Monitoring building fabric and internal environmental behaviour of a recently insulated historic building

(Final report)

A) Brief reminder of the proposal:

The proposal complements a feasibility study project (CIC start online) granted in March 2011 and completed in October 2011.
This project intended to demonstrate the feasibility of insulating existing building with no damage to originality features and aesthetic.

The insulated house

Members of the team involved in the trial with the home owners

This completed study, will require a monitoring process beyond the feasibility stage. This involves a limited 'field inspection' of an extensive new field, central to the energy efficiency improvement of old buildings.

The aim of this research is to build capacity, knowledge, information and techniques required to reduce energy consumption and C02 emissions in historic and traditional buildings. It will do this by identifying methods to adjust, conserve and reinstate them sympathetically and in a manner which will maintain their architectural integrity.
The practical aspect of the project will be to monitor the building behaviour

Objectives are as follows.

1. Monitor and analyse the building behaviour using sensors in the building fabric and living spaces. The data collectors will record data hourly allow us to get clear understanding of the moisture presence and travel though the cavity wall. This will allow us advice on the best way to adjust internal environment.
2. Provide digital and other dynamic media / information specifically designed to influence owners /occupiers and other groups such as the building supply chain of the need to make their buildings more energy efficient and the benefits of doing so.

3. Provide the resources to make the complete building supply chain aware of the need to make traditional buildings more energy efficient.

4. Provide the building actors including energy advisers, targeted information, and knowledge of techniques that they require to undertake this task.

The creation of new skills and jobs would be a clear outcome of development of a successful method and material. Rising energy costs make a compelling case for building owners to insulate if this can be done without loss of historic fabric. Additional benefits include reduction in noise transmission; reduced risk of fire spread and the stabilisation of internal linings. The potential market is large and lucrative.

There is no doubt that this will be the step toward the insulation of the 80% of the existing building stock identified by governmental directives and toward the reduction by 80% of the CO2 emission by 2050.

The findings of this monitoring process and the analysis of the collected data will allow us to better understand moisture behaviour inside this specific type of wall to which an insulation material was injected.

The expected outcomes of this research are to identify appropriate materials and methodologies to adopt for existing buildings, based on material mechanical behaviour. This will result in the development of findings capable of development as installation guidance for professional use.

Positive results will give the building industry a confidence to carry on improving historic buildings' energy efficiency using the material we used and explore other ones.

From academic perspective, we will be in better position to advise historic building societies and local authorities to advise them on the best way to insulate their buildings assets without damaging their original features such as the building fabrics as buildings have specific construction details and each case should be addressed individually, specifically historic buildings.

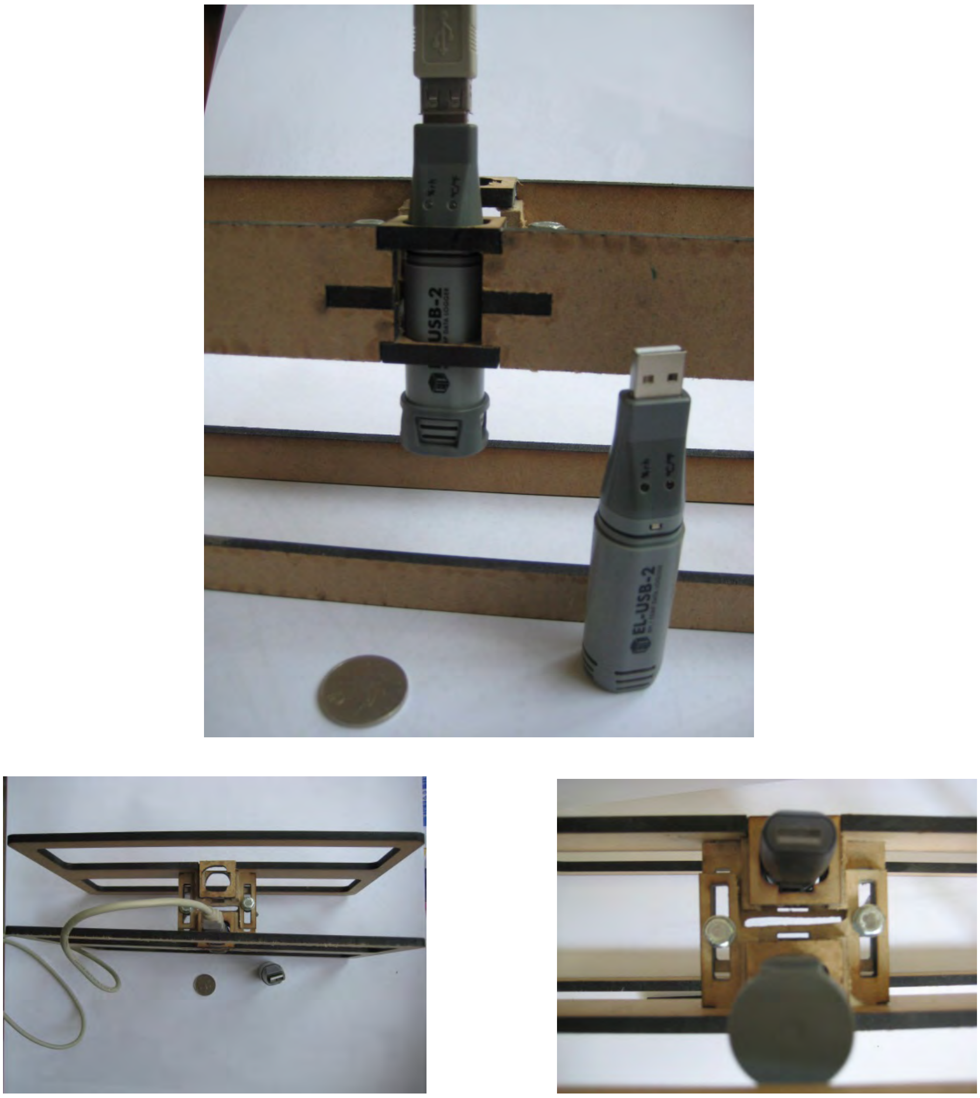
Introduction (report structure)

This report will contain two parts; the first part concerns the outcomes of the monitoring process and will reflect the temperature and humidity variations inside the cavity wall mainly. These variations although recorded hourly they reflect not only season's variations but essentially the before and after the insulation. In this part, and as the objective is to use the data for simulation purpose; we will only highlight the process we adopted to collect these data.

B) Data collection

1- Monitoring the temperature and humidity.

Five months before the insulation was implemented, we equipped the house with data loggers to gather the temperature and humidity in various parts of the house including the loft, le kitchen, le lobby and the cavity-wall itself where the insulation will be injected. We also monitored the external temperature and humidity.



Data loggers mounted in a device to be placed inside the cavity wall

We anticipated putting the data loggers at both insulation edges (close to the lath/plaster in one side and close to the sandstone in the other side). After the preparation of the devises to be implemented inside the cavity wall, we realised that the cavity is not homogeneous and the 70mm cavity space measured at the start of the study was a maximum cavity space and we were not able to introduce the wooden devises holding the 2 data logger inside the wall. We opted for the data logger to be introduced into the cavity wall individually without the wooden support as the space was enough for only one data logger at a time due to the width limitation of the cavity wall. The danger of doing so is that we won't be able to know exactly where the data logger will be situated inside the cavity, but in any case the cavity itself is less than 20mm wider than the data logger itself so we don't think the data will be that different in such limited width.

2) Data collection

The recording started in March 2011, three months before the insulation implementation and ended in June 2012. We assume that 15 months are enough to study the temperature and moisture migration through a wall and specifically through the insulation material that was implemented in August 2011.

We gathered data every now and then and we anticipated that the data logger inside the wall will continue to deliver data until the batteries are dead as the data loggers are attached to USB cables to outside the cavity so we can retrieve the data.

The data were used to generate simulation of the wall for better understanding on how the insulation has affected the moisture and temperature migration in the wall.

We should stress that we observed the graphs and analysed them in regards to the moisture level changes inside the insulation material and we compared them with the changes observed in other spaces where the data loggers were placed; before moving to the simulation exercise.

It was important that we compare the before and after insulation scenarios to draw a clear conclusion.

C) Simulation of moisture movement through the Sandstone wall

Insulation can be fitted inside the air gap of traditional stone and lath and plaster walls in order to improve their thermal performance. There are, however, some concerns about the effect that the insulation will have on moisture transport through the wall. A CFD model of a wall, with and without insulation, has been developed in order to establish what effect the insulation has on the moisture transport.

CFD Model

A CFD model of the wall was developed in ANSYS Fluent 13.0. Figure 1 shows the geometry and boundary conditions used in the simulation. A more detailed description of the model is given in the Appendix.

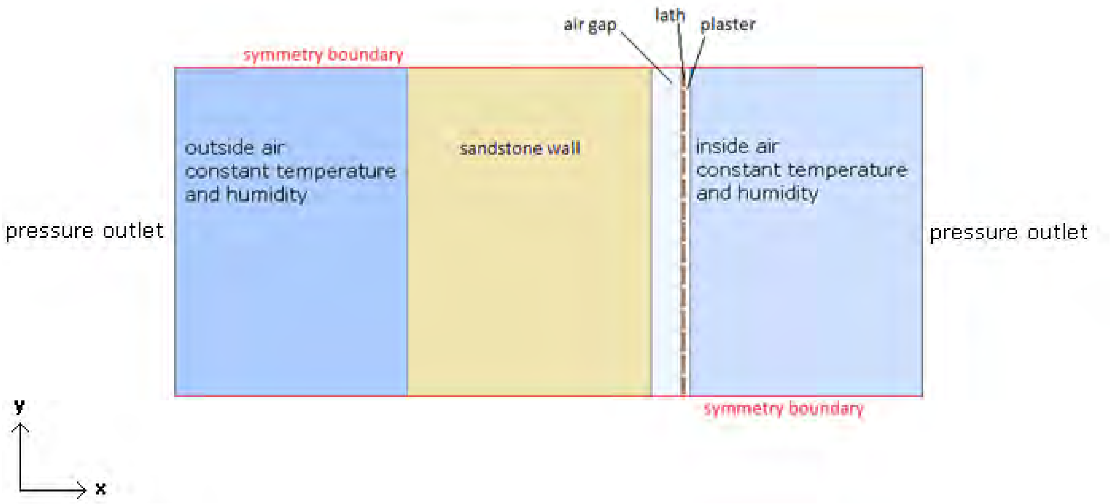


Figure 1- Simulation set up

The height of the domain 705mm and the sizes and details of the zones defined in Figure 1 are given in Table 1.

Table 1- size and description of zones defined in Figure 1

Zone	Width (mm)	Description
Outside air	500	Held at constant temperature and humidity
Sandstone wall	525	Porous zone
Air gap	65	When insulated modelled as a porous zone and assumed to be completely filled with insulation
Lath	8	15 laths, each 37mm high with 10mm gap between them. Each lath is modelled as a porous zone.
Plaster	20mm at max, 12mm at min	Porous zone. The plaster is assumed to entirely fill the gaps between the laths
Inside air	500	Held at constant temperature and humidity

A 2D simulation was chosen because the results from a 2D simulation will be more widely applicable than if a 3D simulation of a particular building was carried out. Another significant advantage of 2D simulations is that they are much less time consuming to set up and run. This allowed many more cases to be simulated, giving a much clearer picture of the effect of the insulation. The section of wall modelled is representative of a section of any wall of similar geometry in regions that are sufficiently far enough away from floors, windows, doors, ceilings or other discontinuities. In the simulations it is assumed that moisture moves only in the x-direction as the wall is sufficiently large in the y-direction for moisture movement in that direction only occurs in small sections near the top and bottom of the wall.

In the simulations the sandstone, lath, plaster and insulation were treated as porous materials. The material properties used in the simulations are given in Table 1. The density, specific heat capacity and thermal conductivity of plaster and wood were taken from the Fluent materials database. The intrinsic permeability and porosity of wood were taken from Li, Zhang and Li (1).The intrinsic permeability of the plaster used in the simulation was calculated from the permeability of multi-function plaster given by Wang and Liu (2)(3). The porosity of the plaster was taken form Hall and Hoff (4). The intrinsic permeability and porosity of sandstone were taken from Hall and Hoff (4) and its density, specific heat capacity and thermal conductivity taken from Engineering toolbox (5-7). The properties of the insulation were taken from information provided by the manufacturer, Icynene.

Table 2- Material properties used in simulations

Material	Density kg/m^2	Specific heat capacity J/(kg K)	Thermal conductivity W/(m K)	Intrinsic permeability (m^2)	porosity
Sandstone	2100	920	1.7	$3.0\text{x}10^{-13}$	0.145
Plaster	2320	1138	0.5	$2.051\text{x}10^{-6}$	0.45
Wood	700	2310	0.173	$4.9346\text{x}10^{-13}$	0.03
Insulation	8.3	1470	0.039	$6.78\text{x}10^{-11}$	0.99

In fluent the effective thermal conductivity of a porous material is based on the thermal conductivity of the solid and the fluid (Equation 1).

$$\boldsymbol{k_{eff} = \gamma k_f + (1 - \gamma) k_s}$$

Equation 1

Where

k_{eff} is the effective thermal conductivity of the porous material

γ is the porosity of the material

k_f is the thermal conductivity of the fluid

k_s is the thermal conductivity of the solid

The thermal conductivities in Table 1 are the effective thermal conductivities of the materials. The thermal conductivities of the solids were calculated from the effective thermal conductivities for use in the model Table 2.

Table 3- Thermal conductivities of solids for porous materials

Material	k_s W/(m K)
Sandstone	1.98
Plaster	0.872
Wood	0.177
Insulation	-0.0059

Cases simulated

In order to ensure that the conditions for which the simulations were run were realistic and represented the entire range of conditions that were likely to occur, temperature and humidity data measured at the site was analysed to find standard and extreme conditions. The measured data sets gave the temperature and humidity outside the wall, in the air gap and inside the room for around 3.5 months before the wall was insulated and 4 months after the wall was insulated. The data was analysed to find the maximum, minimum and mode values of the temperature and humidity before and after the wall was insulated inside the room, in the air gap and outside. Since the mode value of humidity or temperature occurred multiple times for each position, a set of conditions for the simulation was selected by taking the first time and date for which the median value of the other quantity (temperature or humidity) occurred. The details of the cases simulated are given in Table 3.

The simulations did not converge for the air gap mode temperature (representative) conditions measured after the wall was insulted so no results have been obtained for this case.

Table 4- Temperature and humidity values used in simulations

				outside		inside		air gap	
			Time	Temp. (^{o}C)	Relative humidity (%)	Temp. (^{o}C)	Relative humidity (%)	Temp. (^{o}C)	Relative humidity (%)
after insulation	outside values	max temp	30/09/2011 13:49	23.0	72.5	21.0	70.0	21.0	77.2
		max humidity	22/11/2011 05:49	9.0	99.5	17.0	67.7	15.0	67.0
		min temp	10/12/2011 09:49	-3.0	86.5	15.8	42.5	11.2	43.3
		min humidity	22/08/2011 12:49	22.0	53.0	19.3	43.0	19.0	64.7
		mode temp (representative)	20/09/2011 01:49	10.5	93.5	16.5	67.8	16.5	72.2
		mode humidity (representative)	18/09/2011 02:49	9.5	95.0	19.0	66.2	17.0	66.2
	air gap values	max temp	24/08/2011 15:13	18.1	75.2	17.6	76.6	22.5	91.5
		max humidity	24/08/2011 15:13	18.1	75.2	17.6	76.6	22.5	91.5
		min temp	09/12/2011 06:13	3.0	70.2	15.1	44.0	10.5	47.0
		min humidity	10/12/2011 09:13	-2.7	86.2	16.1	42.1	11.5	43.0
		mode temp (representative)	28/08/2011 06:13	11.5	84.0	11.5	84.0	16.0	65.5
		mode humidity (representative)	14/09/2011 06:13	9.3	87.8	9.1	86.4	16.5	66.5
	inside values	max temp	04/09/2011 23:21	10.8	90.8	22.5	61.0	20.0	65.4
		max humidity	02/10/2011 20:21	11.2	95.3	21.0	74.0	19.5	70.4
		min temp	13/12/2011 14:21	3.2	86.0	13.0	47.5	11.4	53.6
		min humidity	11/12/2011 00:21	1.0	92.8	20.0	39.5	14.0	44.0
		mode temp (representative)	24/08/2011 12:21	17.4	71.4	18.0	63.5	19.4	70.2
		mode humidity (representative)	24/08/2011 00:21	9.2	91.5	18.5	66.0	16.4	70.9
before insulation	outside values	max temp	02/06/2011 18:00	27.0	45.5	21.0	61.0	20.0	66.0
		max humidity	13/08/2011 09:00	14.0	98.5	17.5	74.0	16.5	82.0
		min temp	14/05/2011 02:00	4.5	83.0	19.0	57.5	14.0	60.0
		min humidity	09/05/2011 03:00	15.5	39.0	20.0	59.0	14.5	71.0
		mode temp (representative)	29/06/2011 22:00	12.5	86.5	20.0	66.0	19.0	68.0
		mode humidity (representative)	07/05/2011 06:00	11.0	94.0	17.5	60.5	15.0	70.0
	air gap values	max temp	03/06/2011 22:00	18.0	73.0	22.0	63.0	21.5	69.0
		max humidity	13/08/2011 11:00	16.0	93.5	18.0	74.5	17.0	82.5
		min temp	24/05/2011 02:00	8.0	70.5	14.5	57.0	11.0	63.0
		min humidity	20/05/2011 19:00	12.0	57.0	22.0	47.0	16.0	47.0
		mode temp (representative)	17/05/2011 03:00	9.0	78.0	18.5	62.0	16.0	68.5
		mode humidity (representative)	09/05/2011 20:00	12.0	86.5	20.5	57.0	16.5	70.5
	inside values	max temp	21/08/2011 21:00	15.5	74.0	22.0	63.0	19.0	68.0
		max humidity	05/08/2011 05:00	13.5	97.0	20.0	80.5	18.0	78.5
		min temp	24/05/2011 06:00	7.0	78.0	14.0	58.0	11.5	64.0
		min humidity	20/05/2011 21:00	11.0	58.0	22.0	46.0	16.0	48.5
		mode temp (representative)	01/07/2011 21:00	13.5	78.5	19.0	69.5	17.5	67.5
		mode humidity (representative)	21/06/2011 11:00	11.5	94.5	18.5	72.5	15.5	71.5

Comparison of simulation results and measured data

Simulations were run for the outside and inside conditions detailed in Table 3 and the results obtained for air gap temperature and humidity were compared with the measured values. When setting up the simulations the mass fraction of water vapour in the air needed to be input, rather than the relative humidity. Values for mass fraction were calculated from the relative humidity data using data from {{281 Transport Information Service 2012}} using linear interpolation. The results from the simulations can be displayed in terms of relative humidity in Fluent so it was possible to check that the mass fraction of water vapour had been calculated correctly. When checking the relative humidity values it became apparent that the linear interpolation method used to calculate the mass fraction values was leading to some differences between the simulation and measured relative humidity values. For cases where the difference between the simulation and measured values was greater than 1% relative humidity, a trial and improvement method was used to change the mass fraction values until the difference between the simulation and measured values was less than 1%.

The simulation and measured air gap temperatures are compared for a wall without insulation in Table 4.For the wall without insulation 61% of the cases simulated had less than 1^{o}C temperature difference between the measured and average simulated air gap temperatures. The maximum difference was 4.0^{o}C. It should, however, be noted that the temperature varies across the air gap so the temperature and humidity measured by the sensor is likely to differ from the air gap average and will depend on the exact position of the sensor. There are only two cases for which the measured temperature does not fall between the maximum and minimum air gap temperatures of the simulation. In both of these cases the air gap temperatures in the simulation are higher than the measured temperatures.

Table 5- Comparison of measured and simulation air gap temperatures for wall without insulation

		temperature						
		simulation						
	case	min	max	average	measured	In range?	difference between measured and average	% diff
outside values	max temp	21.5	25.5	22.9	20.0	no	-2.9	-14.7
	max humidity	14.9	17.2	16.4	16.5	yes	0.1	0.8
	min temp	8.1	17.9	14.3	14.0	yes	-0.3	-2.1
	min humidity	16.6	19.6	18.5	14.5	no	-4.0	-27.9
	mode temp (representative)	14.3	19.4	17.6	19.0	yes	1.4	7.5
	mode humidity (representative)	12.6	17.0	15.4	15.0	yes	-0.4	-2.6
air gap values	max temp	19.0	21.7	20.7	21.5	yes	0.8	3.7
	max humidity	16.5	17.8	17.4	17.0	yes	-0.4	-2.1
	min temp	9.6	14.0	12.4	11.0	yes	-1.4	-12.7
	min humidity	14.5	21.2	18.8	16.0	yes	-2.8	-17.2
	mode temp (representative)	11.3	17.7	15.4	16.0	yes	0.6	3.6
	mode humidity (representative)	14.1	19.8	17.7	16.5	yes	-1.2	-7.5
inside values	max temp	17.1	21.5	19.9	19.0	yes	-0.9	-4.7
	max humidity	15.1	19.5	17.9	18.0	yes	0.1	0.6
	min temp	8.7	13.4	11.7	11.5	yes	-0.2	-2.0
	min humidity	13.7	21.1	18.4	16.0	yes	-2.4	-15.2
	mode temp (representative)	14.9	18.6	17.2	17.5	yes	0.3	1.6
	mode humidity (representative)	13.2	17.9	16.2	15.5	yes	-0.7	-4.7

In Table 5 the simulation and measured air gap temperatures are compared for a wall with insulation. The variation between the simulation results and the measured results are greater for the insulated wall with only 29% of cases having a difference of less than 1^{o}C between the average air gap temperature and the measured temperature. The measured temperature did not fall between the maximum and minimum simulated air gap temperatures for 41% of the simulated cases. The air gap temperatures in the simulations were typically higher than the measured values.

Table 6- Comparison of measured and simulation air gap temperatures for insulated wall

		air gap temperature						
		simulation						
	case	min	max	average	measured	In range?	difference between measured and average	% diff
outside values	max temp	21.1	22.5	21.7	21.0	no	-0.65	-3.1
	max humidity	10.8	16.4	14.4	15.0	yes	0.61	4.0
	min temp	1.3	14.5	9.7	11.2	yes	1.52	13.6
	min humidity	19.5	21.4	20.2	19.0	no	-1.18	-6.2
	mode temp (representative)	11.9	16.1	14.5	16.5	no	1.95	11.8
	mode humidity (representative)	11.7	18.3	15.9	17.0	yes	1.09	6.4
air gap values	max temp	17.6	18.0	17.8	22.5	no	4.74	21.1
	max humidity	17.6	18.0	17.8	22.5	no	4.74	21.1
	min temp	5.8	14.2	11.2	10.5	yes	-0.66	-6.3
	min humidity	1.6	14.8	10.0	11.5	yes	1.52	13.2
	mode temp (representative)							
	mode humidity (representative)	9.1	9.3	9.2	16.5	no	7.33	44.5
inside values	max temp	13.5	21.7	18.7	20.0	yes	1.31	6.6
	max humidity	13.4	20.3	17.8	19.5	yes	1.69	8.7
	min temp	5.4	12.3	9.8	11.4	yes	1.62	14.2
	min humidity	5.3	18.6	13.8	14.0	yes	0.19	1.3
	mode temp (representative)	17.5	18.0	17.8	19.4	no	1.63	8.4
	mode humidity (representative)	11.3	17.8	15.5	16.4	yes	0.96	5.9

The simulation and measured values of air gap relative humidity are compared for a wall without insulation in Table 6. The difference between the simulated and measured relative humidity values is typically higher than the difference between the simulated and measured temperature values with only one case for which there is a less than 1% difference between the simulation and measured values of relative humidity. The variation of relative humidity over the air gap is much larger than the variation of temperature over the air gap, so it is expected that the difference between the average values and the measured values will be larger. In 56% of the cases the measured value fell within the range of simulated values.

Table 7- Comparison of measured and simulation air gap humidity for wall without insulation

		humidity						
		simulation						
	case	min	max	average	measured	In range?	difference between measured and average	% diff
outside values	max temp	46.6	59.4	54.5	66	no	11.5	17.4
	max humidity	75.5	87.9	79.9	82	yes	2.1	2.6
	min temp	60.8	114.6	78.1	60	no	-18.1	-30.1
	min humidity	59.9	72.0	64.1	71	yes	6.9	9.7
	mode temp (representative)	68.0	93.5	76.7	68	yes	-8.7	-12.8
	mode humidity (representative)	62.9	83.5	70.0	70	yes	0.0	0.0
air gap values	max temp	63.5	74.9	67.5	69	yes	1.5	2.2
	max humidity	75.5	82.4	78.0	82.5	no	4.5	5.4
	min temp	59.3	79.0	66.1	63	yes	-3.1	-4.8
	min humidity	49.7	75.6	58.4	47	no	-11.4	-24.2
	mode temp (representative)	64.2	96.8	75.2	68.5	yes	-6.7	-9.7
	mode humidity (representative)	60.1	86.4	69.0	70.5	yes	1.5	2.1
inside values	max temp	64.5	84.5	71.4	68	yes	-3.4	-5.0
	max humidity	83.1	109.4	92.1	78.5	no	-13.6	-17.4
	min temp	60.7	83.0	68.3	64	yes	-4.3	-6.8
	min humidity	48.8	77.6	58.4	48.5	no	-9.9	-20.4
	mode temp (representative)	70.9	89.5	77.3	67.5	no	-9.8	-14.6
	mode humidity (representative)	74.6	100.8	83.6	71.5	no	-12.1	-16.9

In Table 7 the simulation and measured values of air gap relative humidity are compared for an insulated wall. For this case, as well as for the wall without insulation, the difference between the simulated and measured relative humidity values is typically higher than the difference between the simulated and measured temperature values. There were no cases for which there was a less than 1% difference between the simulation and measured values of relative humidity. For the insulated wall the measured value of relative humidity fell within the range of relative humidity values calculated for the air gap in the simulation 29% of the time.

Table 8- Comparison of measured and simulation air gap humidity for insulated wall

		air gap humidity						
		simulation						
	case	min	max	average	measured	in range?	difference between measured and average	% diff
outside values	max temp	64.3	69.8	67.8	77.2	no	9.4	12.2
	max humidity	69.8	100.5	80.2	67.0	no	-13.2	-19.7
	min temp	45.9	112.3	66.2	43.3	no	-22.9	-53.0
	min humidity	39.2	43.7	42.0	64.7	no	22.7	35.0
	mode temp (representative)	69.5	91.3	77.0	72.2	yes	-4.8	-6.7
	mode humidity (representative)	68.5	104.9	80.7	66.2	no	-14.5	-21.9
air gap values	max temp	74.8	76.5	75.9	91.5	no	15.6	17.1
	max humidity	74.8	76.5	75.9	91.5	no	15.6	17.1
	min temp	46.2	81.3	57.6	47.0	yes	-10.6	-22.6
	min humidity	45.6	111.2	65.7	43.0	no	-22.7	-52.7
	mode temp (representative)							
	mode humidity (representative)	85.6	86.4	86.1	66.5	no	-19.6	-29.5
inside values	max temp	62.6	104.7	76.5	65.4	yes	-11.1	-17.0
	max humidity	76.4	117.6	90.2	70.4	no	-19.8	-28.1
	min temp	50.6	80.4	60.5	53.6	yes	-6.9	-13.0
	min humidity	42.7	102.5	61.1	44.0	yes	-17.1	-38.8
	mode temp (representative)	63.9	65.7	64.5	70.2	no	5.7	8.1
	mode humidity (representative)	68.2	103.6	80.1	70.9	yes	-9.1	-12.9

The agreement between the simulation and measured results is generally reasonable, although there are some cases for which there is a significant difference between the measured and simulation results. The agreement between the measured and simulation results was generally better for the wall without insulation than the insulated wall. It is thought that the differences between the simulated and measured values is due to the fact that the simulations were for static cases whereas the measurements were taken for a dynamic system. The simulations determined the equilibrium condition that would be reached for each set of inside and outside conditions whereas the actual inside and outside conditions may not persist for long enough for an equilibrium state to be reached. For the cases where there were significant differences between the simulation and measured results it is likely that the air gap conditions had not fully changed in response to changes in the inside and outside conditions. This theory is supported by the fact that there was better agreement between the measured and simulation results for cases when the wall was not insulated. The insulation will increase the time that it takes for heat and moisture to travel through the wall, so conditions in the air gap are less likely to reach the equilibrium conditions for a particular set of inside and outside conditions.

The effect of insulation on the moisture in the wall

Since it has been shown that there is reasonable agreement between the model and simulation results, simulations were run to try to establish the effect of the insulation on the moisture transport through the wall. The sets of inside and outside conditions in Table 3 were sorted by outside temperature and each set of conditions was assigned a case number. Table 8 gives the case number assigned to each set of conditions. The wall was simulated for each case both with insulation and without insulation. The results for each case were then compared to see the effect of the insulation.

In Table 9 the places where condensation forms are compared for a wall with no insulation and an insulated wall. For all of the cases where condensation formed in the insulated wall it also formed in the wall with no insulation however the exact position of the start and end points of the region where condensation formed differed. Figure 2 compares the start and end points of the region where condensation formed for a wall without insulation and an insulated wall. Typically the region where moisture formed was larger for the insulated wall than it was for the wall with no insulation.

Greater insight can be gained into how the insulation is affecting the movement of moisture through the wall by considering how mass fraction of H_2O, temperature and relative humidity vary with position in the wall for the insulated walls and walls without insulation. Figure 3 is an example of a plot showing the variation of mass fraction of H_2O for a wall without insulation and an insulated wall. The plot in Figure 3 is for case 1, but the same trends are shown by the other cases. It can be seen from Figure 3 that the presence of insulation has no effect on the distribution of mass fraction of H_2O in the wall. Figure 2 however, shows that position where condensation forms is dependent on whether or not the wall is insulated. This means that the relative humidity variation through the wall must be affected by whether or not the wall is insulated. Figure 4 is an example of a plot showing the variation of relative humidity through the wall for an insulated wall and a wall without insulation. The plot in Figure 4 is again for case 1 but the same trends are shown by the other cases. It can be seen from Figure 4 that the variation in relative humidity in the sandstone and across the air gap is larger when the wall is insulated. This is explained by considering the effect of the insulation on the temperature profile through the wall. Figure 5 shows how the temperature varies through an insulated wall and a wall without insulation for case 1. It can be seen from this figure that the temperature increase from the outside edge of the sandstone to the inside edge of the sandstone is reduced and the temperature increase over the air gap is increased when the wall is insulated. It is this difference in temperature profile that is responsible for the changing location of where moisture forms. Relative humidity is a function of temperature as well as mass fraction of H_2O so, by changing the variation in temperature throughout the wall, the insulation is changing the position of the region where moisture forms.

Table 9- Case numbers assigned to each set of conditions

	Outside and inside conditions from:		Case number
No insulation	Outside	o max temp	36
		o max humidity	26
		o min temp	6
		o min humidity	27
		o mode temp (representative)	23
		o mode humidity (representative)	16
	Air gap	a max temp	31
		a max humidity	29
		a min temp	8
		a min humidity	21
		a mode temp (representative)	10
		a mode humidity (representative)	22
	Inside	i max temp	28
		i max humidity	24
		i min temp	7
		i min humidity	17
		i mode temp (representative)	25
		i mode humidity (representative)	20
insulated	Outside	o max temp	35
		o max humidity	9
		o min temp	1
		o min humidity	34
		o mode temp (representative)	14
		o mode humidity (representative)	13
	Air gap	a max temp	32
		a max humidity	33
		a min temp	4
		a min humidity	2
		a mode temp (representative)	19
		a mode humidity (representative)	12
	Inside	i max temp	15
		i max humidity	18
		i min temp	5
		i min humidity	3
		i mode temp (representative)	30
		i mode humidity (representative)	11

Table 10- Comparison of where condensation forms in wall with no insulation and insulated wall

Case	no insulation			insulated			condensation in sandstone		condensation in air gap	
	condensation forms	start of condensation (m)	end of condensation (m)	condensation forms	start of condensation	end of condensation	no insulation	insulated	no insulation	insulated
1	yes	0.7159	1.0363	yes	0.6973	1.0377	yes	yes	yes	yes
2	yes	0.7263	1.0357	yes	0.7065	1.0370	yes	yes	yes	yes
3	yes	0.7603	1.0303	yes	0.7220	1.0298	yes	yes	yes	yes
4	no			no			no	no	no	no
5	no			no			no	no	no	no
6	yes	0.7250	1.0500	yes	0.7074	1.0438	yes	yes	yes	yes
7	no			no			no	no	no	no
8	no			no			no	no	no	no
9	yes	0.7636	1.0291	yes	0.7136	1.0309	yes	yes	yes	yes
10	yes	1.0167	1.0209	yes	0.9872	1.0262	yes	yes	no	yes
11	yes	0.8111	1.0338	yes	0.7858	1.0352	yes	yes	yes	yes
12	no			no			no	no	no	no
13	yes	0.7304	1.0354	yes	0.7029	1.0367	yes	yes	yes	yes
14	no			no			no	no	no	no
15	yes	0.7922	1.0341	yes	0.7624	1.0355	yes	yes	yes	yes
16	no			no			no	no	no	no
17	no			no			no	no	no	no
18	yes	0.6170	1.0595	yes	0.6093	1.0522	yes	yes	yes	yes
20	yes	0.8356	1.0258	yes	0.8042	1.0332	yes	yes	yes	yes
21	no			no			no	no	no	no
22	no			no			no	no	no	no
23	no			no			no	no	no	no
24	yes	0.6268	1.0494	yes	0.6177	1.0502	yes	yes	yes	yes
25	no			no			no	no	no	no
26	no			no			no	no	no	no
27	no			no			no	no	no	no
28	no			no			no	no	no	no
29	no			no			no	no	no	no
30	no			no			no	no	no	no
31	no			no			no	no	no	no
32	no			no			no	no	no	no
33	no			no			no	no	no	no
34	no			no			no	no	no	no
35	no			no			no	no	no	no
36	no			no			no	no	no	no

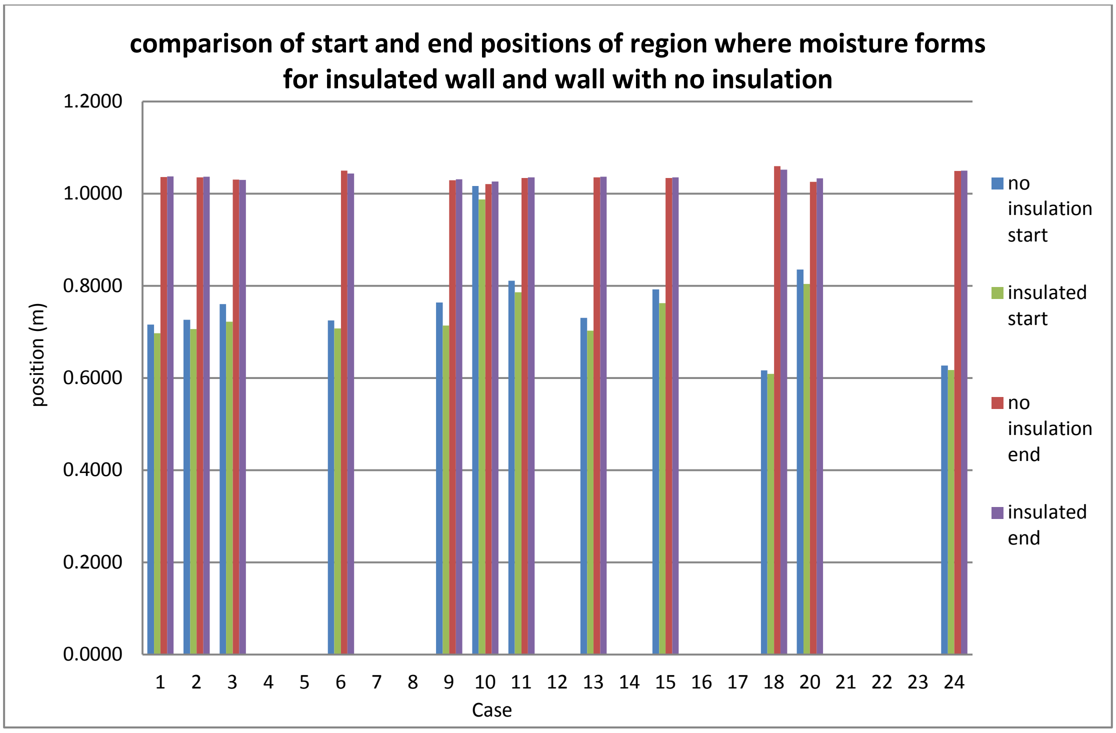


Figure 2- Comparison of start and end points of the region where moisture forms for insulated walls and walls without insulation

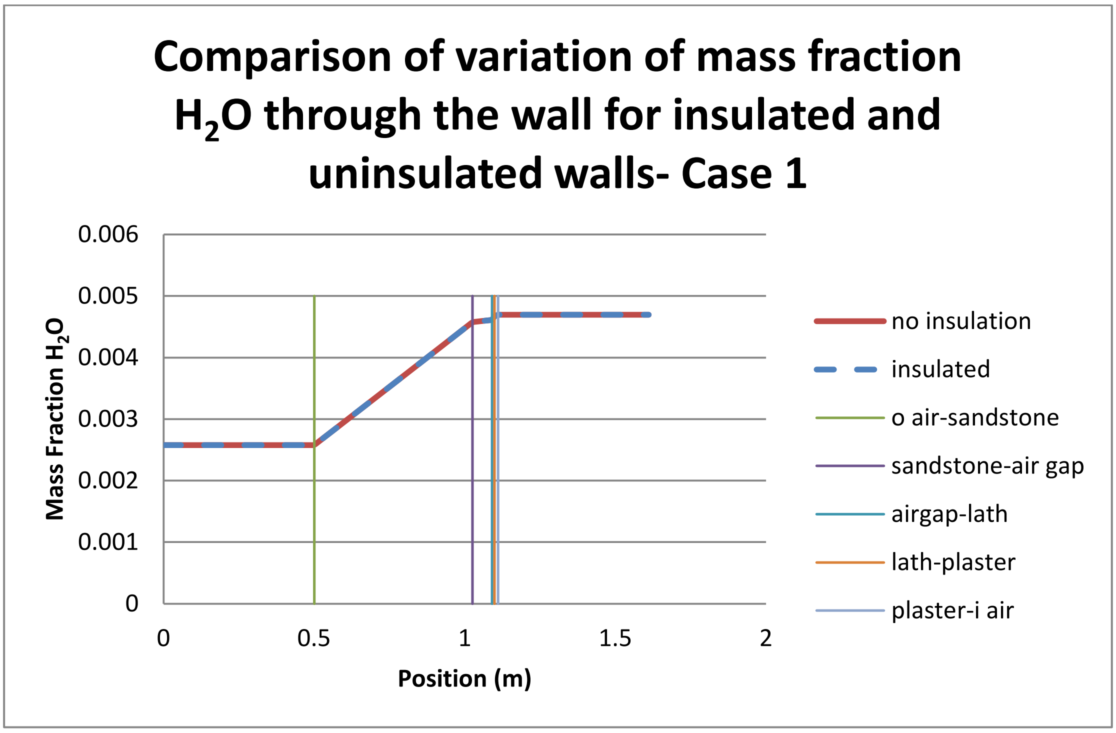


Figure 3- Example of plot of the variation of mass fraction H_2O through the wall (case 1)

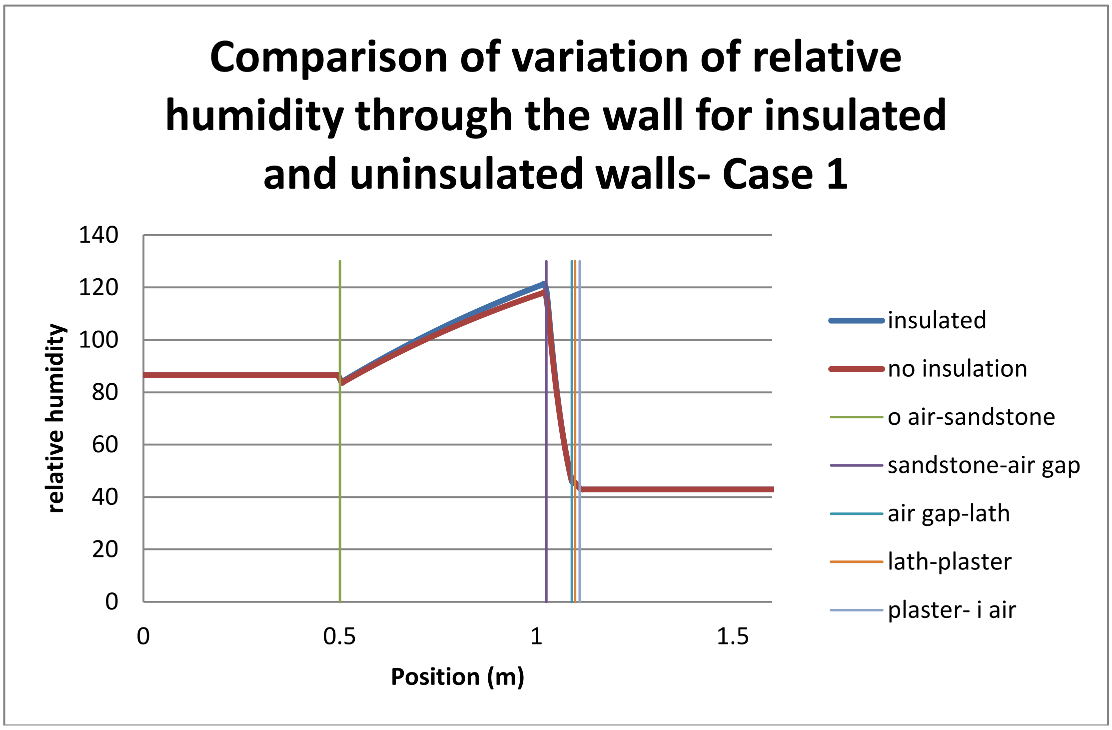


Figure 4- Example of plot of the variation of relative humidity through the wall (case 1)

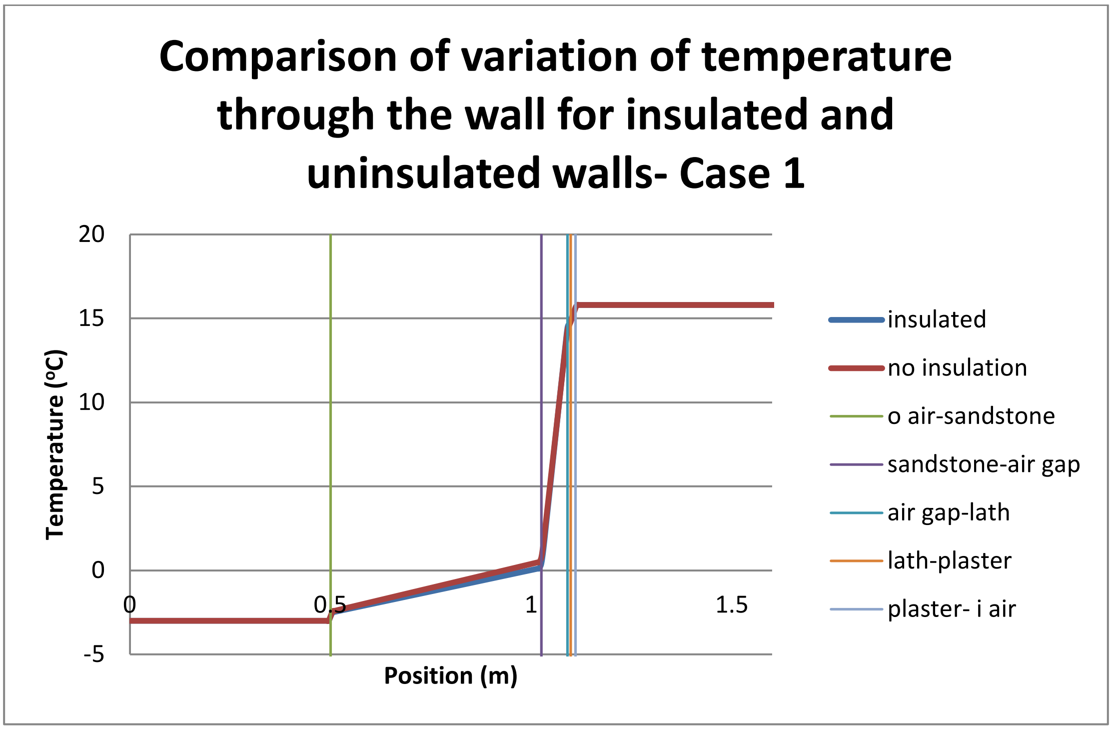


Figure 5- Example of plot of the variation of temperature through the wall (case 1)

Conclusions

A CFD model has been developed which allows the effect of insulation on the moisture movement through and formation of condensation in a wall to be studied. Simulations were run with and without insulation in the air gap of the wall and the results were compared. The results from the simulations suggest that the insulation had a negligible effect on the transport of water vapour through the wall; however it did affect the temperature profile of the wall. Relative humidity and dew point, the point at which condensation forms, are functions of mass fraction of water and temperature so the change in temperature due to the presence of insulation changes where the condensation forms, despite the insulation not having an effect on the distribution water vapour in the wall.

For the cases where condensation formed, condensation was present both when the wall had no insulation and when the wall was insulated. Typically condensation formed in the sandstone and in the air gap close to the sandstone. The start and end positions of the region in which condensation formed were affected by whether or not insulation was present. Typically when insulation was present, the region in which condensation formed was larger than when the wall was not insulated, however the differences were not large.

The simulations were static simulations and so only showed the equilibrium state for given outside and inside temperature and humidity conditions. Comparison of the results from the static simulations with measured data suggested that inside and outside temperature conditions typically varied over a shorter period than it took to achieve equilibrium conditions in the air gap. Ideally time stepped simulations would be run, in which the inside and outside conditions vary with time and the resulting variation of air gap conditions is calculated. The disadvantage of running time stepped simulations is that the results from them would be less widely applicable.

Another important feature of the system that was not captured in the simulations is the circulation of air in the air gap of the wall. Before the wall was insulated there would have been significant circulation of air inside the air gap. This circulation of air will have affected the temperature and humidity inside the air gap. In the simulations the air was static which will have resulted in the temperature difference across the air gap being far larger than that which would actually occur when the air is free to move. It was not possible to model air circulation in the air gap as this is strongly dependent on the exact geometry and condition of the building and the external weather conditions, including wind speed and temperature. The results from a 3D simulation of a building would only apply to that particular building for the weather conditions simulated. This is one of the reasons 2D static simulations were carried out as the results from these are much more generally applicable.

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Appendix- Fluent model settings

Solver:
- Double precision
- Type: pressure based
- Time: steady
- Velocity formulation: Absolute
- 2D space: Planar

Models:
- Multiphase- Off
- Energy- On
- Viscous- Laminar
- Radiation- Off
- Heat Exchanger- Off
- Species- Species Transport
- Discrete Phase- Off
- Solidification & Melting- Off
- Acoustics- Off

Solution Methods:
Pressure velocity coupling
- Scheme- Simple

Spatial Discretization
- gradient- least squares cell based
- pressure- standard
- momentum- second order upwind
- h2o- second order upwind
- energy- second order upwind