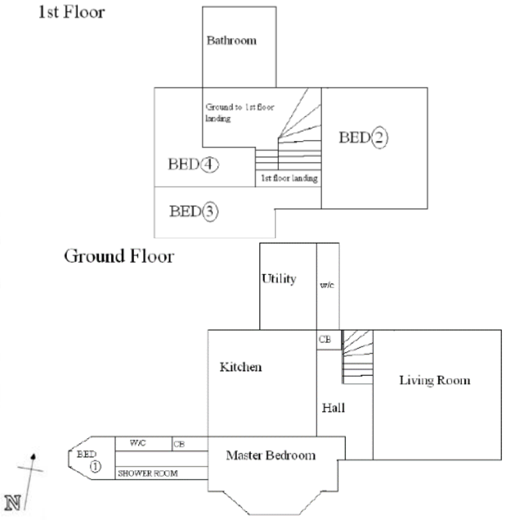


Figure 1. (a) Floor plan of Retrofit A Figure 1. (b) Floor plan of Retrofit B

3. MONITORING OF HYGROTHMAL BEHAVOUR

3.1 In-Situ Thermal Transmittance (U-Value) Calculation

An *in-situ* u-value measurement was carried out in each of the properties in March 2013. Two Hukseflux HFP01 Heat Flux Sensors were used in retrofit A and B for monitoring periods of 350 and 250 hours respectively to assess the heat flux through the wall. Data from the initial 48 hour period after sensor installation was ignored to allow temperatures across the heat flux plate to stabilize. Measurements were recorded on a 16bit data logger with an accuracy of 1μV suitable for the nominal sensor accuracy of 50 μV/W.m^2. Sensors were mounted to the wall with sticking tape using a heat sink paste to ensure good thermal contact. A small film of plastic was placed between the heat sink paste and the wall to protect the internal finish. Calibration of the sensor in conjunction with this mounting technique was carried out in the laboratory prior to site installation to confirm manufacture accuracy of ±5%. The average values obtained from the two sensors was calculated to improve spatial accuracy with the results presented in Figure 2 and 3.

3.1.1 U-Value Analysis of Retrofit A

The wall construction of this property consists of 225mm historic red brick, a 30mm cavity and 12.5mm plasterboard which is secured to the wall with a light-weight metal framing system. Figure 2 shows the average U-value found by the two heat flux sensors over the 350 hour monitoring period. The average value for the period was found to be 1.23W/m^{2}K which is worse than the design value of 1.05W/m^{2}K and the data gathered has a number of large variations. There are two reasons for this variation, the first being the effect of rain on the porous external brick causing increased heat loss due to evaporating moisture. The second is due to air changes occurring in the cavity behind the plasterboard. This cavity space is open to air changes from an area of loft space which is not insulated due to the mineral wool not being laid to the edge of the brickwork. There is not enough space for the required depth of mineral wool at this critical location due to the rafter meeting the wall plate as detailed in Figure 3. The rate of air changes per hour in this cavity is dependent on the natural ventilation of the roof space and therefore the wind speed and wind direction. At the time of installation of sensors it was found that the air in the cavity was moving at up to 0.01m/s, measured with a hot wire anemometer. The effect of thermal bridging caused by lightweight metal framing was not considered by these readings.

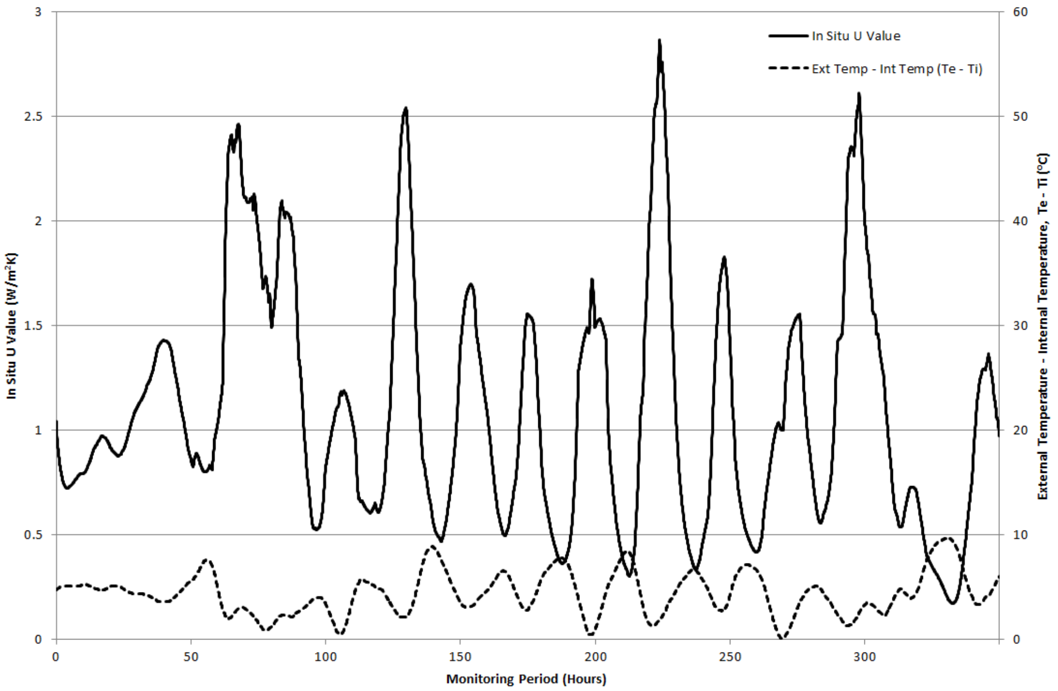


Figure 2. In-Situ U-Value from Wall Assembly of Retrofit A

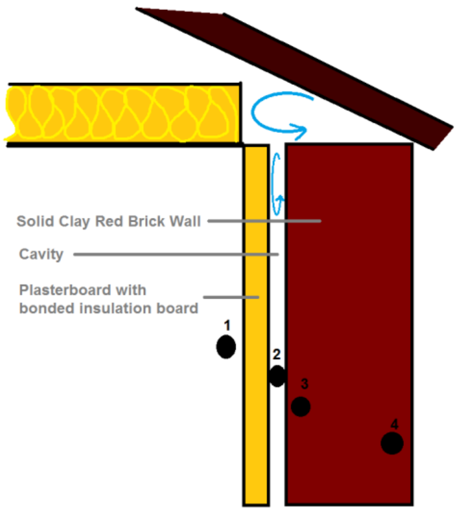


Figure 3 (a). As Built Wall and Roof Assembly of Retrofit A

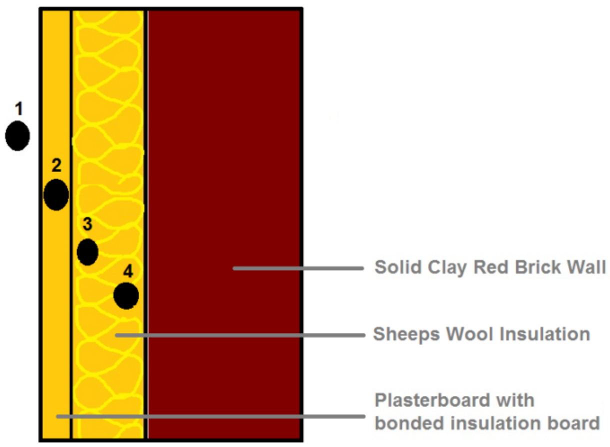


Figure 3 (b). As Built Wall and Roof Assembly of Retrofit B

3.1.2 U-Value Analysis of Retrofit B

The wall construction of Retrofit B is 225mm historic red brick, 75mm sheep wool insulation with timber battons securing 35mm polyurethane insulation and 12.5mm plasterboard. The average U-value measured by the two sensors over the monitoring period of 250 hours was 0.21W/m^{2}K as shown in Figure 4. This is value indicates that the the wall performs better than the design value of 0.24 W/m^{2}K. Although the average U-value for the monitoring period was found to be near to the expected u-value the results did not approach an asymptote and varied widely over the monitoring period. The effect of solar radiation on the wall and the wet weather during the momitoring period could be attributed to this variation in measured result.

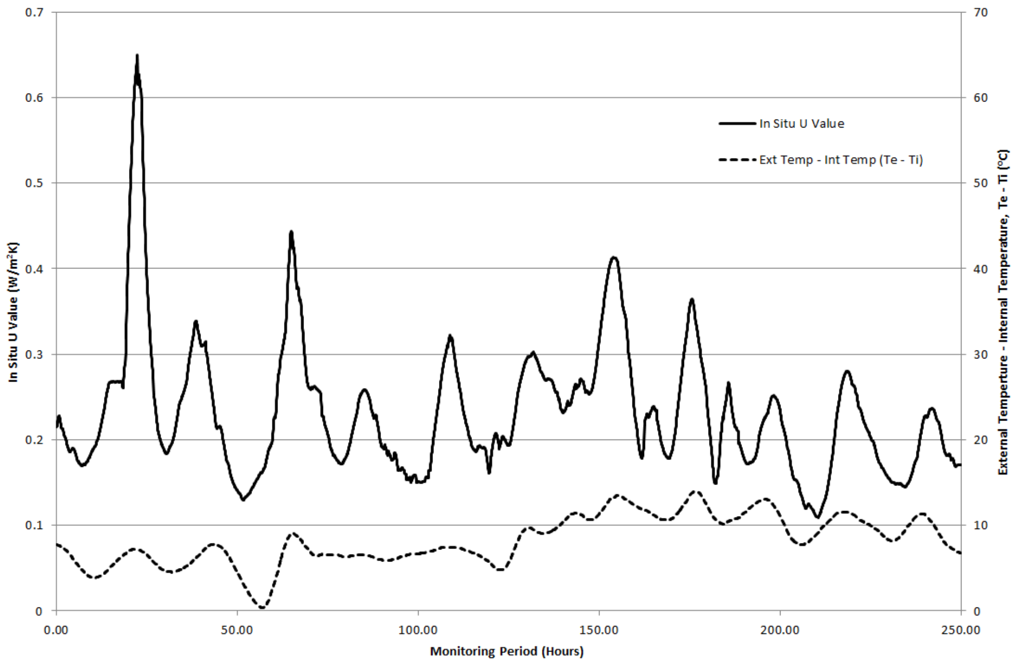


Figure 4. In-Situ U-Value from Wall Construction of Retrofit B

3.2 Internal Conditions

Internal temperature and humidity was monitored in the three main rooms of each property for a period of 14days, the selected rooms were the main living area, master bedroom and main bathroom. Measurements were taken using data loggers accurate to ±0.5°C and ±3% relative humidity. Carbon dioxide readings were also logged in the bedroom with a logger of accuracy of 50 parts per million. The average temperatures within Retrofit A are significantly lower than the CIBSE (2006) recommended internal temperatures of 19-24 °C for living areas and 17-19 °C for bedrooms. This shows that even with existing retrofit measures the tenant is not able to heat there house to a comfortable level. The issues surrounding this matter are socioeconomic as well as technical, many of which lie outside the remit of this paper, but should be of concern to the landlord. Relative humidity measurements were found to be within the CIBSE (2006) recommended guidance of 45-55% for both properties.

Table 2. Summary of Monitored Internal Conditions

		Unit	Retrofit A	Retrofit B
Bathroom	Bathroom Temperature (Mean)	oC	14.4	20.4
Measurements	Bathroom RH (Mean)	%RH	63.1	51.8
Bedroom	Bedroom Temperature (Mean)	oC	14.8	21.4
Measurements	Bedroom RH (Mean)	%RH	54.8	49.1
	Bedroom CO2 Content (Mean)	ppm	551	1414
Living Room	Living Room Temperature (Mean)	oC	17.1	22.6
Measurements	Living Room RH (Mean)	%RH	54.2	42.9

Concentration of CO2 is often used as a proxy for indoor air quality (ASHRAE 62:2010, EN 15251:2007) due to its relative ease of measurement but it is scientifically limited due to its lack of correlation to import indoor air quality parameters such as volatile organic compounds (VOCs). Even with this limitation CO2 levels can be useful as a proxy for adequate ventilation rates as it has been linked to airborne communicable infection via inhalation of exhaled air using the Wells-Ridley equation (Rudnick and Milton, 2003). CIBSE (2006) recommended maximum levels of CO2 is 1350ppm which is exceeded in Retrofit A for a significant period of time with the average value recorded being 1414ppm with a peak value of 2889ppm which indicates very poor ventilation. Ventilation of Retrofit A appears adequate with an average CO2 level of 551 and a peak of 1300ppm but this should be considered in conjunction with the below par performance in regards to internal temperatures of this room.

3.4 Wall Construction Temperature and Humidity Profiles

Thermocouple temperature sensors with an accuracy of ± 0.5^{O}C and lab calibrated Honeywell HIH-4000 relative humidity sensors with an accuracy of ± 3.5% were inserted into the wall at varying depths to assess the moisture content of the assembly. A temperature and humidity sensor was placed in a 10mm plastic housing with one end covered with fine gauze to protect the sensors from dust. The sensor housing was then inserted into the wall to the required depth drilled using a 12mm hole which reduced to a 10mm hole at the measurement point. The tubing was pushed tightly into this to form a sealed chamber were the measurement was taken in the locations. Measurements were taken in 4 locations in each of the wall types, these can be seen in Figure 3 labelled 1-4. For Retrofit A the sensors are located in 30mm from the exterior brick face, 30mm from the interior brick face, the centre of the air cavity and the internal humidity. For Retrofit B the monitoring locations are the internal humidity, the centre of the phenolic insulation board, the internal face of the sheep wool insulation and the external face of the sheep wool insulation. Due to the tight packing of the wool insulation it was not possible to drill into the brickwork to gain readings at this location. The humidity and temperature profiles measured are discuss and compared to the modelled data in the following section.

4. MODELLING HYGROTHERMAL PERFORMANCE

WUFI 5.2 was used to model the hygrothermal performance of each of the wall scenarios described earlier. The Passive House Institute promotion of WUFI software and the introduction of WUFI training courses for UK architectural practitioners has seen its popularity increase over the past number of years. Although this software has been validated extensively in the laboratory [Hens, 1996] results from in-situ buildings are limited as noted by May and Rye (2012). Material data, boundary conditions, internal conditions and external climate information are used to model the humidity profile of the assembly with respect to time allowing users to assess the risk of interstitial condensation or moisture build up.

4.1 Model Input Data and Generation

Internal temperature and humidity is calculated within the model based on BS EN 1506:2007. Idealised values for internal temperature and relative humidity are generated based on the external temperature of the model from the weather file. External weather data within the WUFI 5.2 software does not currently offer data specifically for a UK climate. Common sources of UK weather data for popular software such as EnergyPlus (Crawley et. al., 2000) is available but is not suitable for building element heat and moisture transport modelling due to their lack of rainfall data. A representative file was therefore selected from the software database which is similar to average yearly conditions experienced for Belfast, Northern Ireland. Material properties are also selected using the material database within the software and initial conditions of 80% relative humidity and 20^{o}C is assumed thourhgout the layer. The yearly weather file is ran consectutively until equilibrium is reached. Each of the wall assemblies detailed in Figure 3 are analyses in turn and compared to the measured profiles.

4.2 Modelled and Measured Humidity Profiles

Figure 5 presents the modelled and measured humidity and temperature profile for Retrofit A for 18th April 2013, the modelled results are presented for the same date and time that the measured results are presented to allow direct comparison. Internal relative humidity is very similar in both modelled and measured data at 63.0% and 60.5% respectively but internal temperature was measured at 16.2 °C and calculated at 18.6 °C. The lower than expected internal temperature within Retrofit A was discussed in 3.2. Within the cavity a high relative humidity was predicted and measured at 69.4% and 77.0% meaning that mold growth and condensation risk are high. Within the clay brick hunidity content at the internal face is predicted with good accuracey, within 2% but at the external face there is a large differnce of 18%. Due to the porous and diffusive transport properties of the clay brick the external layers vary widely depending on wind driven rain and therfore this difference can be attributed to the varying rainfall exposures in the modelled climate file and the actual conditions.. Internal faces of the brick change moisture content on a much slower regeime dependant on monthly or seasonal conditions rather than spikes caused by individual rainfall events. Importantly the modelled data finds close correlation with the high humidity measured on the internal face of the brick. Both the modelled and measured data indicate that there is a high chance of condensation and mould growth within the cavity for Retrofit A due to the high humidity.

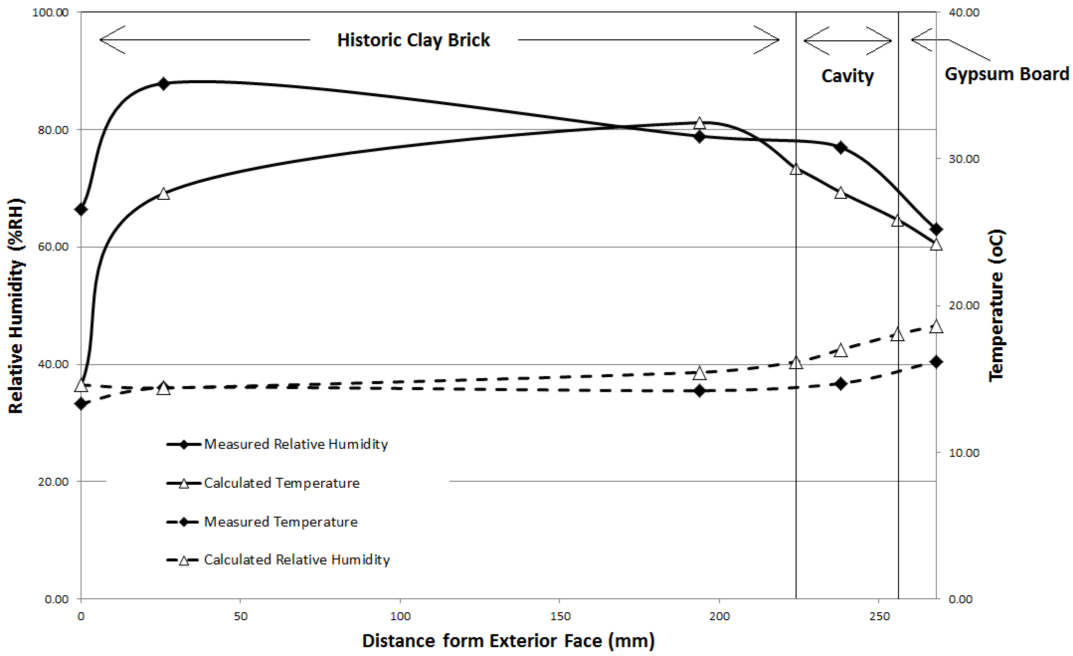


Figure 5. Modelled and Measured Humidity and Temperature Profile of Retrofit A

In the case of Retrofit B WUFU Pro 5.2 over estimates the humidity profile of the wall assembly within the insulation materials although the trend is correct with a high humidity occurring at the brick-wool interface. Measured humidity within the sheep wool insulation reduced significantly from the measured value of 78.6% to 53.9% 10mm from the wool-phenolic. Risk of condensation and mould growth if organic matter is available is still high at these humidities, particularly at the brick-wool interface. Humidity levels within the phenolic insulation are good at 46.1% and may be helped by the moisture barrier provided by its foil covering. Long term high humidity in the sheep wool may lead to degradation of both the wool and phenolic insulation. Concerns should also be raised about the moisture content of timber floor joists supported by the brick wall in light of the high humidty recorded within the wool layer. WUFI Pro has proved accurate in the overall trend found within this wall assembly although the conditions predicted are worse than measured *in-situ*.

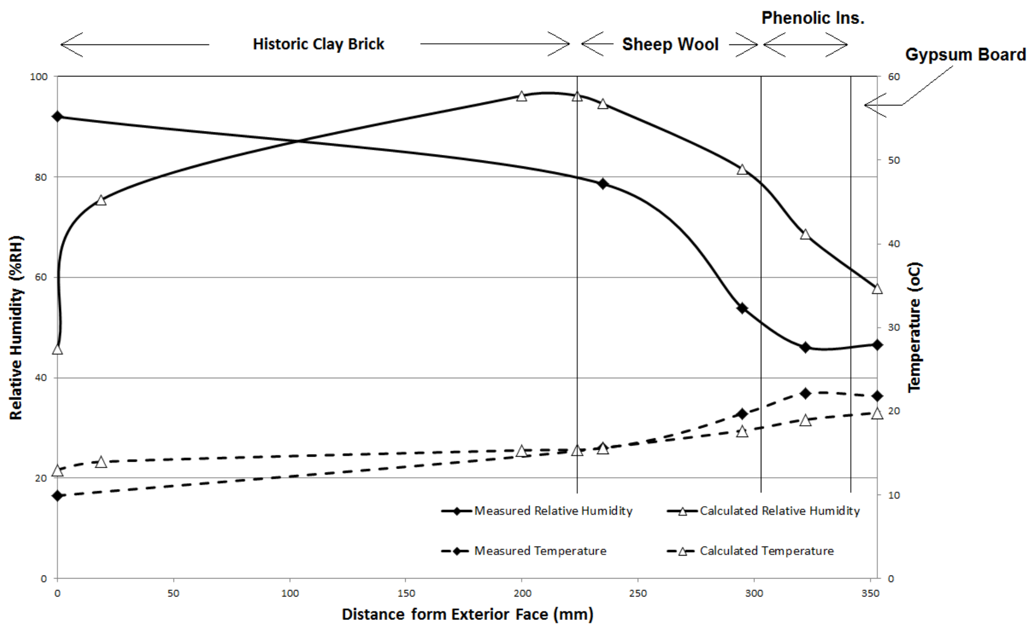


Figure 6. Modelled and Measured Humidity and Temperature Profile of Retrofit B

5. CONCLUSIONS

This paper presented monitoring and modelling results from two internally insulated solid wall houses in Northern Ireland. The importance of correct construction detailing to avoid below design *in-situ* U-values was discussed as well as the need to consider proper ventilation to maintain healthy internal hygrothermal conditions. Concerns have been raised in both case studies regarding high humidity within the wall assembly as calculated by WUFI Pro 5.2 and measured on site. In these initial case studies WUFI Pro 5.2 has proven to be accurate in highlighting to designers potential hygrothermal issues within the construction assembly. Further monitoring data is needed to assess the performace of both internal solid wall insulation and the accuracey of WUFI Pro 5.2 for site conditions.

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