Title: QUB/e: Validation of a transient method for determining whole building thermal performance and building element U-values in situ under actual operating conditions

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Abstract: Growing evidence in recent years has suggested that a difference exists between the design and the as-built thermal performance of UK dwellings. This difference commonly known as the 'performance gap' may have serious implications on the UK government's emissions reduction targets. Determining the theoretical design thermal performance of whole dwellings (Heat Loss Coefficient, HLC) and building elements (U-value) can be straightforward; however in situ measurements of actual thermal performance can be much more difficult to achieve. Several methods have been developed to measure these properties in situ with the most common usually involve quasi-steady state conditions that necessitate long testing periods. The duration of such tests is deemed impractical from a building access perspective and wider uptake has therefore not been achieved.

The QUB/e method, developed by Saint-Gobain, is a dynamic method used to experimentally measure in-situ the thermal performance of a building in order to determine the whole dwelling HLC and U-values. The method is an advancement on the usual quasi-steady methods as it has the benefit of being able to be performed typically in a single night without occupancy. Validity of results has been demonstrated in a climate chamber under controlled conditions in a previous work. In this work, validation of the QUB/e method is performed under actual operating conditions by conducting a series of measurements on a daily basis in a modern well-insulated property located at the University Park Campus, University of Nottingham. Results were compared to those obtained with quasi steady-state measurements; the HLC was compared to that obtained with a coheating test and the U-values with those obtained by means of the procedure as per BS ISO 9869-1:2014 average method. Good agreement was found for both the HLC (7.5% relative difference between the two methods on average) and the U-values (in most cases the relative difference of the quasi-static and dynamic methods was approximately 2% while in one instance it was 12.5% on average), thereby increasing confidence in the ability of the QUB/e method to provide reliable results and highlights its potential to test the actual performance of buildings.

Keywords: QUB/e method, Coheating test, ISO 9869, Heat Loss Coefficient, U-value

1. INTRODUCTION

Building regulations in the UK have been setting progressively stricter requirements over the last years on the energy efficiency of new-built dwellings in order to reduce greenhouse gas emissions from the domestic sector that currently accounts for 27% of the country's final energy consumption (DBEIS, 2016). However, it has been found that the design thermal performance is often inconsistent with the actual as-built thermal performance of a dwelling. This difference is commonly referred to as the 'performance gap' and is considered a significant risk that may compromise the efforts on reducing greenhouse gas emissions. Calculating the thermal performance of a dwelling is part of the regulatory process using the UK Government's Standard Assessment Procedure (SAP) and is based on information of the building geometry, location, surroundings and material properties (DECC, 2014). In contrast, assessing the as-built performance is not as simple and straightforward.

Several methods have been developed to determine the actual as-built thermal performance of the building fabric in situ. With regards to whole building thermal performance, the coheating test is perhaps the most widely used. The coheating test is a quasi-steady state method that determines the Heat Loss Coefficient (HLC) of a building by maintaining a fixed internal elevated temperature using heaters and fans and monitoring the power required to do so as well as the external temperature and weather conditions. Despite the wide acceptance of the method by industry and research institutions, it is not considered practical as it involves long testing periods (typically 2 – 4 weeks) and is restricted during the heating season when external temperature and the levels of solar radiation are typically low. In terms of elemental performance, the BS ISO 9869-1:2014 Standard describes the recommended procedure for determining the U-value of building elements in-situ with the 'average method' being the most commonly used analysis technique. This method considers measuring the heat flow at the surface of a building element and temperatures at each side of that element and averaging them over long periods of time so that heat storage effects are minimised (i.e. quasi-steady state conditions are assumed); again long testing periods are usually required in order to meet the criteria set by the average method.

Alternatively, other methods that require shorter testing periods have been developed (e.g., see Janssens 2016 and references therein). In this paper the performance of the QUB/e method to measure both whole house HLC and building element U-value in much shorter period is evaluated. The method builds on the QUB method, a dynamic method developed by Saint-Gobain to determine the as-built HLC of dwellings typically within one night; based on the same analysis principle the QUB/e method takes into account the heat flow on building elements to determine the U-values. The ability of the QUB/e method to provide reliable results, has been demonstrated numerically (Alzetto et al., 2014) and experimentally in a climate chamber under steady conditions as well as (Meulemans et al., 2016, Alzetto et al, 2018a). Several studies have also reported on the performance of method under actual climatic conditions in different regions of Europe (Alzetto et al, 2018b, Meulemans, 2018). With regards to investigating the performance of the QUB/e method in the UK climate a long-term study was conducted in a property in Nottingham; repeatability and consistency of the results as well the effect of weather conditions were examined (Sougkakis et al, 2017).

However, that work was conducted in a poorly insulated property. In this work, results from a series of QUB/e tests performed on a daily basis in a well-insulated property in the UK climate are presented. In addition, a coheating test was also performed to determine the HLC and data from the heat flow meters during this test were also analysed considering the BS ISO 9869-1average method. The aim was to assess the ability of the QUB/e method to deliver consistent results and assess its performance against well-established quasi-static methods.

2. IN-SITU EXPERIMENTAL METHODS

In the following sections a brief description of both the quasi-steady state and the QUB/e methods is presented.

2.1. Quasi-steady state methods

Coheating method

The method statement for the coheating test is described by Johnston et al. (2013). In summary, the test procedure involves heating the building with electrical heaters to a fixed elevated temperature, significantly higher than the mean external temperature (usually 25ºC) so that an adequate temperature difference between internal and external environment is achieved (ΔT). Fans are also used to mix the air and achieve homogeneous temperatures throughout the building. Internal zone temperatures, the external temperature and the power consumption of the fans and heaters are monitored. The HLC is then determined by plotting the daily average electrical consumption against the daily average difference between the average internal and external temperatures (Johnston et al., 2013). This is usually referred to as 'uncorrected HLC'. In order to account for the effect of solar gains, which are a major contributor to the heat gains of a house when performing a coheating test the following simplified steady-state energy balance is considered:

Equation 1: Energy balance in a coheating test

$$Q_{elec} + Q_{solar} = Q_{loss}$$

Where:

- Q_{loss} = the rate of heat loss of the dwelling (W). This is the product of the Heat Loss Coefficient, HLC (W/K) and the temperature difference between the average internal and average external temperature, ΔT (K)
- Q_{elec} = the power consumption of the electrical heaters (W)
- Q_{solar} = the solar gains (W). This is the product of the solar aperture, R (m^2), and the solar irradiance, S (W/m^2),

Therefore Equation 1 can also be expressed:

Equation 2: Expanded energy balance in a coheating test

$$Q_{elec} + R \cdot S = HLC \cdot \Delta T$$

Solar gains can be accounted for by measuring the solar irradiance, S, using a pyranometer and calculating the solar aperture, R. There are two main methods for calculating the solar aperture and therefore the solar corrected HLC. The first is through multiple regression analysis where Q_{elec} is the dependent variable and the daily average temperature difference, ΔT, and solar irradiance, S are the independent variables. The second is the 'Siviour method' where Equation 2 is rearranged as follows:

Equation 3: Energy balance for the 'Siviour method'

$$\frac{Q_{elec}}{\Delta T} = HLC - \frac{S}{\Delta T} \cdot R$$

The HLC is then determined by plotting a graph of the daily average values of the $Q_{elec}/\Delta T$ at the y-axis and the S/ΔT at the x-axis and fitting a regression line. The HLC is the intercept of the line at the y-axis and the solar aperture, R, is the slope of the line (Johnston et al., 2013).

There is no specific requirement on the duration of the test, however Johnston et al. (2013) suggested that a minimum of 1 week is expected after a building has been thermally saturated (i.e. reached quasi-steady state) ranging to 3 weeks depending on the construction type and the weather conditions, while Stamp (2015) reported on duration of published tests varying from 6 to 32 days.

BS ISO 9869-1:2014 – Average method

BS ISO 9869-1:2014 describes the procedure for determining the U-values of building elements in-situ with the use of heat flow meters. The average method is based on the assumption that after a significant amount of time, the average values of the temperature and density of heat flow rate are approaching steady state conditions (BSI, 2014). The analysis is based on dividing the mean heat flux through a building element by the mean temperature difference between the internal and external side of that element over a long period of time (Equation 4). The duration of the test is determined by specific criteria that have been set to assume quasi-static conditions are met; the test is completed once the resistance value obtained over different sub-periods of the whole test period does not deviate more than ±5% (BSI, 2014).

Equation 4: Thermal transmittance (ISO 9869-1:2014 average method)

$$U = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n} (T_{ij} - T_{ej})}$$

Where:

- U = thermal transmittance of the building element (W/m^2)
- q_j =density of heat flow rate at time step j (W/m^2K)
- T_{ij}, T_{ej} = internal and external environmental temperature at time step j (K)

In practice, when both internal and external temperatures fluctuate on a daily basis, it may be difficult for these criteria to be met which may result in significantly long testing periods. However, when this method is applied when a coheating test is performed (i.e. internal temperature remains stable) the required testing period to meet the criteria is reduced (Stafford et al, 2014). In any case the minimum (normative) test duration is 3 days for the most favourable conditions and lightweight elements.

2.2. The QUB/e test

The QUB/e method is a dynamic method developed by Saint-Gobain to determine the HLC of a building and the U-values of building elements in a single night without occupancy. The QUB/e test commences after sunset and finishes before sunrise of the following day (Figure 1 (left)). The principle of the method to determine the HLC is based on a single resistance and capacity model where the building is represented by a global thermal resistance R (the reciprocal of HLC of the building) and a global capacitance, C (the internal heat capacity) (Mangematin et al., 2012; Pandraud and Fitton, 2013; Pandraud et al., 2013). Internal and external temperature nodes (T_{int} and T_{ext}

respectively) are considered homogeneous and heat exchange between the two nodes occurs through the thermal resistance, R. Therefore, the energy input, P, is heat lost through the envelope and stored/released by the thermal mass of the fabric. This is described as follows:

Equation 5: Energy balance for an RC model

$$P = \frac{T_{int} - T_{ext}}{R} + C\frac{dT_{int}}{dt}$$

In the above equation there are two unknowns R (i.e. the reciprocal of the HLC) and C. The HLC of a building can then be determined by using two different constant powers in two different phases (respectively noted 1 and 2) and solving Equation 5 (Pandraud et al., 2014). To achieve this, the test comprises two phases of equal duration; the heating phase (phase 1) when a constant power, P_1, is injected to the dwelling and the cooling phase (phase 2) when the building is typically allowed to cool down (i.e. $P_2 \approx 0$). The temperature and power profile during the two phases of a QUB test is presented in Figure 1 (right) below.

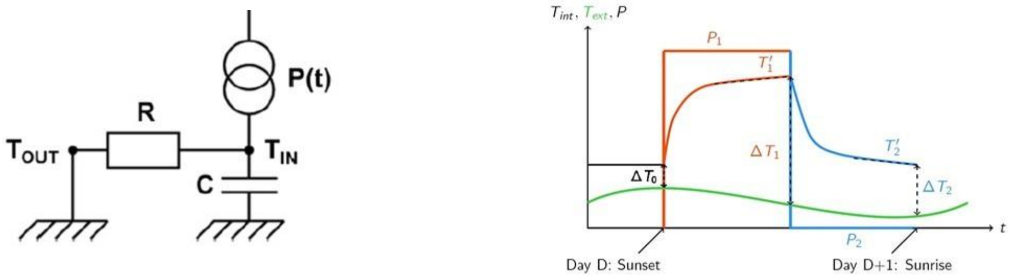

Figure 1: RC model used in the QUB method (left) and evolution of temperature and power during a QUB measurement (right)

The HLC is provided by the following formula (Meulemans et al., 2016):

Equation 6: Heat Loss Coefficient (QUB/e method)

$$HLC = \frac{T_2'P_1 - T_1'P_2}{T_2'\Delta T_1 - T_1'\Delta T_2}$$

Where:

- P_i = Power input during phase i (W)
- T'_i = Slope of the temperature profile at the end of phase i (defined as the t_i – min(t_i/2,τ), where t_i is the duration of the ith phase and τ = 2 hours)
- ΔT_i = Internal to external temperature difference at the end of phase i (K)

The same analysis method is applied to determine the U-value of building elements by substituting in Equation 6 the density of heat flow rate at the surface of the element (instead of the power) and the temperature in the vicinity of the surface (instead of the ambient temperature) (Meulemans et al., 2016):

Equation 7: Thermal transmittance (QUB/e method)

$$U = \frac{T_2'q_1 - T_1'q_2}{T_2'\Delta T_1 - T_1'\Delta T_2}$$

Where:

- q_i = density of heat flow rate in phase i (W/m^{2}K)
- T'_i = the slope of the temperature profile in the vicinity of the element surface in phase i
- ΔT_i = temperature difference between this internal temperature and the external temperature (K).

The Taylor series method for uncertainty propagation (Coleman & Steele, 2009) is used to compute the relative uncertainty associated to the HLC and the U-values.

The accuracy of the method is dependent on a dimensionless parameter inherent to the QUB method, the α-parameter (Pandraud et al., 2014). This is determined by:

Equation 8: α-parameter

$$\alpha = 1 - \frac{HLC_{ref}\Delta T_0}{P_1}$$

Where,

- HLC_{ref} = the reference Heat Loss Coefficient (theoretical or determined experimentally) (W/K),
- ΔT_0 = the initial temperature difference between the interior and the external environment (K) as shown in Figure 1 (right)
- P_1 = the power input during the heating phase (W).

It has been demonstrated that the α-parameter has minimum effect on the resulting HLC for values $0.4 < \alpha < 0.7$, while for $\alpha > 0.7$ there is usually an overestimation of the HLC mostly at very short tests (Pandraud et al., 2014; Meulemans et al., 2016, Sougkakis, 2017). Hence, meeting this criterion is considered a measure of confidence level for test accuracy.

3. MATERIALS AND METHOD

The tests were carried in a detached house located at 6, Green Close, at the Creative Energy Homes site at the University of Nottingham Park Campus. The house was completed in 2008 and achieved level 4 of the UK's Code for Sustainable Homes. The design of the house considered a fabric first approach; the walls and roof had a design U-value of 0.15W/m²K. Ground floor walls were built with Insulating Concrete Formwork (ICF) construction and the first floor walls and roof were constructed with timber Structural Insulated Panels (SIPs). The south façade is a sunspace with internal and external fully glazed surfaces. The north wall has small windows while the east and west walls do not have any windows (BASF, no date). The ground and first floor plans of the house are presented in Figure 2 below.

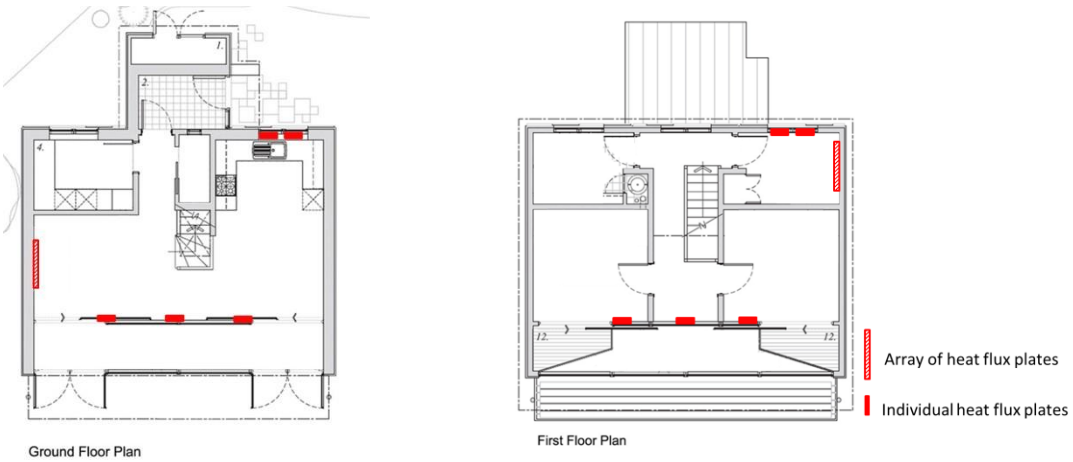

Figure 2: Ground floor (left) and first floor plan (right) of the test house and location of heat flux sensors

In order to perform the quasi-static and dynamic tests the following parameters were required to be monitored: internal ambient temperatures in the different zones, external air temperature, heat flux at the surface of the building elements of interest, temperature at the vicinity of these elements and power input. During the coheating test, temperatures at the different locations were measured with the use of Platinum RTD sensors (PT100) and the heat flux was measured with the use of HUKSEFLUX HFP01 sensors. Heat flux sensors were installed at the ground and first floor walls (an array of heat flux sensors was installed in each wall area to obtain an average U-value), the external windows and the internal sunspace windows as shown in Figure 2. The energy consumed by the heaters was monitored by pulse meters. Data were stored in two Datataker DT85 loggers with two CEM-20 expansion modules. Two Skye SKS-1110 pyranometers were installed externally in the south façade in order to obtain an average measurement of the south facing vertical solar irradiance. This was then used to account for the solar gains in the resulting HLC.

The QUB/e measurement was performed with the use of the prototype kit developed by Saint-Gobain. This comprises wireless Fibaro sensors to measure air temperatures and Fibaro wall plugs for measuring power input in order to determine the HLC of the building. The U-values during the QUB/e measurements were derived using data from the same heat flux plates and temperature sensors that were used at the coheating test in order to compare the U-values determined with the two methods at exactly the same locations. The schedule for each set of measurements is presented in Table 1 below.

Table 1: Testing schedule of quasi-static and dynamic measurements

	From	To
Quasi-static measurements (coheating, ISO 9869-1:2014)	04.11.17	26.11.17
Dynamic measurements (QUB/e)	27.11.17	19.12.17

The coheating test was conducted in November 2017 over a period of 22 days. As the south façade had such a large area of glazing, special consideration had to be given to minimise the effect of solar gains through the sunspace. It was considered that the dwelling could be subject to great swings in solar gains, and at times of high solar radiation, this heat gain could dominate the heat input to the dwelling, which may lead to difficulties maintaining the internal fixed temperature. It was therefore decided in order to mitigate this effect that the blinds in the external glazing of the sunspace would be kept closed while windows that did not have blinds would be covered with aluminium foil to reflect incoming radiation. In addition, the top windows were left open (Figure 3). Therefore, the heated area of the house did not include the sunspace. This arrangement was kept the same throughout the whole course of the quasi-static and dynamic measurements.

Figure 3: External view of the south façade of the dwelling with the location of the pyranometers. Most glazed areas were covered to minimise the effect of solar radiation

4. RESULTS AND DISCUSSION

To determine the HLC of the house, recorded data of ambient temperatures (internal and external), power consumption of heaters and south vertical solar radiation were averaged on a daily basis. This resulted in obtaining 22 data points for the analysis during the coheating test. In order to smooth the effects of thermal mass, data were aggregated from 06:00 am until 05:59 am the following morning in order to allow for solar gains to be readmitted back to space (Everett, 1985, Johnston et al, 2013). The result of the coheating test using Multiple Linear Regression analysis is presented in Figure *4* below. The south vertical irradiance measured was used as the independent variable. For better visualisation in a 2-D diagram, the solar aperture calculated by the MLR analysis was multiplied by the daily average solar irradiance measured to determine the average daily solar gains. These gains were then added to the average daily power consumed by the heaters. In other words, the y-axis of Figure *4* represents the sum of electrical power and the solar gains (Q_{elec} and Q_{solar} in Equation 1). MLR analysis in general has been reported as statistically better in correcting the HLC for solar gains than Siviour Analysis as it treats both solar irradiance, S, and the temperature difference ΔT as independent variables (Baker, 2015). Bauwens and Roels (2014) also recommended the use of MLR analysis as the Siviour analysis may lead to unreliable results when ΔT is close to 0 K. However, the test protocol considers a minimum ΔT of 10 K and it has been shown in literature that both methods result in very similar values HLC (Stamp, 2015).

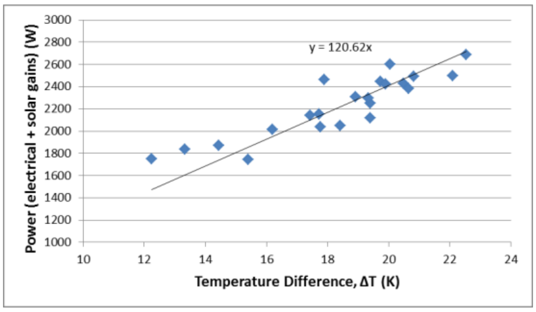

Figure 4: Multiple Linear Regression Analysis of coheating results

The HLC was found to be 120.6 ± 3.5 W/K when using the MLR analysis. This value will be referred to as HLC_{static}. For reasons of comparison, it should be mentioned that the Siviour analysis resulted to a HLC of 122.5 ± 3.8W/K which is consistent with the literature findings suggesting that the two methods lead to very similar results. As the sunspace was unheated, the internal glazing of the sunspace that was the boundary of the heated space was not in direct contact to the external conditions (despite the fact that the windows were left open the area in the sunspace was consistently in a somewhat higher than the external temperature). For this reason the HLC_{static} was adjusted by subtracting the heat loss from that area (in W/K) as described in Equation 9. The adjusted HLC, $HLC_{static,adj}$ was 105.2 W/K ± 3.5 W/K. This is the reference quasi-static HLC against which the QUB/e results will be compared.

Equation 9: Adjusted HLC $$HLC_{adj} = HLC - U_{sunspace,eff} \cdot A_{sunspace}$$

Where,

- HLC_{adj} = the adjusted HLC that considers heat losses only from those elements in contact to the external temperature (W/K)
- $U_{sunspace,\ eff}$ = the effective U-value of the internal glazing that is in contact to the sunspace (W/m^{2}K)
- $A_{sunspace}$ = the area of the internal glazing that is in contact to the sunspace (m^2)

With regards to the dynamic tests, in total 20 QUB/e tests were performed between November and December 2017. In all these tests the power input and the internal temperature were controlled such as to keep the α – parameter within the recommended limits (0.4 < α < 0.7) and therefore all results were considered reliable. The HLC was calculated on a daily basis (HLC_{QUB}). The average HLC_{QUB} from all QUB/e tests was found 114.0 ± 2.9 W/K. The adjusted HLC ($HLC_{QUB,adj}$) was then determined by subtracting the heat losses to the sunspace according to Equation 9. The average $HLC_{QUB,adj}$ was 97.2 ± 2.8 W/K This was in good agreement with the coheating results; the relative difference between $HLC_{QUB,adj}$ and $HLC_{static,adj}$ was 7.6%. Results plotted against the dimensionless parameter α are shown in Figure 5 below.

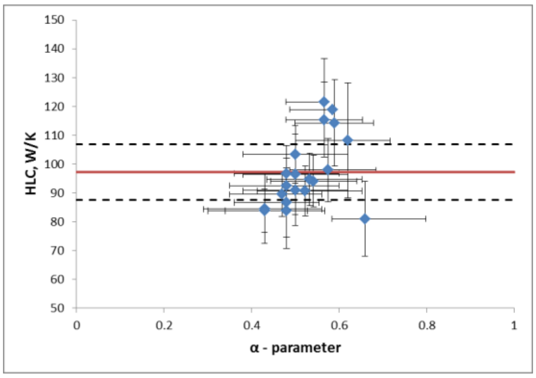

Figure 5: Summary of QUB/e results plotted against the a-parameter

It should be noted that each data point in Figure 5 shows the HLC calculated for that night (in contrast to Figure *4* where one HLC is calculated from all data). The average HLC of the QUB/e tests is shown with the red solid horizontal line in Figure 5; the black dashed lines represent the ±10% deviation from the mean. It can be seen that most of results fell within the ±10% band (or very close to it) with a few occasions where this was slightly higher (in one instance reaching +20%). This was consistent with the findings reported in a previous study regarding the repeatability of the method in a poorly insulated property of masonry construction under two different levels of airtightness (Sougkakis, 2017). It also suggests that repeatability of the QUB/e method was similar regardless of the levels of insulation of the building investigated. However, further work will be required in order determine whether the larger deviations were the result of specific weather conditions. With regards to the α-parameter calculation, the HLC_{static} determined with the coheating test was used as the HLC_{ref} in Equation 8.

To determine the elemental performance, heat flux sensors were installed at the external walls, the external window panes and the internal glazing of the sunspace in each floor. The U-value was then calculated considering the procedure set by BS ISO 9869-1:2014 and the QUB/e analysis (Equation 4 and Equation 7 respectively). In order to comply with the ISO 9869 requirements, U-values from heat flux sensors that were installed on areas away from thermal bridges are reported here, i.e. at clear wall areas and centre of pane (in the case of glazing U-values). In total, 17 heat flux sensors were installed in locations away from thermal bridges; 7 on the walls, 4 on the external windows and 6 on the internal glazed areas. The U-values calculated with the two methods are presented in Figure 6 and Figure 7 below. In the graphs the x-axis shows the ISO-9869 U-values and the y-axis the QUB/e U-values. This allows visualising where the QUB/e values stand compared to the quasi-static ones. The red dashed lines show the ±28% uncertainty limits of the U-value calculation suggested by the ISO Standard. For ease of comparison the x=y line was also plotted (diagonal). Similarly to reporting HLC values, the static method (ISO 9869) resulted in one U-value for each sensor; the whole testing period was chosen for the analysis in order to increase confidence on the results (as averaging of the heat flows and temperatures would be over a large period of time) and also to obtain the U-values from all sensors over the same averaging period. In most cases the ISO 9869 criteria were met within 4 days, while in one case after 7 days of testing. On the other hand the QUB/e method was able to determine the U-values on a daily basis (i.e. 20 results per sensor were obtained during the dynamic testing period).

Results from the sensors installed at the ground floor and first floor walls are shown in Figure 6 (left and right respectively). It can be seen that in the first floor wall (Structural Insulated Panel construction) there was very good agreement between the dynamic and quasi-static results since the QUB/e U-values were very close to the quasi-static ones both in terms of mean value from all tests as well as the individual values and well within the uncertainty limits. With regards to the ground floor wall (Insulating Concrete Formwork construction) it can be seen that there was also good agreement between the two methods, however there was larger dispersion of the dynamic U-values. As a result, the average dynamic U-value was very close to the quasi-static one but the individual values had a larger deviation from the mean. Nevertheless, in almost all cases the QUB/e U-values were within the ±28% uncertainty band. It is believed that the larger dispersion observed on the ICF wall is due to the increased levels of thermal mass of this construction type compared to SIP panels; however, further work is required to verify this.

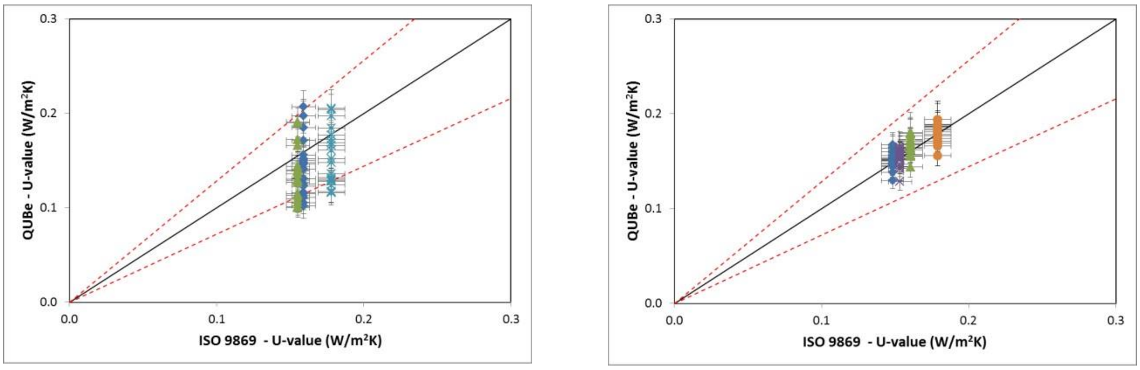

Figure 6: U-values of the ground floor wall (left) and the first floor wall (right) determined with the ISO-9869 and QUB/e method

The U-values determined at different locations of the external windows and the internal curtain wall of the sunspace is presented in Figure 7; these are all centre of pane U-values. It should be noted that the U-values obtained for the internal sunspace glazing presented here were in fact the actual U-values (not the effective U-values used in Equation 9); these were calculated considering the temperature difference between the heated space and the unheated sunspace in the vicinity of the glazing. It can be seen that in all cases there is good agreement between the two methods as the dynamic U-values were quite close to the quasi-static ones at all times and well within the uncertainty limits. This was particularly the case for the internal glazing of the sunspace where the external temperature considered (i.e. the temperature in the sunspace) was more stable than the actual external temperature. The internal curtain wall of the sunspace consisted by double glazed panels and two opaque uPVC panels to ensure privacy in the bedrooms. In total six sensors were installed on the curtain wall, four on the glazed panels and two on the uPVC panels (that are marked separately in Figure 7 (right)).

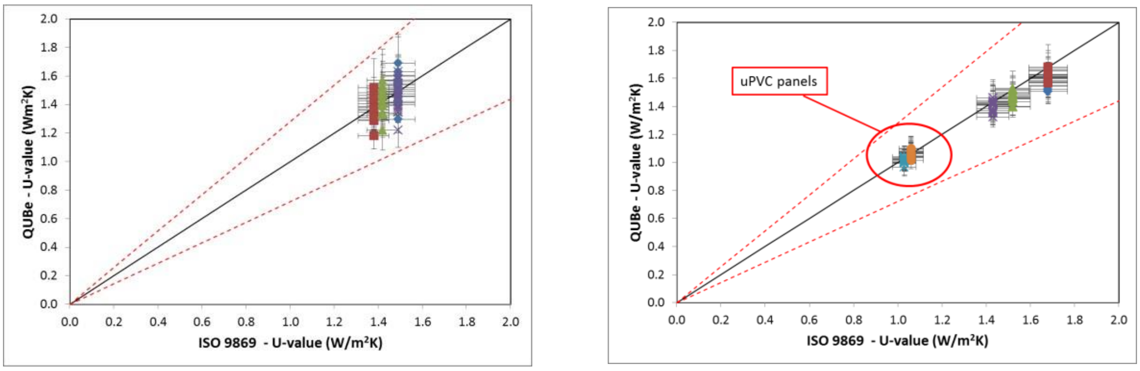

Figure 7: U-values of external windows (left) and internal sunspace glazing and panels (right) determined with the ISO-9869 and QUB/e method

The average U-values for each building element determined with the two methods are shown in Table 2. It can be seen that both methods result in very similar U-values. The maximum relative difference was observed in the ground floor wall (ICF) where the QUB/e method underestimated the U-value by approximately 12.5%. Practically the same U-values were observed for the first floor wall (SIP), the internal sunspace curtain wall and the external windows (centre of pane). A maximum relative difference of about ±2% was observed. It should also be noted that there does not appear systematic overestimation or underestimation of U-values when using the QUB/e method.

Table 2: Average U-values determined with the ISO 9869 and the QUB/e method

	ISO 9869 U-value (W/m²K)			QUB/e U-value (W/m²K)			Relative difference
Ground Floor wall	0.16	±	0.03	0.14	±	0.01	-12.5%
First Floor Wall	0.16	±	0.02	0.16	±	0.00	1.4%
External windows	1.44	±	0.20	1.44	±	0.02	-0.3%
Internal sunspace glazing	1.58	±	0.22	1.545	±	0.01	-2.0%
Internal sunspace vinyl panels	1.04	±	0.21	1.04	±	0.00	-0.74%

5. CONCLUSIONS

The findings from an in situ monitoring study conducted to assess the performance of the QUB/e method under actual operating conditions against more widely used quasi-static methods was presented in this paper. The QUB/e method is able to estimate the HLC of a building and the U-values of building elements within just one night, significantly less than the 2-4 week period required for a coheating test or other quasi steady-state methods (Janssens, 2016). The performance of the QUB/e method was assessed in a well-insulated detached dwelling located in the University Park campus, University of Nottingham from November until December 2017. The objectives of the study were to:

- Assess the HLC of the house derived with the QUB/e method and compare against that obtained with a coheating test;
- Evaluate the ability of the method to provide reliable and consistent results on a daily basis in a dwelling with high levels of insulation for the UK weather conditions;
- Assess the U-values of external building elements obtained with the QUB/e method against those obtained using the average method of BS ISO 9869-1:2014.

Results suggest that the method was able to provide reliable results in terms of both the whole building HLC and the building element U-values. On average the relative difference between the corrected HLC calculated with the coheating and the QUB/e test was 7.6%. In addition, the QUB/e method was found to have reasonable repeatability since most results were within ±10% from the mean with some cases within ±15%. This was consistent with previous findings reported by Sougkakis et al. (2017) from the in situ study conducted in a poorly insulated property, suggesting that the method had similar levels of performance regardless of the levels of insulation. In addition, the U-values determined were very close to those obtained with the average method of the BS ISO 9869-1:2014 Standard; a maximum of 12.5% relative difference was observed on average in one wall, while in the rest of building elements (SIP wall and glazed surfaces) the U-values were practically the same on average (with maximum difference of approximately 2% between the two methods). Some degree of variation was observed on a daily basis but the values were well within the uncertainty limits the suggested by the ISO Standard. These results were consistent with previous findings reported by Meulemans (2018) from in situ measurements (QUB/e and ISO 9869-1) undertaken in a multi-storey residential building in Sweden.

Therefore, the QUB/e method is considered to have performed well in comparison to the quasi- static methods for determining both the whole building HLC and element performance.

The QUB/e method is less intrusive and requires much shorter period than the conventional long-term quasi-static methods. Consequently, the QUB/e method allows for obtaining a series of results on a building’s performance parameters on a daily basis during a specified testing period (rather than obtaining one result over the whole testing period that is the case with the coheating and ISO-9869 method). Furthermore it is able to derive both the building’s HLC and U-values in-situ, while a separate method is required to determine each of these parameters using the conventional quasi-static methods. For these reasons, the method has great potential as a research tool as well as a building diagnostics tool to be used by industry. The findings of this work, the first field study in a well-insulated property in the UK, support previous evidence and increase confidence on the ability of the QUB/e method to provide reliable results in the field. Additional work is required to evaluate the effect of the weather conditions on the resulting HLC and U-values, particularly the effect of the wind and temperature that has been shown previously in an uninsulated property that is a factor which may affect the results. Furthermore, similar studies in buildings that are more representative of the current building stock in the UK will be useful for the wider verification of the results and the broader acceptance of the method by researchers and building performance practitioners.

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7. REFERENCES

ALZETTO, Florent, GOSSARD, Didier, PANDRAUD, Guillaume, 2014. Mesure rapide du coefficient de perte thermique des bâtiments. Proceedings of Ecobat Sciences et Techniques. Paris, France

ALZETTO, Florent, FARMER, David, FITTON, Richard, HUGHES, Tara, SWAN, Will, 2018a. Comparison of whole house heat loss test methods under controlled conditions in six distinct retrofit scenarios. Energy and Buildings, 168, pp 35 – 41

ALZETTO, Florent, PANDRAUD, Guillaume, FITTON, Richard, HEUSLER, Ingo, SINNESBICHLER, Herbert, 2018b. QUB: a fast dynamic method for in-situ measurement of the whole building heat loss. Energy and Buildings, (Accepted manuscript)

BAKER, Paul, 2015. A retrofit of a Victorian terrace house in New Bolsover: A whole house thermal performance assessment. Tech. rep. Historic England & Glasgow Caledonian University.

BASF, no date. Building a Sustainable Future: The BASF House - UK Project [online], BASF plc. Available at: www.nottingham.ac.uk/creative-energy-homes/documents/basfhousebrochure.pdf [Accessed: 14th June 2018]

BAUWENS, Geert, ROELS, Staf, 2014.Co-heating test: A state-of-the-art. *Energy and Buildings*,82,pp 163– 172

BSI, 2014. BS ISO 9869-1:2014 - Thermal insulation – Building elements – In situ measurement of thermal resistance and thermal transmittance - Part 1: Heat flow meter method.

COLEMAN, Hugh W. and STEELE, Glenn W., 2009. *Experimentation, Validation, and Uncertainty Analysis for Engineers*. John Wiley & Sons, Inc., Hoboken, New Jersey.

DBEIS, 2016. Digest of United Kingdom Energy Statistics (DUKES) - Energy: Chapter 1. Department for Business, Energy and Industrial Strategy

DECC, 2014. The Government's Standard Assessment Procedure for Energy Rating of Dwellings 2012 edition. Garston: BRE

EVERETT, Robert, 1985. Rapid Thermal Calibration of Houses; Open University Energy Research Group: Milton Keynes, UK, 1985.

JANNSENS, Arnold, 2016. Overview of Methods to Analyse Dynamic Data. International Energy Agency, EBC Annex 58, Reliable building energy performance characterisation based on full scale dynamic measurements. Leuven: KULeuven

JOHNSTON, David, MILES-SHENTON, Dominic, FARMER, Dave and WINGFIELD, Jez, 2013. Whole House Heat Loss Test Method (Coheating). Leeds (UK): Leeds Metropolitan University

MANGEMATIN, Eric, PANDRAUD, Guillaume and ROUX, Didier, 2012. Quick measurements of energy efficiency of buildings. Comptes Rendus Physique, 13 (4), pp. 383–390.

MEULEMANS, Johann, ALZETTO, Florent, FARMER, David and GORSE, Christopher, 2016. QUB/e – A novel transient experimental method for in situ measurements of the thermal performance of building fabrics. In: Gorse, C. and Dastbaz, M. (eds), International SEEDS conference 2016: Sustainable Ecological Engineering Design for Society, 14-15 September, 2016, Leeds (UK). Leeds (UK): Leeds Beckett University

MEULEMANS, Johann, 2018. An assessment of the QUB/e method for fast in situ measurements of the thermal performance of building fabrics in cold climates. In: The 9th International Cold Climate Conference - Cold Climate HVAC 2018 – Sustainable Buildings in Cold Climates, 12-15 March 2018, Kiruna (Sweden).

PANDRAUD, Guillaume and FITTON, Richard, 2013. QUB: Validation of a Rapid Energy Diagnosis Method for Buildings. In: IEA–EBC Annex 58, 4th Expert meeting, 8–10 April 2013, Holzkirchen (Germany)

PANDRAUD, Guillaume, MANGEMATIN, Eric, ROUX, Didier. and QUENTIN, Emilie,2013. QUB: a new rapid building energy diagnosis method. In: Kabele, K., Urban, M., Suchý, K. and Lain, M. (eds), Proceedings of CLIMA 2013, the 11th REHVA World Congress and the 8th International Conference on IAQVEC, 13–19 June 2013, Prague (Czech Republic). Prague (Czech Republic): Society of Environmental Engineering (STP).

PANDRAUD, Guillaume, GOSSARD, Didier and ALZETTO, Florent, 2014. Experimental optimization of the QUB method. In: IEA–EBC Annex 58, 6th Expert meeting, 14–16 April 2014, Ghent (Belgium)

SOUGKAKIS, Vasileios, MEULEMANS, Johann, ALZETTO, Florent, WOOD, Chris, GILLOTT, Mark and COX, Tom, 2017. An assessment of the QUB method for predicting the whole building thermal performance under actual operating conditions. In: Gorse, C. (Ed.) International Sustainable Ecological Engineering Design for Society (SEEDS) Conference 2017–Conference Proceedings, 13–14 September 2017, Leeds (UK). Leeds Beckett University.

STAFFORD, Anne, JOHNSTON, David, MILES-SHENTON, Dominic, FARMER, Dave, BROOKE-PEAT, Matthew and GORSE, Christopher. Adding value and meaning to coheating tests. Structural Survey, 32(4):331–42, 2014.

STAMP, Samuel, 2015. Assessing Uncertainty in co-heating tests: Calibrating a whole building steady state heat loss measurement method. PhD thesis, University College London.