Measuring thermal performance in steady-state conditions at each stage of a full fabric retrofit to a solid wall dwelling

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**Abstract**

The methodology used for measuring the thermal performance of fabric retrofit systems which were applied to a solid wall UK Victorian house situated within an environmental chamber is explored in detail. The work describes how steady-state boundary conditions were approximated, then repeated at the Salford Energy House test facility. How established methods of measuring the fabric thermal performance of buildings *in situ* were adapted to test the effectiveness of retrofit measures within a steady-state environment. The results presented show that steady-state boundary conditions enable the change in fabric heat loss resulting from the retrofit of a whole house or individual element to be measured to a level of accuracy and precision that is unlikely to be achieved in the field. The test environment enabled identification of heat loss phenomena difficult to detect in the field. However, undertaking tests in an environment devoid of wind underestimates the potential reduction in ventilation heat loss resulting from an improvement in airtightness, and hides the susceptibility of retrofit measures to various heat loss mechanisms, such as wind washing. The strengths and weaknesses of the methods employed, the Energy House test facility, and a steady-state environment, for characterising retrofit building fabric thermal performance are demonstrated.

**Highlights**

- First known measurement of HTC in steady-state conditions.
- Fabric retrofit thermal performance measured in steady-state conditions.
- Established thermal performance test methods adapted for steady-state measurement.
- Recommendations provided for assessing Energy House retrofit thermal performance.
- Strengths & weakness of the Energy House test facility for testing retrofit explored.

## 1. Introduction

*Table 1 – Nomenclature*

| Term | Symbol | Unit |
|---|---|---|
| Whole building heat transfer coefficient | HTC | W/K |
| Thermal transmittance | U-value (U) | $W/m^2K$ |
| Target retrofit thermal transmittance | $U_t$ | $W/m^2K$ |
| Thermal conductivity | λ | W/mK |
| Thermal resistance | R-value (R) | $m^2K/W$ |
| Internal surface thermal resistance | $R_{si}$ | $m^2K/W$ |
| External surface thermal resistance | $R_{se}$ | $m^2K/W$ |
| Measured baseline thermal resistance | $R_b$ | $m^2K/W$ |
| Thermal resistance of retrofit materials | $R_m$ | $m^2K/W$ |
| Power input | Q | W |
| Heat flux density | q | $W/m^2$ |
| Internal air to external (chamber) air temperature difference | ΔT | K |
| Air permeability at 50 Pa | $q_{50}$ | $m^3.h^{-1}.m^2$ @ 50 Pa |
| Air change rate at 50 Pa | $n_{50}$ | $h^{-1}$ @ 50 Pa |
| Background ventilation rate | n | $h^{-1}$ |
| Ventilation heat transfer coefficient | $HTC_{(V)}$ | W/K |
| Internal surface area | A | $m^2$ |

"Improving the energy efficiency of the existing [UK housing] stock is a long-term, sustainable way of ensuring multiple gains, including environmental, health and social gains." (Marmot Review Team, 2011[1]). Pre-1919 homes are ripe to yield the aforementioned gains as they comprise 21% of England's housing stock and have the lowest average energy performance rating (DCLG, 2017[2]). However, these homes typically have solid wall construction (Everett, 2007[3]) and it is not currently considered economically viable to the apply solid wall insulation required to make them energy efficient (Galvin and Sunikka-Blank, 2017[4]).

The incentive to perform retrofit is further diminished as the anticipated reductions in energy use are often not realised (Gupta *et al*., 2015[5]). This has been attributed to incorrect assumptions regarding occupant energy use behaviour pre-retrofit (Sunikka-Blank and Galvin, 2012[6]) and post-retrofit (Galvin, 2014[7]). Evidence is also growing to suggest that assumptions regarding heat loss from a home pre- and post-retrofit are incorrect. UK Government schemes to incentivise retrofit such as the Energy Company Obligation (ECO) (OFGEM, 2015[8]) and the now defunct Green Deal (Dowson *et al.*, 2012[9]) calculate baseline thermal performance using the Reduced Data Standard Assessment Procedure (RdSAP) (BRE, 2012[10]). The average measured heat loss from solid walls has been found to be substantially less than the standard values used by the RdSAP calculation (BRE, 2014[11] and Li *et al.*, 2015[12]), meaning the baseline heat loss prediction could be overestimated. A performance gap between the measured and predicated reduction in heat loss from fabric retrofit measures has also been observed (Doran, 2008[13] and Miles-Shenton *et al*., 2011[14]). Thus, it can be argued that more measurements should be undertaken pre- and post-retrofit to understand the nature of the prediction and performance gaps in retrofit.

The effectiveness of a thermal retrofit can be assessed at a whole building level by measuring the change in heat transfer coefficient (HTC). ISO 13789 defines the HTC as the *"*heat flow rate divided by temperature difference between two environments*"* (BSI, 2007[15]). It represents the steady-state aggregate total fabric and ventilation heat transfer coefficient ($HTC_{(V)}$) from the entire thermal envelope in Watts, per kelvin of temperature difference (ΔT) between the internal and external environments, and is expressed in W/K. The coheating test has been shown to be reliable a reliable method of determining the HTC of a building (Jack *et al.*, 2017[16]). The improvement in HTC resulting from retrofit has been measured using coheating tests by Miles-Shenton *et al*. (2011[14]) and Rhee-Duverne and Baker (2013[17]). In both instances the baseline HTC measured was lower than that predicted using RdSAP, which highlights the importance of calculating potential improvements in thermal performance from a measured baseline. Miles-Shenton *et al.* found performance gaps between the measured and predicted HTC reduction at each stage of the retrofit process. However, HTC measurements are not targeted enough to explain the cause of a performance gap.

The thermal transmittance of a building element (U-value) is defined in ISO 7345 as the "Heat flow rate in the steady state divided by area and by the temperature difference between the surroundings on both sides of a flat uniform system" (BSI 2017[18]). Measurement of *in situ* U-values is typically undertaken in accordance with ISO 9869 (BSI, 2014[19]). Doran (2008[13]) and Miles-Shenton *et al.* (2011[14]) both measured U-value performance gaps for retrofitted cavity wall insulation (CWI). Miles-Shenton *et al.* found that U-value performance gaps measured for the CWI retrofit and for the subsequent external wall insulation (EWI) retrofit were sufficient enough to account for the discrepancy between the measured and predicted HTC reduction following each retrofit.

Work undertaken by Everett (1985[20]) and Stamp *et al*. (2013[21], 2017[22]) investigating the coheating test method uncovered a number of variables that not only increase the complexity of the data analysis, but can also result in greater uncertainty. Variables identified include: inaccurate estimation of solar gains, delayed release of stored solar gains from the thermal mass, variation in air infiltration (background ventilation rate (n)) caused by a change in wind velocity and/or direction, thermal lag caused by external temperature variation, long-wave radiative heat exchange with the sky, solid ground floor heat loss not directly driven by the internal air-to-external air ΔT, and inter-dwelling heat transfer across a party wall. Many of these variables are also known to increase the uncertainty of *in situ* U-value measurements. The variables listed are all caused by variations in the external boundary conditions and, with the exception of inter-dwelling heat transfer, cannot be practically controlled. The effects of solar radiation on the building fabric mean that it is recommended that coheating tests are only undertaken during the winter months.

As a consequence, it is accepted that when measuring the thermal performance of an unoccupied house, the main sources of uncertainty result from variations in the external boundary conditions. This problem is compounded when attempting to measure the improvement in thermal performance resulting from thermal retrofit, due to the uncertainty associated with both the pre- and the post-retrofit measurements. Coheating test accuracy is estimated to be ±8–10% (Jack *et al*., 2017[16]). The uncertainty of *in situ* U-value measurements undertaken in accordance with ISO 9869 is quoted as ±14% (BSI, 2014[19]). The uncertainty of air permeability ($q_{50}$) measurements using a blower door is highly dependent upon the wind velocity, with the uncertainty ranging from <±2% in calm conditions and ±15% at a velocity of 6 m/s (Persilly, 1982[23]), the maximum velocity in which measurements can be undertaken in accordance with ATTMA Technical Standard L1 (ATTMA, 2016[24]). Such levels of measurement uncertainty can make it difficult to confidently measure minor improvements in building fabric thermal performance. Additionally, if the analysis of the test data does not account for any major difference in external boundary conditions, experienced during the pre- and post-retrofit test periods, then the measured difference in thermal performance could be misleading. Both Miles-Shenton *et al*. (2011[14]) and Rhee-Duverne and Baker (2013[17]) reported notable differences in the external boundary conditions present during a series of pre- and post-retrofit tests, particularly regarding solar radiation and wind respectively. In an coheating test, solar radiation and wind velocity are included as independent variables in the multiple regression analysis to try to normalise for any difference in these variables that is experienced between the tests. However, it is recognised that the analysis techniques employed on coheating data are often unable to isolate the effect of many of the physical phenomena present during a test (Bauwens *et al.* 2014[25]).

One way to eliminate the uncertainties caused by variations in external boundary conditions is to perform measurements at a steady-state within a laboratory setting. Hot boxes have been used since the 1970s to create steady-state conditions to reliably measure the thermal performance of many building components (Asdrubali and Baldinelli, 2011[26]). However, it is only since the opening of the Salford Energy House test facility in 2011 that it has been possible to undertake steady-state thermal performance measurements on an entire building. The work presented in this paper details the first HTC measurements of a building in steady-state conditions and the improvement in thermal performance resulting from the application of a range of fabric retrofit systems. The methodology describes in detail how steady-state boundary conditions were approximated and repeated and how recognised methods for measuring the fabric thermal performance of buildings *in situ* were adapted to test the effectiveness of retrofit measures within a steady-state environment. The analysis of the test results is primarily focused on assessing the utility of the Salford Energy House test facility for measuring retrofit thermal performance and identifying any potential causes of underperformance using established measurement techniques. It is hoped that the work presented in this paper will provide those undertaking similar work at the Salford Energy House, or other similar full-scale indoor test facilities, and to a lesser extent in the field, with guidance for conducting experiential work and interpreting their findings.

## 2. Methodology

### 2.1 The Salford Energy House Test Facility

The Energy House (Figure 1) is a full scale replica pre-1919 solid-wall Victorian end-terrace house constructed inside an environmentally controlled chamber at the University of Salford. The construction of the Energy House was achieved using reclaimed materials and methods of the time, it shares a party wall with an adjacent house (Guard House). Details of the baseline Energy House construction are provided in Table 2.

*Figure 1 – The Salford Energy House test facility*

*Table 2 - Baseline Energy House construction details*

| **Thermal element** | **Construction** |
|---|---|
| External walls | Solid wall – 222.5 mm brick arranged in English bond (5 courses) with 9 mm lime mortar and 10.5 mm British Gypsum Thistle hardwall plaster with a 2 mm Thistle Multi-Finish final coat. The ground and intermediate floor joists are built-in to the gable wall. |
| Roof | Purlin and rafter cold roof structure with insulation at ceiling level. 100 mm existing mineral wool insulation (λ 0.044 W/mK) between 100x50 mm ceiling joists running parallel to the gable wall at 400 mm centres above lath (6 mm) and plaster (17 mm) ceiling. |
| Ground floor | Suspended timber ground floor above a ventilated underfloor void (20 mm depth). 150x22 mm floor boards fixed to 200x50 mm floor joists at 400 mm centres. Floor joists run between the gable and party wall with joists ends built into masonry walls. |
| Windows | Double glazed units in PVCu frames fitted with trickle vents. Typical of 1980's replacement double glazing (**single glazed timber sash windows were present during the preliminary experiment**). |
| Doors | UPVC of amid range type, again typical of a 1980's replacement (**uninsulated timber doors units with single glazing were present during the preliminary experiment**). |
| Party wall | Solid wall – same as external walls, except unplastered on the Guard House side. |

The environmental chamber is a large reinforced concrete structure. The chamber walls are insulated with 100 mm PIR foam insulation to the walls and ceiling and 35 mm expanded polystyrene insulation to the floor element (reinforced concrete slab on short bored piles). The chamber has the ability to maintain a constant temperature between the range -12 °C and +30 °C with an accuracy of ±0.5 °C at a 5 °C set-point. The chamber is cooled by an air handling unit that is supplied with cooling by four condenser units, with a total of 60 kW of cooling (15 kW per unit). This is supplied to the chamber via a ducted heating, ventilation, and air conditioning (HVAC) system. This system reacts to the heat load of the house in the chamber and maintains a set-point of ± 0.5 °C.

### 2.2 Test programme and experimental design

#### 2.2.1 Preliminary experiment

A preliminary experiment was undertaken to measure the heat transfer coefficient (HTC) of the Energy House at a range of ΔT's considered typical of those that are likely to be encountered in the North West of England during the coheating test heating season (October – March). The experiment was designed to test the assumption whether a linear relationship exists between Q and ΔT and to establish whether HTC measurements of the Energy House within the selected range of ΔT's are significantly affected by differences in radiative heat exchange with the chamber fabric and apparatus, and stack effect driven n. Most pertinent to the work contained within this paper, the preliminary experiment would determine the validity of measuring the Energy House HTC at a single ΔT prior to undertaking the retrofit experiment.

The limited test duration allocated to the preliminary experiment (eight days, plus a three-day heat-up and instrumentation period) resulted in only three different steady-state ΔT periods being considered (10 K, 15 K and 20 K). Time constraints also meant that it was only possible to undertake the HTC measurements during the final eight hours of each steady-state ΔT period. The thermostatic heating controllers in the Energy House and the adjacent Guard House were set to maintain an internal air temperature of 25 °C, as recommended by the 2010 Leeds Beckett University Whole House Heat Loss Test Method (Wingfield *et al.*, 2010[27]). The chamber HVAC was initially set to maintain an air temperature of 15 °C during the initial steady-state measurement ΔT period. Subsequently, the chamber air temperature set-point was reduced on two further occasions to 10 °C and 5 °C, thus increasing the ΔT.

### 2.2.2 Retrofit experiment

The purpose of the retrofit experiment was to quantify the impact that a full fabric retrofit would have on the building fabric thermal performance of the Energy House using commercially available thermal upgrade measures. Therefore, the experiment was designed to enable the change in building fabric thermal performance resulting from the application of the various retrofit measures when applied individually, or in combination, to be measured; as well as identify and investigate the cause for any discrepancy between the calculated and measured thermal performance (performance gap) of the various retrofit measures.

The Energy House underwent a staged retrofit process with the thermal elements of the Energy House being retrofitted individually, or in combination. For practical reasons, it was deemed appropriate to undertake the full retrofit first, then remove or replace individual thermal retrofit measures throughout each stage of the experiment. However, given the time constraints associated with the experiment, it was not possible to measure the ground floor retrofit in isolation. The configuration of the Energy House at each stage of the experiment is provided in Table 3.

*Table 3 - Energy House configuration at each test stage of the retrofit experiment (shading represents retrofit installed)*

<table>
<tr><th rowspan="2">Test stage</th><th colspan="4">Condition of thermal element at each test stage</th></tr>
<tr><th>External wall</th><th>Roof</th><th>Glazing</th><th>Floor</th></tr>
<tr><td>1 (Full retrofit)</td><td rowspan="3">Hybrid solid wall insulation system<br>90 mm EPS EWI to gable and rear walls<br>80 mm PIR IWI to front wall</td><td rowspan="2">270 mm mineral wool</td><td rowspan="2">A+++ glazing, argon fill, low e</td><td>200 mm mineral wool + membrane</td></tr>
<tr><td>2 (Full retrofit with original floor)</td><td rowspan="5">Uninsulated (suspended timber)</td></tr>
<tr><td>3 (Solid wall)</td><td rowspan="2">100 mm mineral wool</td><td>1980s style double glazing units</td></tr>
<tr><td>4 (Glazing)</td><td rowspan="3">Uninsulated (solid wall)</td><td>A+++ glazing, argon fill, low e</td></tr>
<tr><td>5 (Roof)</td><td>270 mm mineral wool</td><td rowspan="2">1980s style double glazing units</td></tr>
<tr><td>6 (Baseline)</td><td>100 mm mineral wool</td></tr>
</table>

Measurements of building fabric thermal performance were undertaken at each stage of the experiment, with the most relevant to the work presented here being the steady-state HTC, the *in situ* U-value measurements and $q_{50}$ measurements. These measurements provided either the baseline or retrofit value for each thermal element. The change in thermal performance attributable to the retrofit of each thermal element was calculated as the difference between the measured retrofit and the baseline values. As the retrofit process was performed in reverse order, the retrofit value was measured prior to the baseline value. Unfortunately, this had the effect of limiting the analysis that could be undertaken during the experiment to identify the cause for any underperformance measured.

The average internal and external air temperatures experienced by houses situated in North West England during the heating season were chosen for the retrofit experiment. The chamber HVAC system was set to maintain an air temperature of 5 °C. This was based on findings from the preliminary experiment relating to the behaviour of the chamber's HVAC temperature control system (refer to Section 3.1), and its proximity to the mean external air temperature for North West England during the October to May heating season contained within the Standard Assessment Procedure of 6.6 °C (BRE, 2012[10]). The thermostatic heating controllers in the Energy House and the adjacent Guard House were set to maintain an internal air temperature of 20 °C. This temperature was selected as it is the average central heating thermostat set-point for homes in England (Shipworth *et al.*, 2010[28]). It was considered acceptable to reduce the internal temperature from the coheating test method recommendation of 25°C selected for the preliminary experiment, as the test environment guarantees a positive ΔT throughout the duration of a coheating test. Thus, a 15 K ΔT was maintained during the retrofit experiment.

### 2.3 Thermal performance measurements

#### 2.3.1 Heat transfer coefficient (HTC)

The Energy House HTC was measured using an coheating test. In the field, the coheating test is termed a 'quasi-steady-state' test method and while the elevated, stable, and homogenous air temperature present within the internal environment during a coheating test facilitates a steady-state condition, the variation in weather experienced in the field means that in practice it is unlikely that a test house will ever be at steady-state. Hence, a typical measurement period of between one and three weeks is required to reduce the effects of thermal mass, and to estimate the power input from solar radiation using linear regression techniques. However, the control of the external boundary conditions at the Salford Energy House test facility makes steady-state measurements possible and within a shorter period of time than would normally be required within the field.

The coheating test typically assumes the steady-state whole house energy balance in Equation (adapted from Everett, 1985[20]).

$$Q + R.S = (\Sigma U.A + C_v).\Delta T \qquad [1]$$

Where: R = Solar aperture of the house (m$^2$)
S = Solar irradiance (W/m$^2$)

At the Salford Energy House test facility, the terms R and S can be removed from the whole house energy balance, and the equation rearranged to show how at steady-state, the HTC can be calculated from measurements of just Q and ΔT. Equation 2 shows the HTC calculation for each steady-state measurement.

$$HTC = \frac{Q}{\Delta T} \qquad [2]$$

No formally recognised standard currently exists for undertaking an coheating test. The 2010 Leeds Metropolitan (now Beckett) University Whole House Heat Loss Test Method became recognised as an established test method in the UK when it was incorporated within the Post Construction and Initial Occupation studies undertaken under the Technology Strategy Board's (now Innovate UK's) Building Performance Evaluation Programme (TSB, 2010[29]). This method was adapted to undertake the HTC measurements in the preliminary experiment. The 2013 version of the test method (Johnston *et al.*, 2013[30]) was adapted to undertake HTC measurements in the retrofit experiment. The test methods were adapted to account for a steady-state environment, the most notable changes being a shorter test duration (refer to Section 2.3.4), an alternative analysis method and no requirement for a weather station.

The internal environment of the Energy House and adjacent Guard House were heated using portable electric resistance heaters placed in each zone (room), with each heater being capable of providing 750 W, 1250 W, or 2000 W of heat input. Each heater was controlled by a PID thermostatic temperature controller with a PT100 RTD temperature sensor (accuracy ± 0.1 K), which was set to maintain an air temperature in each zone of 25 °C during the preliminary experiment and 20 °C during the retrofit experiment. An electrically driven air circulation fan was placed in each zone and the internal doors were left open to increase air temperature homogeneity. Power input (Q) from the heaters, fans, and logging equipment was measured by a Wh energy meter (uncertainty ± 1%). The internal temperature in each zone was measured with a PT100 RTD temperature sensor (accuracy ± 0.1 K) positioned in the centre of each zone at mid-storey height. The chamber air temperature was measured using PT100 RTD temperature sensors positioned at the mid-storey height of the ground floor and first floor on each elevation. The internal air temperature of the Guard House was also maintained at the same temperature as the Energy House in each experiment, in order to minimise inter-dwelling heat transfer across the party wall. Energy consumption, along with internal and chamber environmental data, were logged throughout the experiments using an Eltek Squirrel RX250AL data logger. Missing data (~10%) were corrected using linear interpolation. Measurements were recorded at intervals of ten minutes throughout the preliminary experiment and one minute throughout the retrofit experiment.

As very little variation in the mean internal air temperature was measured between the rooms during the preliminary and the retrofit experiment, the ΔT was obtained by subtracting the arithmetic mean internal temperature of the Energy House from the arithmetic mean chamber temperature. Uncertainty for each HTC measurement was calculated by error propagation of the uncertainty associated with measured Q and the SD of the internal and chamber air temperature measurements used to calculate ΔT.

### *2.3.2 In situ* U-value and R-value measurements

*In situ* U-value measurements were generally undertaken in accordance with ISO 9869 (BSI, 1994[31]), however the analysis period was shortened due to the measurements being undertaken within a steady-state environment (refer to Section 2.3.4). *In situ* U-values were calculated for each steady-state measurement using Equation 3 adapted from ISO 9869. Thermal resistance (R-value) was obtained by taking the reciprocal of the U-value.

$$U = \frac{q}{\Delta T} \qquad [3]$$

Heat flux density (q) was measured using Hukseflux HFP01 (uncertainty ± 3%) heat flux plates (HFPs) installed at 75 locations on the thermal elements of the Energy House during the retrofit experiment. HFPs were positioned, with the aid of thermography, in locations considered to be representative of each element. The HFPs were affixed to surfaces using adhesive tape and thermal contact paste. The voltage induced by the HFPs was recorded at one minute intervals by a Thermo Fisher Scientific dataTaker DT80 data logger. *In situ* U-values were corrected to account for the R-value of the HFP (6.25 x $10^{-3}$ $m^2K/W$). The air circulation fans were positioned to avoid them blowing directly onto HFPs. The air-to-air ΔT was measured in the vicinity of each HFP location using PT100 RTD temperature sensors.

The baseline and retrofit *in situ* U-value reported for entire thermal elements were calculated as the mean of the individual *in situ* U-values measured on a thermal element at locations deemed uncompromised by thermal bridging at junctions with neighbouring thermal elements (typically distances > 1 m from junctions as heat flow ≤ 1 m is included in thermal bridging calculations). Uncertainty for each *in situ* U-value measurement was calculated by error propagation of the uncertainty associated with the measured variables q and ΔT in Equation 3.

The target retrofit U-value for elements which were thermally upgraded (rather than replaced) were calculated using Equation 4. The additional R-value provided by the retrofit materials was calculated in accordance with ISO 6946 (BSI, 2007[32]) using values for λ and material thicknesses provided by the manufacturers' product datasheets.

$$U_t = \frac{1}{R_b + R_m} \qquad [4]$$

### 2.3.3 Blower door tests

Blower door tests in accordance with ATTMA Technical Standard L1 were performed at each stage of the retrofit experiment. The tests were undertaken to measure the change in $q_{50}$ resulting from each retrofit measure, to induce a pressure differential between the Energy House and chamber to enable air infiltration points to be identified with thermography, detect any potential air movement within the building fabric using HFPs and temperature sensors, and to estimate n. The chamber doors were left open throughout each test to equalise the pressure between the chamber and external environment. Based on the assumption of zero wind velocity within the chamber the uncertainty associated with each measurement is ±2%, this value is based on the findings of Persily (1982[23]).

The air change rate at 50 Pa ($n_{50}$) measured at each stage of the retrofit experiment was used to approximate n of the Energy House using the $n_{50}/20$ 'rule of thumb' (Kronvall, 1978[33]), adjusted to $n_{50}/19.2$ to account for storey height and sheltering factor (Sherman, 1987[34]). Typically, a single zone trace gas technique such as that detailed by Roulet and Foradini (2002[35]) is also used to determine n during tests in the field. However, it was found during the preliminary experiment that the $CO_2$ released into the Energy House moved in a cycle between the Energy House and the chamber, thus precluding the use of a single zone tracer gas decay method for the retrofit experiment. Unfortunately, a multi-zone tracer gas measurement was not available to the research team.

The approximated n was multiplied by the internal volume of the Energy House and by the specific heat capacity of air (0.33 Wh/m$^3$K) to determine $HTC_{(V)}$ (W/K). By subtracting $HTC_{(V)}$ from the measured HTC enables the HTC to be disaggregated into its fabric and ventilation components.

### 2.3.4 Repeatable steady-state measurements at the Salford Energy House test facility

ISO 9251 defines a steady-state as a "*Condition for which all relevant parameters do not vary with time*" (BSI 1987, p.1[36]). In practice, steady-state boundary conditions can only be approximated, as it is not possible to create a true steady-state due to the limitations of existing apparatus to accurately control and measure such an environment. Hence, the existence of standards which define the requirements for practicable determination of steady-state heat transfer. No recognised standard currently exists which defines the requirements for steady-state boundary conditions for the measurement of heat transfer (whole house or elemental) using an indoor full-scale test facility. The standards for steady-state U-value measurement using a guarded hot box and for *in situ* measurements undertaken in the field are ISO 8990 (BSI, 1996[37]) and ISO 9869-1 (BSI, 2014[19]) respectively. However, neither standard is considered appropriate for the Salford Energy House test facility, as unlike measurements taken in the field, the internal and external boundary conditions can be controlled and repeated, but not to the precision or accuracy that can be achieved in a guarded hot box due to the scale of the Salford Energy House test facility. The relevant boundary condition requirements for measurements to comply with ISO 8990 and ISO 9869 relate to: air temperature fluctuation and variation, heat content, moisture distribution and air velocity. These requirements, as well as test duration, will now be considered in regard to the Salford Energy House test facility.

ISO 8990 requires temperature fluctuations to be kept within 1% of the air-to-air ΔT when determining the steady-state thermal transmittance of building components in a guarded hot box. ISO 9869 contains no such requirement, as *in situ* U-value measurements in the field experience a diurnal temperature fluctuation externally and potential internal fluctuations resulting from space heating patterns in occupied dwellings. Therefore, it can be argued that given the close control of the internal temperature fluctuations during a coheating test of ± 0.1 K, and the regular chamber air temperature fluctuation of ± 0.5 K, a fluctuation in the air-to-air 15 K ΔT of 3% can be considered close to what is considered practicable at a whole house scale.

ISO 8990 states that air temperature variation across a specimen surface should to not exceed 2% of the air-to-air ΔT. Coheating test equipment creates a reasonably homogenous air temperature within each zone, resulting in a typical floor to ceiling air temperature gradient of ~0.3 K. However, the internal arrangement of the first floor in the Energy House means that achieving a homogenous internal air temperature throughout the Energy House is challenging. Consequently, a variation in air temperature of up to 1 K between zones within the Energy House could be expected. An air temperature variation of up to 1 K within the chamber is considered typical. If the thermal envelope of the Energy House is considered to constitute the specimen surface for HTC measurements, then the variation in air-to-air ΔT is ≤ 9%, which far exceeds that required by ISO 8990. However, in the event that internal air temperature variation throughout the Energy House was reduced to zero, the variation in chamber air temperature alone would result in an air temperature variation exceeding 2% across the entire thermal envelope. This suggests that the 2% limit detailed in ISO 8990 is not practicable for an Energy House HTC measurement at a 15 K ΔT (a 65 K ΔT would be required to meet the 2% limit). To reconcile this potential source of measurement error, the variation in air temperature measured internally and within the chamber was included in the uncertainty calculation for each HTC measurement. To compensate for the variation in internal and chamber air temperatures, the ΔT for *in situ* U-value measurements was measured locally, which fulfils the requirements of ISO 8990 and ISO 9869.

The fluctuation in ΔT causes a fluctuation in the heat flow rate throughout a measurement, thus precluding an instantaneous steady-state measurement. However, averaging the heat flow rate and ΔT over a sufficient period of time can smooth out the effects of these fluctuations. An averaging period of 24 hs was chosen, as it enables analysis of *in situ* U-value measurements be undertaken in accordance with ISO 9869 and is greater than the minimum period of three hours required by ISO 8990. Comparison can then be made between successive averaging periods to determine whether the heat flow rate can be considered constant, thus approximating to a steady-state.

The high thermal mass of the external walls and foundation slab of the Energy House means that charging or discharging of the thermal mass could be occurring even when a constant ΔT is being measured. To ascertain whether the heat flow rate was constant prior to steady-state measurements, a stabilisation period existed in which a constant ΔT was maintained and Q into the Energy House monitored. The stabilisation period ended once the average Q measured over a 24 h period differed by less than ± 5% from that measured during the previous 24 h period; at this point the heat flow rate was considered to be close to steady-state.

A steady-state test period of 72 h in duration followed each stabilisation period, during which the chamber and Energy House were left undisturbed. A 72 h test duration was chosen as it is the minimum test duration at a stable ΔT required for *in situ* U-value measurements to comply with ISO 9869 (BSI, 2014[29]) if required. Each steady-state test period comprised two components, an initial 48 h period to allow any perturbations in the heat flow rate caused by disturbances to the test environment during the stabilisation period (e.g. visits by researchers) to settle. This was followed by a 24 h period in duration when the reported steady-state measurements were undertaken. The steady-state measurements undertaken during the final 24 h period of a test were only considered valid if they differed by less than ± 5% from those measured during the previous 24 h period. The ± 5% from the previous 24 period criterion is based upon one of the conditions for fulfilling the requirements of ISO 9869 for *in situ* U-value measurements, but greater than the ± 1% between successive measurements required by ISO 8990. Without the time constraints imposed on the experiment, a stricter criterion would have been specified. Although the 24 h measurement period is less than that stipulated by ISO 9869 (BSI, 2014[29]), it can be justified, as the 72 h period stated by ISO 9869 is based upon three diurnal temperature cycles. As the chamber air temperature cycles at a frequency of ~20 minutes, it can be argued that each 24 h period is equivalent to ~72 diurnal cycles. Additionally, the undisturbed test environment during the prior 48 h period increased the likelihood of achieving a steady-state.

The requirement to return the Energy House to its 'as found' condition following each experiment meant that it was not possible to measure moisture content or distribution within the building fabric of the Energy House to detect whether any changes were taking place. The sheltered test environment meant that the only noteworthy source of additional moisture that the building fabric of the Energy House was exposed to during the experiment was the wet plaster finish applied to the IWI on the front wall prior to test stage 1 of the retrofit experiment. In lieu of a direct measurement, RH measurements of the internal and chamber air were taken as a proxy. Air temperature set-points close to 0 °C were ruled out during experimental planning to ensure that any phase changes would not affect the measurements.

The continuous operation of air circulation fans within the Energy House and the chamber HVAC equipment ensured a constant air velocity across the internal and external surfaces of the Energy House during each steady-state measurement. Thus, any change in n following alteration to the building fabric can be attributed to a change in the airtightness of the Energy House. The location and speed setting of each air circulation fan remained unchanged throughout each experiment to ensure the internal surface thermal resistance ($R_{si}$) and external surface thermal resistance ($R_{se}$) were consistent between test stages. $R_{si}$ and $R_{se}$ were measured on each element throughout the retrofit experiment to identify whether any change occurred.

## 3. Results and discussion

### 3.1 Preliminary experiment

Table 4 provides the ΔT, Q, and HTC measured during each steady-state measurement period in the preliminary experiment.

Table 4 - Measured ΔT, Q, and HTC for each steady-state measurement period of the preliminary experiment (differences in HTC calculated using table values are due to rounding)

| ΔT (K) | Q (W) | HTC (W/K) |
|---|---|---|
| 11.1 | 2440 | 220.2 (± 10) |
| 15.6 | 3441 | 220.0 (± 7.8) |
| 20.7 | 4555 | 220.5 (± 7.1) |

Table 4 shows that there was no significant difference between HTC measurements of the Energy House at each steady-state ΔT. Figure 2 shows the relationship between measured ΔT and Q during each steady-state ΔT measurement period.

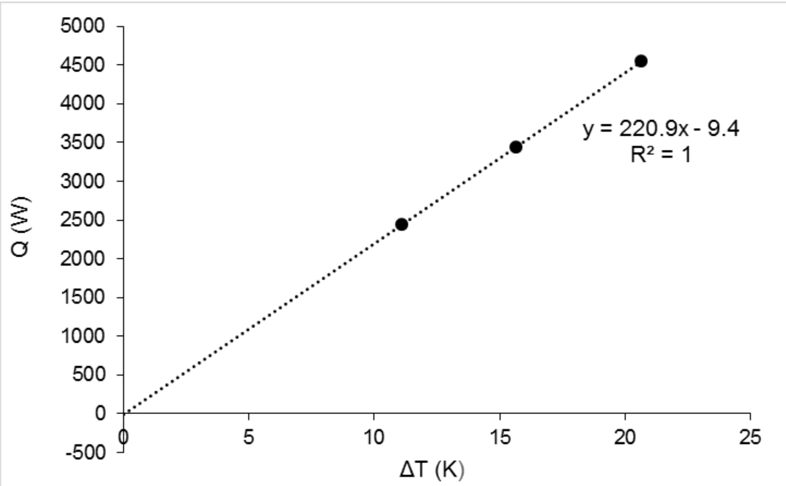


*Figure 2 - Relationship between measured ΔT and Q during each steady-state ΔT measurement period in the preliminary experiment*

Figure 2 shows a perfect $R^2$ linear correlation between ΔT and Q measured during each steady-state measurement period. The linear regression derived HTC of 220.9 (± 0.8) W/K is in good agreement with that measured at each steady-state ΔT. This suggests that any differences in radiative heat exchange and stack effect over the ΔT range measured did not significantly affect the HTC measurement of the Energy House. Therefore, the use of a single ΔT within the measurement range used in the preliminary experiment can be considered appropriate to measure the HTC of the Energy House.

The preliminary experiment also found that the chamber HVAC system achieved the greatest level of temperature control with a 5 °C set-point. The chamber air temperature oscillated around the 5 °C set-point with an amplitude of 0.5 °C with regular frequency of ~20 minutes. This suggests that steady-state measurements of the Energy House HTC should be undertaken with a chamber set-point of 5 °C.

#### 3.1.1 Retrofit experiment

##### 3.1.1.1 HTC measurements

Figure 3 shows Q into the Energy House and mean internal and chamber air temperatures measured throughout the full retrofit HTC steady-state measurement.

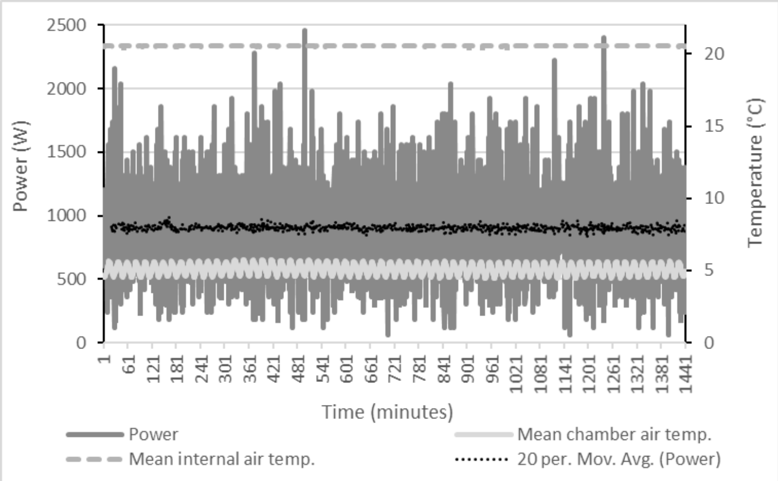


*Figure 3 - Q and mean internal and chamber temperatures measured during the full retrofit HTC steady-state measurement*

A stable internal air temperature close to the 20 °C set-point and the regular chamber air temperature oscillation around the 5 °C set-point are evident in Figure 3. This indicates that, as far as can be considered practicable at the Energy House test facility, a steady-state ΔT was present. A large variation in Q is also evident, however, the 60 minute moving average of Q indicates that the rate of heat flow was generally stable. Similar behaviour was observed throughout the measurement periods at each stage, providing confidence of a consistent test environment close to steady-state throughout the entire retrofit experiment.

Table 5 provides the HTC measurements for each stage of the retrofit experiment and the contribution of each thermal element retrofit to the reduction in HTC from baseline resulting from the full retrofit.

*Table 5 - HTC measured at each stage of the retrofit experiment and contribution of each thermal element retrofit to the reduction in HTC from baseline resulting from the full retrofit*

| **Test stage** | **HTC (W/K)** | **Reduction on baseline (W/K)** | **Contribution of each thermal element retrofit towards full retrofit HTC reduction (%)** |
|---|---|---|---|
| 1 (Full retrofit) | 69.7 (± 2.4) | 117.8 | n/a |
| 2 (Full retrofit with original floor) | 82.7 (± 2.6) | 13[1] | 11 |
| 3 (Solid wall) | 103.6 (± 3.6) | 83.9 | 72 |
| 4 (Glazing) | 174.2 (± 5.4) | 13.3 | 11 |
| 5 (Roof) | 180.5 (± 6.9) | 7 | 6 |
| 6 (Baseline) | 187.5 (± 7.6) | n/a | n/a |

The full retrofit resulted in a 63% reduction in the HTC of the Energy House from the baseline. The sum of the HTC reductions from the baseline for each thermal element retrofit measured in isolation (test stages 2, 3, 4, and 5) was 117.2W/K. This represents a discrepancy of 0.5% from the measured HTC reduction for the full retrofit from the baseline of 117.8 W/K. The close agreement between these values suggests that the boundary conditions were repeated throughout the experiment, resulting in precise HTC measurements. Such precision also allows the contribution of each thermal element to the HTC reduction to be disaggregated with confidence. In this experiment, the retrofit measure that achieved the greatest saving was the hybrid solid wall

[1] As the ground floor retrofit was not measured in isolation, its contribution to the HTC reduction was derived from the measured HTC change between test stage 1 and 2.

insulation applied to the external walls. This measure constituted 72% of the full retrofit HTC reduction. Importantly, the results also show, that in this instance, undertaking a full retrofit all at once provides no additional fabric heat loss improvement than would otherwise be achieved if the individual thermal elements were retrofitted sequentially. It is unlikely such granularity could be achieved in the field to confidently report these findings.

### 3.2 *In situ* U-value measurements

Table 6 provides a summary of the mean baseline and retrofit *in situ* U-values for each thermal element and the target retrofit U-value calculated for each retrofit measure.

*Table 6 - Measured baseline and retrofit and target retrofit U-values for each thermal element*

| **Thermal element** | **U-value (W/m$^2$K)** | | |
|---|---|---|---|
| | **Baseline** | **Target retrofit** | **Measured retrofit** |
| External wall (EWI) | 1.74 (± 0.06) | 0.30 | 0.33 (± 0.01) |
| External wall (IWI) | 1.84 (± 0.08) | 0.24 | 0.22 (± 0.01) |
| Roof (between joists) | 0.35 (± 0.01) | 0.15 | 0.16 (± 0.07) |
| Glazing (centre pane) | 2.39 (± 0.09) | 1.33 | 1.34 (± 0.05) |
| Ground floor (between joists) | 0.61 (± 0.01) | 0.12 | 0.13 (± 0.03) |

From Table 6 it can be seen that the calculated target retrofit U-value was within the uncertainty bounds of most thermal element's measured retrofit U-value, which suggests that retrofit measures performed close to the calculated improvement at the locations measured. The exception were the external walls retrofitted with EWI and IWI. The front external wall retrofitted with IWI performed better than calculated. However, this can be explained by the additional R-value resulting from the 10 mm unventilated airspace (0.15 m$^2$K/W obtained from ISO 6946) created by the adhesive dabs used to affix the IWI to the inner surface of the external walls which is not included in the BBA certificate. The baseline U-value of the gable external wall was 17% lower than the RdSAP default value of 2.10 W/m$^2$K. In this instance retrofitting the external walls with EWI reduced the U-value by 81%, calculating the U-value reduction on the default RdSAP baseline performance and manufacturer's data predicts a saving of 86%. The discrepancy would be larger if EWI with a lower R-value was applied and *vice versa*. This finding demonstrates the importance of measuring retrofit pre- and post-retrofit to assess the change in fabric heat loss.

Comparing the difference in baseline and retrofit R-value enables a direct comparison with the R-value of the applied retrofit materials at each location. Figure 4 shows the measured increase in the R-value from baseline of the EWI retrofitted external wall at locations > 1 m from junctions and the calculated R-value increase for the EWI system. Two areas of notable underperformance on the gable external wall were identified from the measurements (living room and bedroom 2), these became the focus of further investigation during the blower door tests (refer to Section 3.4).

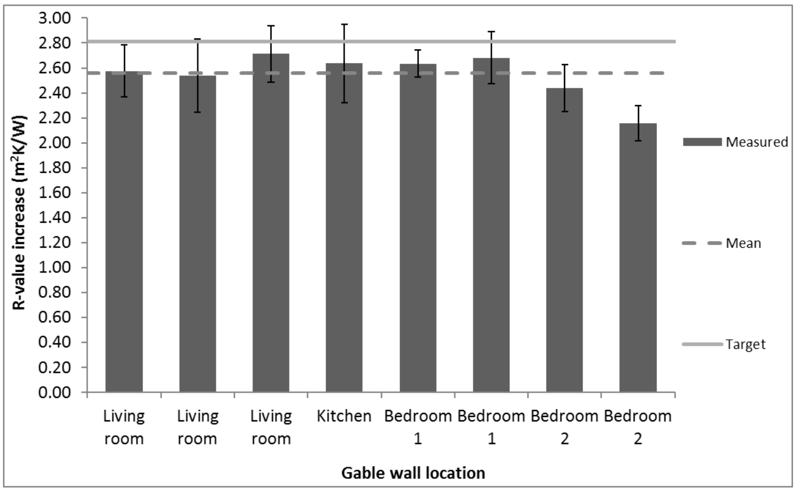


*Figure 4 – Measured increase in R-value of the gable external wall upgraded with EWI at locations > 1 m from junctions and the calculated R-value increase for the EWI system*

### 3.3 Comparison of heat loss reductions using differing methods

Table 7 compares differing methods for obtaining the total, fabric, and ventilation heat loss reductions resulting from the retrofit of individual thermal elements.

*Table 7 - Comparison of total, fabric, and ventilation heat loss reduction resulting from the retrofit of an individual thermal element using differing methods*

| Thermal element retrofitted[2] | Reduction in heat loss from baseline (W/K) | | | | |
|---|---|---|---|---|---|
| | Total | | Fabric | | Ventilation |
| | Aggregate method (coheating) (*a*) | Disaggregate method (*b*+*c*)[3] | Coheating & $n_{50}$/19.2 derived (*a*-*c*) | U-value reduction*A (*b*)[4] | $n_{50}$/19.2 derived (*c*) |
| Ground floor (test stage 2) | 13 | 26.1 | 0 | 13.1 | 13 |
| External walls (test stage 3) | 83.9 | 93.1 | 81 | 90.2 | 2.9 |
| Roof (test stage 5) | 7 | 9.4 | 4.4 | 6.8 | 2.6 |

The reduction in total heat loss obtained using the disaggregate method is substantially greater than that obtained using the aggregate method (coheating HTC measurement) for each thermal element retrofitted. The discrepancy between the two values can be explained by questioning the values inputted into the disaggregate method calculation. The representative nature of the roof and ground floor U-values can be doubted as the heat loss observed across these elements showed greater variation than the external walls. The depth of the retrofitted mineral wool in the loft was inconsistent due to the shallow roof pitch and structural timber hindering the retrofit. In addition, Pelsmakers *et al* (2017[38]) also measured significant variation in the heat loss across the surface area of the Energy House ground floor. However, despite this, the greatest concern

[2] Replacement glazing excluded from this analysis as the effect of the window frame would have to be calculated for each window.
[3] Budgetary constraints prevented the calculation of the total heat loss from thermal bridging at junctions to include in the disaggregate method calculation.
[4] The U-value reduction for each thermal element was multiplied by its internal surface area. The U-value reduction for inhomogeneous thermal elements were area weighted to include the measured reduction in heat loss through the loft hatches and structural timber within the ceiling and ground floor.

surrounds the veracity of the $n_{50}$/19.2 derived $HTC_{(V)}$ approximation. The coheating and $n_{50}$/19.2 derived fabric heat loss approximation suggests that the ground floor retrofit provided no fabric thermal performance improvement; this is in stark contradict to the *in situ* U-value measurements. The close agreement between the fabric heat loss reduction derived from the *in situ* U-value measurements and the measured HTC reduction for the roof and ground floor retrofits suggests that using 19.2 (or 20) as the devisor of $n_{50}$ greatly overestimates n, and a much higher devisor is required for the Energy House. It is thought that the lack of wind within the environmental chamber during the tests resulted in a substantially lower background ventilation rate than would normally be experienced by similar houses in the field. Therefore, it is likely that the measured HTC of a home similar to the Energy House in the field would be greater due to a higher rate of wind driven $HTC_{(V)}$, lower $R_{se}$, and cooler loft and underfloor void temperatures. The results also suggests that the ventilation heat loss rate remained similar throughout the retrofit experiment, and that the reduction in HTC measured for each retrofit measure would have been greater if the Energy House was exposed to wind, notably for the ground floor where the retrofit delivered the greatest improvement in airtightness (refer to Table 8).

If one assumes that there was very little change in the $HTC_{(V)}$ resulting from each retrofit measure, the discrepancy between the external wall retrofit measured HTC reduction and the fabric heat loss reduction derived from U-value measurements can be attributed to an increase in thermal bridging heat loss post-retrofit, caused by the decision not to insulate the opening reveals. The fabric heat loss reduction derived from *in situ* U-value measurements was based upon measurements taken > 1 m from junctions, so can be considered reasonably unaffected by geometric thermal bridging. The normal distribution of baseline and retrofit *in situ* U-values measured at these locations suggested a consistent rate of heat loss, confirming this assumption. The distribution of *in situ* U-values which included measurements > 0.5 m from junctions was normal for the baseline external wall, but displayed positive skew for the retrofitted wall, suggesting an increase in the influence of thermal bridging. This was confirmed by thermographic surveys and thermal bridging calculations undertaken using Physibel TRISCO version 12.0w software (Physibel, 2010[39]), which predicted that the window jamb Ψ-value increased post-retrofit from a 0.072 W/mK baseline to 0.107 W/mK on the IWI retrofitted front wall and 0.206 W/mK on EWI retrofitted rear wall[5]. If the 6.3 W/K discrepancy is divided by the external envelope area of 133.3 $m^2$, it suggests an increase in y-value of 0.05 $W/m^2K$ of the Energy House following the external wall retrofit. It is doubtful whether the pre- and post-retrofit HTC and *in situ* U-value measurements in the field would be accurate or precise enough to isolate such a change in y-value.

### 3.4 Blower door tests

Table 8 provides $q_{50}$ and $n_{50}$ of the Energy House measured using a blower door test at each test stage of the retrofit experiment and n estimated using $n_{50}$/19.2.

*Table 8 - Blower door test results showing reduction on baseline and $n_{50}$/19.2 derived background ventilation rate at each stage of the retrofit experiment*

| Test stage | $q_{50}$ ($m^3.h^{-1}.m^2$ @ 50 Pa) | $q_{50}$ reduction on baseline (%) | $n_{50}$ ($h^{-1}$ @ 50 Pa) | n ($h^{-1}$) |
|---|---|---|---|---|
| 1 (Full retrofit) | 6.0 (± 0.1) | 50 | 7.3 (± 0.1) | 0.38 |
| 2 (Full retrofit with original floor) | 10.4 (± 0.2) | 42[6] | 12.5 (± 0.3) | 0.65 |
| 3 (Solid wall) | 11.1 (± 0.2) | 8 | 13.4 (± 0.3) | 0.70 |
| 4 (Glazing) | 11.1 (± 0.2) | 8 | 13.4 (± 0.3) | 0.70 |

[5]Insulating the EWI reveals would have reduced the jamb Ψ-value to 0.045 W/mK.
[6] As the ground floor retrofit was not undertaken in isolation, the reduction from baseline was calculated as the measured $q_{50}$ change between test stage 1 and 2.

| | | | | |
|---|---|---|---|---|
| 5 (Roof) | 11.2 (± 0.2) | 7 | 13.5 (± 0.3) | 0.70 |
| 6 (Baseline) | 12.1 (± 0.2) | n/a | 14.5 (± 0.3) | 0.76 |

The absence of wind within the chamber during the blower door tests meant that the measured air flow rate and induced pressure differential remained stable for each of the 12 tests (six for each pressurisation and depressurisation measurement) required to measure $q_{50}$ and $n_{50}$ at each stage of the retrofit experiment. This was signified by an $r^2$ of 1 for each blower door test in which the same flow ring was in place for all measurements (test stages 1 and 6). The sheltered conditions increase confidence that the measurements were both accurate and repeatable and justifies the use of a 2% uncertainty value. The blower door tests measured a 50% reduction in $q_{50}$ from baseline for the full retrofit. The ground floor retrofit resulted in the single greatest reduction in $q_{50}$ of 42%. Air infiltration investigation during depressurisation using thermography suggested that the vapour membrane sealed to the walls, rather than the insulation between floor joists, was responsible for the scale of the reduction. This finding is consistent with those documented by Gillott *et al.* (2016[40]). A reduction in $q_{50}$ from the baseline of the scale measured for the full and ground floor retrofits could be confidently detected in the field using blower door tests. However, the sensitivity of blower door test measurement accuracy to changes in wind velocity means that it is questionable whether the reductions in $q_{50}$ of <10% achieved by retrofitting the other thermal elements could be measured with confidence in the field.

The blower door tests provided valuable insight for diagnosing the reasons for the measured underperformance of the EWI system. Thermocouples had been affixed to the outer leaf of the gable external wall prior to the installation of the EWI, in a 2 m horizontal array out from the junction with the IWI front wall, at intervals of 0.4 m and a height of 0.7 m above ground floor level. During blower door tests, the temperature measured at the interface between the outer leaf of brickwork and EWI 2 metres from the gable/front wall junction reduced. When a hairdryer was used to warm the air in the vicinity of the edge seal at the gable/front wall junction during depressurisation at 50 Pa, the interface temperature measured 2 m from the junction increased. This location corresponded to the area of greatest measured underperformance in the living room identified from the *in situ* U-value measurements. q measured in this region also took longer than better performing areas to return to a steady-state following a blower door test. From these observations, it was concluded that the EWI edge seal was not airtight, resulting in an air path between the chamber and the interface between the outer leaf of the external wall and EWI along the mortar joints to areas of poor contact between the EWI and uneven wall surface, enabling convective bypassing of the insulation layer. This finding provides evidence that poor edge sealing of mechanically fixed EWI boards without an adhesive coat reduces its performance. The observations made during the blower door tests suggest that thermal performance measurements in a test environment devoid of wind pressures could fail to identify the susceptibility of retrofit measures to a number of important heat loss mechanisms, such as wind washing, unless differing conditions are imposed upon the test subject. However, a steady-state environment prior to and following a blower door test enabled the use of temperature and q measurements to isolate where air movement within the building fabric had occurred during the test. Identifying air movement within the building fabric in the field from temperature and q measurements is inherently more complex and problematic due to the noise created by thermal mass effects.

## 4. Conclusions

The Salford Energy House test facility was found to enable the change in fabric heat loss resulting from the application of fabric retrofit measures to be measured to a level of accuracy which cannot be guaranteed in the field, due to the ability to precisely control external boundary conditions across successive test periods. Although the findings also suggest that the absence of wind within the environmental chamber underestimates the potential reduction in $HTC_{(V)}$ resulting from improvements in airtightness, the test environment does enable the identification of other important heat loss phenomena, such as thermal bypassing, which may prove difficult to detect in the field. However, the absence of wind in the environmental chamber may mask the susceptibility of thermal elements to other thermal phenomena, particularly wind washing. Thus, the utility of the Salford Energy House (and other full-scale test facilities) for testing the applicability of various thermal performance retrofit solutions to the field needs to be carefully considered. This is because the environmental chamber can never truly replicate the external environmental conditions experienced by houses the field, or contain houses that are constructed in a manner truly representative of all the houses within its archetype. However, it is also the case that thermal performance test methods deployed in the field are not yet accurate or precise enough to fully account for the presence of a complex combination of dynamic and often interacting external boundary conditions. Additionally, no individual house in the field can ever be considered representative of an entire archetype. Therefore, the Salford Energy House can be considered an incredibly useful facility for testing the effectiveness of a thermal fabric retrofit to a solid wall dwelling with characteristics similar to a sizable proportion of the UK's 'hard to treat' housing stock, providing those undertaking tests are aware of (or can adapt to) the limitations that come from testing within such an environmental chamber.

As the coheating test is based upon a steady-state energy balance, it is ideally suited for application in a steady-state test environment. Such an environment not only increases coheating test accuracy, it also enables tests to be undertaken over a much shorter duration than is possible in the field, unconstrained by a heating season. *In situ* U-value measurements can also be undertaken free from the uncertainty caused by thermal mass effects and the influence of direct solar radiation. Blower door tests are not only more accurate than those generally undertaken in the field, but importantly, they also provided more potential for diagnosing the cause of underperformance by artificially inducing air movement. Since the experimental work detailed in this paper has been undertaken, fans have been installed within the environmental chamber to simulate wind upon the external façade of the Energy House. It is suggested that future retrofit experiments undertake a number of steady-state measurements at a range of differing wind speeds, at each retrofit stage, to measure the change in thermal performance attributable to wind washing effects ($R_{se}$ and the rate of ventilation in unconditioned voids would need to be measured).

During the tests, it was not possible to accurately compare HTC values for each test stage against a predicted HTC, as thermal bridging calculations were not performed for all junctions, and problems arose establishing n. Despite this, the change in HTC observed from coheating testing is considered the most robust measurement with which to assess the impact of retrofit, as it encapsulates the change in plane element U-value (especially non-homogeneous elements where obtaining representative measurements is difficult), thermal bridging at junctions, $HTC_{(V)}$, and can account for other complex heat loss mechanisms, such as thermal bypassing and wind washing.  Attempting to account for all of these heat loss mechanisms using disaggregated measurement techniques, is not practically possible or cost-effective. Further testing work at the Energy House should include calculation of all thermal bridges and a more robust method of determining n (e.g. a multi zone trace gas technique) should be used to enable the various heat loss mechanisms to be accurately disaggregated. Measuring the change in HTC resulting from heating of the underfloor void may also enable the suspended timber floor heat loss to be more accurately measured.

A recognised steady-state measurement standard for testing the thermal performance of a whole house or individual thermal element using a full-scale indoor test facility is needed. This would provide existing and future indoor full-scale facilities with the necessary requirements for boundary condition control and the method required to undertake steady-state measurements that can be considered acceptable for regulatory compliance.

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