AN ASSESSMENT OF THE QUB METHOD FOR PREDICTING THE WHOLE BUILDING THERMAL PERFORMANCE UNDER ACTUAL OPERATING CONDITIONS

Vasileios Sougkakis[1], Johann Meulemans[2], Florent Alzetto[2], Chris Wood[1], Mark Gillott[1] and Tom Cox[3]

[1]Faculty of Engineering, The University of Nottingham, University Park, Nottingham NG7 2RD, UK

[2]Saint-Gobain Recherche, 39 quai Lucien Lefranc B.P. 135, F-93303 Aubervilliers, France

[3]Saint-Gobain Delegation UK & Ireland, East Leake, Leicestershire, LE12 6HX, UK

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Abstract

The performance gap between the design and the as-built thermal performance of buildings is an issue of high importance for the construction industry and reducing this gap has been the subject of significant research. Assessing the design thermal performance is straightforward; however estimating the as-built performance of a building presents several technical challenges that often restrict its wider implementation. One of the most common challenges is the time required to perform such testing. The QUB method is a transient method developed to estimate the Heat Loss Coefficient (HLC) in a single night without occupancy. The ability of the method to provide reliable results was demonstrated experimentally in a climate chamber with controlled conditions in a previous work.

The work presented in this paper reports on the findings from a long-term field study conducted in order to assess the applicability of the QUB method under actual operating conditions and to identify key parameters that may affect its performance. A series of tests were performed during the whole heating period in a detached house located in the University Park campus, University of Nottingham considering two distinct conditions: as-built and with increased air tightness. The results suggest that the QUB method was able to estimate the HLC of the house with reasonable repeatability in both cases. The reliance of the results to the experimental conditions that may affect the test is also discussed in order to improve the robustness of the method.

INTRODUCTION

Energy consumption of the domestic sector in the UK accounted for 27% of the nation's final energy consumption in 2015 (DBEIS, 2016). It therefore comes as no surprise that building regulations have been setting increasingly stricter requirements on the insulation levels of buildings as a result of the UK policy on climate change. Under the Climate Change Act, the UK government set the legally binding target to reduce its greenhouse gas emissions by 80% in 2050 compared to the 1990 emissions levels (DECC, 2011). Despite the increasing regulatory requirements, there exists a growing body of evidence suggesting that there is a significant difference between the design and the as-built performance of new UK buildings; this is commonly called 'performance gap' (Zero Carbon Hub, 2014).

Assessing the design thermal performance of the building fabric is quite straightforward; the UK methodology for this is provided by the Government's Standard Assessment Procedure (SAP) (DECC, 2014). The calculation is based on the energy balance of the dwelling and it takes into account factors such as U-values and respective areas of building elements, thermal bridges and the dwelling infiltration characteristics to determine the Heat Loss Coefficient (HLC), expressed in W/K, of the building fabric. A typical energy formula of the different mechanisms that determine the HLC is given in Eq.1.

$$HLC = \sum U_i \cdot A_i + H_{TB} + \rho \cdot c_p \cdot Q_v \text{ , with}$$

$$Q_v = \sqrt{Q_s^2 + Q_w^2} = \frac{A_L}{1000} \cdot \sqrt{C_s \cdot |\Delta T| + C_w \cdot U_w^{\,2}} \qquad (1)$$

Where, U_i is the U-value (W/m^{2}K) of element i with area A_i (m^2) and H_{TB} is the heat loss from thermal bridges (W/K). Collectively, these terms account for the transmission losses. Infiltration losses are determined by the product of the air density (kg/m^3), the specific heat capacity of air, c_p, (J/(kgK)) and the volumetric flow rate, Q_v, (m^3/s). Q_v is a combination of the stack driven flow rate, Q_s, and the wind driven one, Q_w. Here, the model developed by Sherman and Grimsrud (1980), also referred to as the 'Basic model' by ASHRAE is considered (ASHRAE, 2013). These properties are dependent on the stack, C_s ((L/s)^2/(cm^{4}K)), and wind coefficient, C_w ((L/s)^2/[cm^4(m/s)^2]) , respectively A_L (cm^2) is the effective leakage area at 4Pa, U_w is the wind speed (m/s) and ΔT (K) is the internal to external temperature difference.

On the other hand, several methods have been developed to assess the thermal performance of a building's fabric experimentally (Janssens, 2016). The most widely used method is the coheating method, a quasi-steady state method that provides an estimate of the HLC of a building. The procedure for the coheating test is described by Johnston et al. (2013). In practice, determining the as-built HLC of a building with a coheating test is quite challenging due to the required duration of the method (a testing period of a minimum of two weeks is usually required) and the fact that it is restricted to the heating season where external temperatures remain consistently low and the effect of solar gains is minimised.

QUB method

The QUB method is a dynamic method developed by Saint-Gobain to determine the as-built HLC of dwellings within a much shorter period. The test commences after sunset and finishes before sunrise of the following day (Figure 1). The principle of the QUB method is based on a single resistance and capacity model (left)) (Mangematin et al., 2012; Pandraud and Fitton, 2013; Pandraud et al., 2013) 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) (Figure 1 (left)). Internal and external temperature nodes (T_{IN} and T_{OUT} respectively) are considered homogeneous and heat exchange between the two nodes occurs through the thermal resistance, R. Therefore, the energy input, P(t), is heat lost through the envelope and stored/released by the thermal mass of the fabric (Eq. 2). Temperature evolution is described as a single decaying exponential.

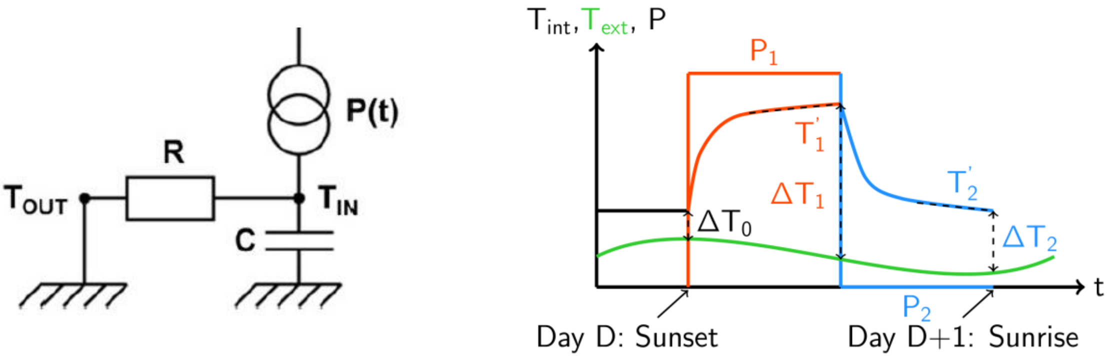

Figure 1: RC model used in the QUB method (left) and evolution of temperature and power during a QUB measurement (right)

$$P=\frac{T_{IN}-T_{OUT}}{R}+C\frac{dT_{IN}}{dt} \qquad (2)$$

The two unknowns, R and C in Eq.2, can then be determined by using two different constant powers in two different phases (respectively noted 1 and 2 in Figure 1 (right)).The HLC can then be determined by the following formula:

$$HLC=\frac{T'_2P_1-T'_1P_2}{T'_2\Delta T_1-T'_1\Delta T_2} \qquad (3)$$

Where P_i is the power input during phase i, T'_i is the slope of the temperature profile at the end of phase i (defined as the $t_i - \min(t_i/2,\tau)$, where t_i is the duration of the ith phase and τ = 2 hours) and ΔT_i is the internal to external temperature difference ($T_{IN} - T_{OUT}$) at the end of phase i (Meulemans et al., 2016).The Taylor series method for uncertainty propagation is used to compute the relative uncertainty associated to the HLC. For increased accuracy it is aimed that the test is carried in an empty unoccupied dwelling without additional heat sources and in most cases there is no power input in phase 2 (P_2 = 0 W), i.e. this is the free cooling phase.

The HLC of a building can be estimated in one night using the QUB method (Pandraud et al., 2014). This makes it suitable for large scale use by industry to test the actual performance of buildings. Furthermore, it is a research tool since it allows a large number of consecutive tests to be performed in a short period of time. However, there are some issues that need to be considered for increasing confidence on a measurement. As described earlier, the model assumes homogeneous internal temperature. In practice, this means that care should be taken when arranging the power input and location of heaters inside the building. Furthermore, as the method is able to estimate the HLC within one night, the result may be affected by the weather conditions within that night; evaluating the effect of certain weather parameters was the scope of this work.

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

$$\alpha=1-\frac{HLC_{ref}\Delta T_0}{P_1} \quad (4)$$

Where HLC_{ref} is the reference Heat Loss Coefficient (theoretical or determined experimentally) (W/K), ΔT_0 is the initial temperature difference between the interior and the external environment (K) and P_1 is the power input during the heating phase (W). It has been demonstrated that the α-criterion has no 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). Hence, the α-criterion is considered as a measure of confidence level for test accuracy with recommended values 0.4-0.7.

Aim of work

The ability of the QUB method to provide reliable results, has been demonstrated numerically (Alzetto et al., 2014) and experimentally in a climate chamber under steady conditions (Meulemans et al., 2016). The aim of the work presented here was to evaluate the performance of the method under actual operating conditions, i.e. assess reproducibility of results and identify reliance of the method on specific weather and testing conditions.

MATERIALS AND METHOD

The tests was carried in a circa 1950s detached house located at 5, Wortley Close at the University Park Campus, University of Nottingham. The property, designed by Thomas Cecil Howitt, is a two storey L-shaped detached house. The wall construction is a 50 mm unfilled masonry cavity and the floor is solid uninsulated concrete slab. It has a cold pitched roof with insulation at ceiling level and the windows are single glazed. The house has North – East Orientation and ground floor area of approximately 93m^2. A view of the house and the plans for the ground and first floor are shown in Figure 2**Error! Reference source not found.** below.

Monitoring equipment

In order to perform a QUB test the following parameters need to be monitored: zone air temperatures, external air temperature and the power input. Air temperatures were monitored with platinum RTD sensors (PT100) and the energy consumed by the heaters was monitored by pulse meters. Data were stored in two Datataker DT85 loggers and a DT80 logger at 1 minute intervals. Weather conditions were recorded with a WSD1 sensor by EML and a Skye rht^{+} sensor installed on the roof of a neighbouring house.

Figure 2: External view (left) and Ground and First Floor plans(right)

Testing protocol

The HLC of the house was determined under two different airtightness configurations: a) baseline (as-built including minor interventions, i.e. repairing of broken window glass by applying boarding) and b) with increased airtightness by applying polyethylene films across the entire window reveals, in order to prevent air leakage through the old window frames (Figure 3). The air permeability at 50 Pa, q_{50} (in m^3/m^{2}h), was measured by performing a blower door test (ATTMA, 2016). It was found to be 9.3 and 6.5 m^3/m^{2}h for the baseline configuration and for the increased airtightness configuration, respectively.

The house was heated by means of STANLEY 2 kW fan heaters controlled by timers. The timers were programmed to switch on the heaters after the sunset of each day and switch them off several hours later at the end of the heating phase (Phase 1 in Figure 1). Each test was then completed at the end of Phase 2 (of same duration as Phase 1) before the sunrise of the following day. A constant power input, P_1, of approximately 11 kW was used throughout the whole testing period. This was the maximum allowable power input imposed by the electrical installation of the house. In order to maintain a desired temperature inside the house prior to each test, a second set of STANLEY heaters controlled by thermostats and timers was also installed. It was attempted that each test would be conducted with an α-value within the recommended range ($0.4 < \alpha < 0.7$) in order to ensure measurement accuracy and avoid systematic overestimation of the HLC. As the power input was kept constant due to restrictions of the electrical installation, this effectively meant that the starting internal temperature was adjusted with respect to the external one.

The house was tested on a daily basis from the end of September 2016 until the end of April 2017 with minor interruptions during this period. Due to the fact that the duration of the night changed over the different months, the duration of the QUB test was also amended. However, the minimum duration of the heating phase at any test was five hours (i.e. the minimum test duration was ten hours as the test consists of two phases of equal duration);

it has been demonstrated that for heating duration higher than 4 hours the results were not affected by the α-criterion for $0.4 < \alpha < 0.7$ (Meulemans, 2016). The different configurations as well as the different test durations are shown in Table 1. In total 161 tests were conducted, out of which 146 (i.e. 91%) lied within the recommended values.

Figure 3: Polyethylene film applied on windows to increase the air tightness of the fabric

Table 1: Test configuration and heating duration

Configuration	Airtightness q_{50} (m^3/m^2h)	Number of tests	Period	Heating duration
Baseline	9.3	58	22.09 – 10.11.2016	5 hours
			11.11 – 05.12.2016	7 hours
Increased airtightness	6.5	103	07.12.2016 – 30.01.2017	7 hours
			31.01 – 21.03.2017	6 hours
			04.04 – 25.04.2017	5 hours

RESULTS AND DISCUSSION

The analysis focused on assessing the ability of the method to provide robust estimates of the HLC. The effect of α-criterion, wind conditions and external temperature were investigated.

α-criterion

Results from the first set of tests (baseline) and the associated uncertainties of measurements were calculated with the use of Eq. 3 and are presented in Figure 4. In order to determine the α-criterion, the value of the mean HLC was used as the reference HLC (HLC_{ref} in Eq.4). In total 52 QUB tests were performed for the baseline configuration that successfully met the α-criterion requirement. The mean HLC of these tests with $0.4<\alpha<0.7$ was 522.3 ± 5.2 W/K. This is shown by the red solid horizontal line in Figure 4, while the black solid lines represent the ±10% band. Some degree of fluctuation between the results was observed and the majority of tests were within ±10% from the mean value. However, there have been few occasions when the resulting HLC was slightly above this limit, while in one instance it reached 20%. For values of the α-criterion higher than 0.8 the HLC was significantly overestimated. This result is consistent with previous studies (Pandraud et al., 2014; Meulemans et al., 2016). It can be seen that there is no effect of the α-criterion on the HLC when the former lied within the range 0.4 to 0.6. A rising trend is observed with the calculated HLC when the value of the α-criterion is greater than 0.6. At $\alpha > 0.7$, the HLC was consistently within the +10% region. In addition, relative uncertainty lied within ± 10 - 15%

for the vast majority of the measurements. It was also seen that both durations yielded very similar HLC values.

The respective results for the increased airtightness configuration are presented in the right hand side of Figure 4. With regards to the increased airtightness configuration the mean HLC of 94 tests with 0.4 < α < 0.7 was found to be 508.2 ± 4.6 W/K. Reduction in the mean HLC as a result of increasing the air tightness of the building was approximately 14.1 ± 12.8 W/K. This could be attributed to the fact that the building is fairly sheltered from three sides, with just the West façade exposed. It should be noted that a simplified theoretical calculation showed an estimated reduction of the infiltration heat losses by 19.5 W/K of the increased airtightness compared to the baseline configuration (infiltration losses from 64.5 to 45 W/K). This was consistent with the reduction observed through the testing procedure.

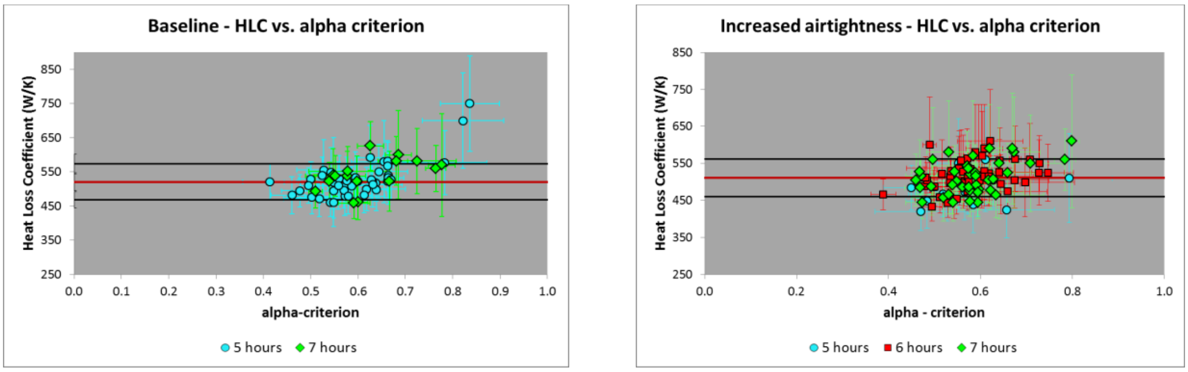

Figure 4: Summary of results against the α-criterion obtained for the baseline (left) and the increased airtightness configuration (right)

Results again appear to fluctuate around the mean HLC as with the baseline configuration and again the majority of the results falls into the ± 10% band. However, in this case they appear to be more dispersed; there are some results extending to ± 15%, with a couple of points approaching ± 20%. Again, it can be seen that there was no correlation between the α-criterion and the HLC for α values even up to 0.8. It should be noted that measurements at the increased airtightness configuration presented larger relative uncertainties than at the baseline configuration; approximately 15% on average compared to 12% for the baseline configuration. With regards to the duration of the tests it can be seen that tests with heating duration of 6 and 7 hours presented very similar results. Tests with 5-hour heating duration appeared to result similar HLC values, albeit somewhat at the lower band. However, this is the result of just 13 tests. In any case it can be derived that longer tests result in consistent HLC that have minimum reliance on the α-criterion. This is of particular importance since the α-criterion relies in turn on the HLC_{ref} (Eq. 4). Poor estimation of the HLC_{ref} may lead to high values of the α-criterion and lead to the overestimation of HLC. Therefore longer test duration provides confidence on the accuracy of the test results. In practical terms this means that a 12 hour QUB test (i.e. heating duration of 6 hours) may be performed from end of October until end of March with great confidence that the result will not been overestimated by the α-criterion. 10-hour tests also provide confidence on the results as they were affected only at very high values of the α-criterion (close to 0.85). These can be performed from end of September until end of April in the UK.

Wind

Wind conditions are likely to affect the measured heat loss coefficient of a building as expected from Eq.1. Several research studies investigated the impact of wind conditions on infiltration losses during coheating tests (Everett, 1985, Miles-Shenton et al., 2011, Siddal et al., 2011). For this reason, the effect of wind was examined under the baseline and the increased airtightness configurations in order to determine whether there is correlation between the measured HLC and the average wind speed measured.

Figure 5 shows the relationship between the HLC and the respective average wind speed for both configurations for tests where $0.4 < \alpha < 0.7$. With regards to the baseline configuration (left) it can be seen that there is no correlation between wind speed and HLC. The relationship between HLC and the average wind speed for the increased airtightness configuration is presented in the right hand side of Figure 5. In this case, more data points were available and there were some tests within a higher region of average wind speed recorded, i.e. at average wind speeds higher than 3 m/s. Similarly to the baseline configuration, there was no correlation between the average wind speed and the HLC.

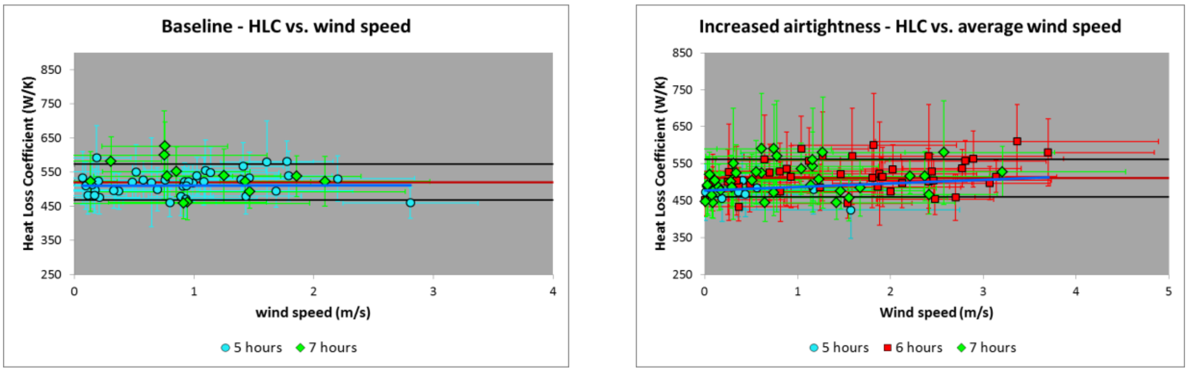

Figure 5: Effect of average wind speed on the measured HLC for the baseline (left) and the increased airtightness (right) configuration

In both cases it was found that the HLC was not related to the average wind speed and therefore, there was no scope for correcting the HLC based on this parameter. Infiltration heat losses are fairly complex and they are not solely linearly related to wind speed. Other factors such as temperature, the airtightness of the building, air leakage paths and sheltering are also affecting heat as well as mechanisms such as wind washing and thermal bypass (Sidall, 2011, Johnston et al., 2013, Stamp, 2015). The weak relationship observed here can be attributed to the fact that the building is fairly sheltered from three sides. The wind coefficient, C_w, that determines the wind flow rate in Eq. 1 depends on the shelter factor of the building and the building height (ASHRAE, 2013). Furthermore, it can be seen in Eq.1 that wind driven flow is not linear to the wind speed and becomes dominant at high wind speeds. Recorded average wind speeds were relatively low and therefore infiltration losses were mainly driven by the stack effect. Stamp (2015) reported the findings of several field tests attempting to find correlation between wind speed and the whole building HLC. It was found that in some cases there was no correlation and in some cases a relationship between these two variables could be established. The findings of this study therefore are in agreement with the ones reported by Stamp (2015).

Temperature and ground floor losses

The effect of external temperature on the obtained results was also investigated. The temperature difference between the internal and external environment is included in the formula of the α-criterion (Eq.4) and therefore the external temperature was already considered an important environmental parameter on the QUB measurement. In addition, the HLC of a building is expressed in W/K with respect to the temperature difference between the internal environment and the external air temperature. However, heat loss in a building occurs not only to the external air temperature but also to the ground temperature (which does not follow the seasonal variation of the air temperature) through the floor. This issue was highlighted by Everett et al. (1985) and floor losses (as well as infiltration losses) were isolated from the HLC in the 'Thermal calibration' method. To identify any potential relationship between these parameters, HLC for the baseline and the increased airtightness configurations were plotted together with the initial external temperature (Figure 6 and Figure 7).

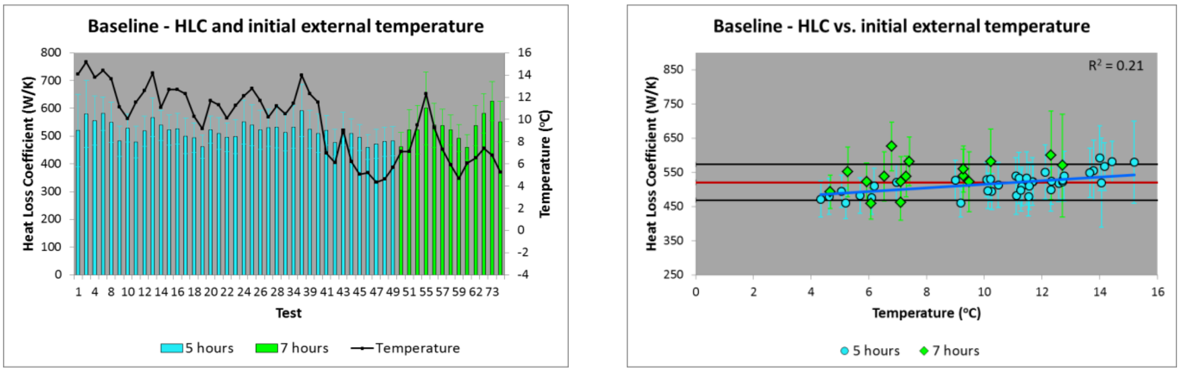

Figure 6: Heat Loss Coefficient against initial external temperature for the baseline configuration in a bar chart (left) and scatterplot (right) for the different test durations

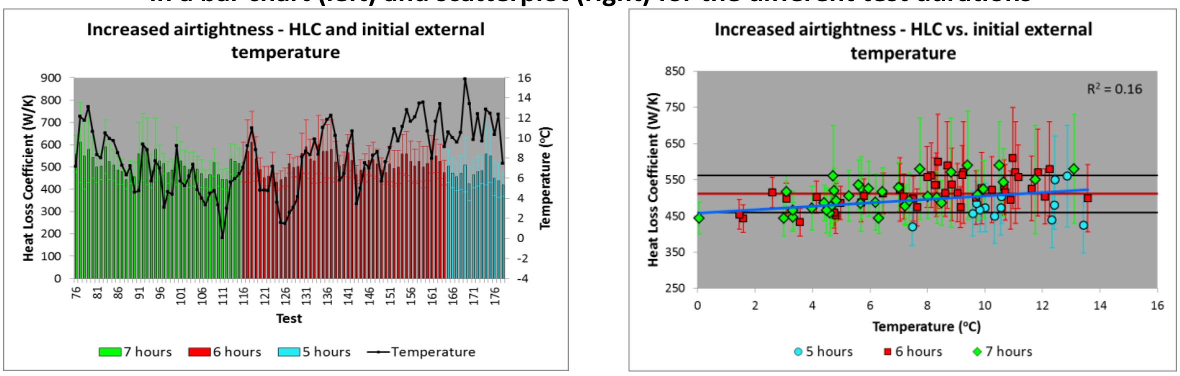

Figure 7: Heat Loss Coefficient against initial external temperature for the increased airtightness configuration in a bar chart (left) and scatterplot (right) for the different test durations

The HLC and the external temperature followed very similar fluctuation throughout the testing period. This was the case for both airtightness configurations. A clear trend is shown in both graphs where the HLC appears to increase when the external temperature increases. Correlation between these two variables is consistent in both cases (i.e. the adjusted R-squared R^2 was 0.21 for the baseline and 0.16 for the increased airtightness configuration) and it is suggesting that some of the variance in the HLC is attributed to the variance in the external temperature. This can be explained by the way the test was carried out. As seen in Eq. 4 the two testing parameters that can be controlled to adjust the value of α are the temperature difference and the power input. As described in the 'Testing protocol' section the power input was kept the same throughout the testing period while the internal starting temperature was changed according to the external temperature on any given test day such that the α-criterion lied within the recommended range (i.e. between 0.4 and 0.7). Effectively, this meant reducing the internal temperature on colder nights and increasing it on warmer nights by adjusting the thermostats on the second set of heaters.

However a complication exists in relation to the heat loss via the ground floor. The ground floor temperature is influenced by a large thermal mass and therefore does not follow the air temperature variation. The consequence of this is that the floor temperature is very slow to change (over weeks rather than days) and therefore the floor heat loss, and the subsequent HLC, is shown to be higher on warmer nights. It should be noted that the HLC plotted in Figure 6 and Figure 7 is the raw HLC of the whole dwelling (i.e. including the ground floor losses). Heat flux on the floor was monitored with heat flux plates. Data from these sensors will be analysed further in order to correct for the floor losses and investigate whether this correlation is then eliminated and the consistency of the results is improved.

CONCLUSIONS

The findings from a series of in situ tests in a circa 1950s detached dwelling carried to assess its thermal performance were presented in this work. The objectives of the study were to evaluate the performance of the QUB method on site, investigate repeatability of the results and assess reliance of the results to the prevalent test conditions. The QUB method is able to estimate the HLC of a building 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 tests were conducted on a daily basis from the end of September 2016 until the end of April 2017 under two distinct airtightness configurations. This was only made possible due to the short duration of the method. Therefore, QUB does not only have significant potential for use as a diagnostics tool in industry; it is also a research tool. The following conclusions were drawn from the analysis:

1. The QUB method was able to provide reasonably consistent results (i.e. with a coefficient of variation of ± 10%)) provided the α-criterion lied within the recommended range (i.e. between 0.4 and 0.7).

2. In the UK a test may be conducted from late October until late March (or even late September until late April) with confidence that results would not be affected by the α-criterion or any assumption made in calculating the HLC_{ref}.
3. No significant correlation was found between wind speed and the building's HLC. This could be attributed to the fact that that the building was sheltered from three sides and the wind speeds experienced were not excessive.
4. External temperature appeared to affect the resulting HLC and this was attributed mainly to the ground floor heat losses.

Results from the first long term in situ monitoring study in the UK with the QUB method were presented in this paper. The aim was to establish specific trends on the performance of the QUB method in situ. Further analysis is required on the particular conditions of each test performed and the heat flux on the building elements to investigate the outliers that appear to affect the level of consistency of the test results. Data from heat flux sensors installed on the floor will help to investigate further the effect of external temperature and assess whether consistency of results is improved when isolating the floor heat losses. Reliance of the results on additional weather parameters (solar radiation, precipitation, night long-wave radiation) and the thermal performance of building elements (i.e. U-values with the QUB/e method; Meulemans et al., 2016) will also be investigated in future studies.

It should be stressed out that these findings apply to measurements performed in an uninsulated dwelling. Therefore additional testing is required to investigate whether the same reproducibility of results would be achieved for well insulated buildings representative of new built or retrofitted properties. Climate chamber testing suggested that similar reliability can be expected (Meulemans et al. 2016), however testing in field conditions is required to verify this assumption. Testing a well-insulated property will allow greater flexibility in the power input to adjust the α-criterion. In addition, further validation and verification of results will be achieved by comparing results obtained with the QUB method to the ones obtained with coheating or other similar methods (Janssens, 2016).

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