Evaluating Floor Losses in the Context of QUB Measurements of a Passivhaus Dwelling

Mark Collett[1], Adam Hardy[1] , Johann Meulemans[2] , David Glew [1]

[1] Leeds Sustainability Institute, Leeds Beckett University, Leeds, LS2 9EN
[2] Saint-Gobain Research Paris, 39 quai Lucien Lefranc, F-93303 Aubervilliers, France

Correspondence: m.collett2827@student.leedsbeckett.ac.uk

Abstract. Measuring the performance of building fabric is increasingly important as stakeholders wish to compare as-built performance with design expectations. When measuring whole house performance (Heat Transfer Coefficient) heat losses through the floor in slab-on-ground type constructions are intractable and introduce uncertainty into measurements. As such efforts are often made to isolate them from measurements. The QUB method is a practical method of measuring whole house building performance. Previous work has shown floor losses can successfully be isolated from measurement through use of heat flux measurements and additional calculation steps. To further test this isolation procedure, three QUB tests were performed on a slab-on-ground Passivhaus dwelling. Whilst the whole house performance measurements agree with the design performance (all results within 11% of the design) the floor losses measured appear unrealistically high. The conditions of the tests, conducted in late summer and in a highly insulated property, are likely causing the heat flux measurements to capture heat being stored in the floor construction rather than heat being lost from the property. Follow up measurements in more preferable conditions are planned which will assist in determining the cause of these observations.

1. Introduction

The performance of building fabric is a critical component in the decarbonisation of heat to enable reaching of national and international net zero targets. The current energy crisis has added another immediate perspective to this issue. Efforts to improve fabric performance and reduce heat loss have existed for decades both in the regulations that govern new buildings as well as through retrofitting insulation measures to existing properties [1,2].

However, there is evidence that shows the actual performance of buildings is often different from what is expected. The causes of this discrepancy, often referred to as a "performance gap" broadly fall into the following two categories.

1) *Physical performance deficiencies.* The quality of the finished construction not matching design through issues such as product substitutions, lack of attention to detail regarding airtightness or continuity of insulation [3–5].
2) *Prediction / Modelling Gap.* The calculations for determining fabric performance contain assumptions or default performance values that do not match as built performance [6,7].

Awareness of the performance gap has popularised the concept of measuring building fabric performance to give stakeholders confidence in the thermal performance of their buildings [7,8]. QUB is an in-situ rapid measurement technique that can measure the whole house performance of a property within a single night. Multiple other measurement methods exist with their respective reliability naturally being a matter of interest to ensure measurements are accurate and repeatable. Heat losses through the floor in slab-on-ground properties are known to introduce uncertainty into these measurement methods for a variety of reasons. This study details work undertaken to evaluate floor losses in such houses in the context of the QUB measurement method.

2. Literature Review

2.1. Heat Transfer Coefficient

The fabric perforamance of an entire home can be characterised by its HTC (Heat Transfer Coefficient) [9]. This metric quantifies the heat needed to maintain a given temperature difference with units of WK^{-1}. The HTC quantifies heat loss from all mechanisms. Equation 1 presents an abridged model of the HTC capturing the applicaple heat transfer mechanisms in the context of this reserch. This mirrors the calculation of the metric in the UK's regulartory standard assessment procedure [10]. Other more comprehensive models of HTC do exist [9].

$$HTC = \sum UA + \sum \rho C_p Q_v + \sum \psi_j L_j \tag{1}$$

The first expression of equation 1 is the summation of transmittance heat loss through building fabric elements of U-value, U ($WK^{-1}m^{-2}$) and area, A (m^2). The second expression is the summation of infiltration losses (uncontrolled ventilation) where ρ is air density (kgm^{-3}), C_p is the specific heat of air ($Jkg^{-1}K^{-1}$) and Q_v is the infiltration rate (m^3s^{-1}). The final expression is the sum of heat lost through thermal bridges (items that have comparatively lower thermal resistance than their surrounding area) of length L (m) and transmission constant ψ ($Wm^{-1}K^{-1}$). Both infiltration and purpose provided ventilation will contribute to the in-use energy demand of a building. Only infiltration is analysed in this context as it reflects heat lost through gaps in the fabric. Heat loss will occur through purpose provided ventilation but this is a consequence of a buildings mechanical systems rather than fabric.

2.2. QUB Method

The QUB method is an in-situ, dynamic measurement technique capable of mesuring the as built HTC and elemental U-values of an unoccupied property within a single night. Steady-state and in-use methods have durations of several weeks [11,12] making the duration of QUB a comparatively preferable and more practical technique. The QUB method considers the thermal performance of the test house as analogous to a single RC circuit where the internal and external temperature nodes are separated by a single thermal resistance (electric resistance). The thermal capacitance of the building (analogous to the electrical capacitance) and power source are located at the inside temperature node.

The procedure consists of subjecting the house to a constant heat input and free cooling phase. This takes place overnight so no solar radiation is incident on the property with the only heat coming from purpose provided electrical heaters distributed throughout the property. Through recording the internal and external temperatures and power demand throughout the QUB test, equation 2 can be used to compute the HTC.

$$HTC = \frac{T_2'P_1 - T_1'P_2}{T_2'\Delta T_1 - T_1'\Delta T_2} \tag{2}$$

Where subscript 1/2 indicate the measurements taken at the end of the heating / cooling phase respectively, $T'$is the slope of the temperature profile (K $hour^{-1}$), P is power input (W) and ΔT is the internal-external temperature difference (K)**.**

The QUB method has been validated theoretically[13,14] and through testing in the field as well as in a controlled artifical climate [11,15–17]. Additionally it has been used in UK government funded building evaluation projects [12,18]. This work has validated the QUB method across property characteristics of age, insulation levels and air permeability. However, the behaviour of floor heat losses in an insulated property of slab-on-ground construction has not yet been investigated.

2.3. Floor Losses in Slab-on-Ground Constructions

For properties with slab-on-ground type construcitons (the floor resting directly on the ground), heat losses through the floor are intractable. The primary reason for this is that rather than heat loss being driven by the internal – external air temperature difference they are dictated by other variables, principally the ground temperature. As floor constructions of this type often have a high thermal mass, the subsequent large thermal inertia means that their thermal performance may have to be characterised over a long time period [19]. The make up of the ground can also contribute to heat loss. Parameters such as thermal conductivty, thermal diffusivity and ground moisture level are liable to vary heat loss levels and these can vary seasonly and by location [20].

Due to their complexity attempts are often made to isolate ground losses from fabric performance measurement for the purpose of more repeatble tests. A modification of the popular coheating test, known as a "thermal calibration test", involves recording floor losses through use of heat flux plates and then subtracting them from the energy used to maintain a constant internal temperature for a period of two weeks or more [21,22]. When applied in practice Everett *et al.* found that heat loss does indeed follow subsurface temperature when uninsulated. With the addition of insulation the long-term behavior of the heat flux becomes irregular and does not follow this pattern, although this result was deemed inconclusive [22].

Sougkakis *et al.* [16] proposed a method for isolating floor losses during the QUB method through placement of heat flux plates on the floor of a 1950's built house with an uninsulated concrete slab-on-ground floor. Through quantifying the heat lost through the floor and subtracting this from total heat loss, HTC_{adj} was calculated with the floor losses isolated (equation 3)(equation 4).

$$P_{ext} = HTC_{raw}\Delta T_{avg} - q_{floor,avg}A_{floor} \quad (3)$$

$$HTC_{adj} = \frac{P_{ext}}{\Delta T_{avg}} \quad (4)$$

Where P_{ext} is the heat lost from the whole house in the test minus the heat lost through the floor (W), HTC_{raw} is the HTC measured through the QUB test with no adjustment made (WK^{-1}) , ΔT_{avg} is the average temperature difference over the duration of the QUB test (K), $q_{floor,avg}$ is the average area-weighted heat flux occurring through the floor (Wm^{-2}) and A_{floor} is the area of the concrete floor (m^2).

The result of this showed the precision of the test improved with the floor losses isolated. Over 58 QUB tests the standard deviation reduced from 8% to 5% of the mean mesaurement and the standard error of the mean reduced from 8.3% to 6.5% with the application of equation 3 and equation 4.

In this case study, the uninsulated nature of the floor may be well suited to the method applied whereby the heat loss is more responsive to temperature gradient and storage effects are less detectable. This method has not been applied to QUB measurements on insulated constructions.

A further motivation for isolating ground losses is to quantify heat loss to a particular element. This dissagregation of the HTC is advantagous for detecting if particular elements are or are not performing in line with expetaiton [8]. The QUB method has shown to be effective in measuring elemental heat loss in all other external facing elements [17,23].

3. Method

3.1. Research Design

This study aims to answer the research question: "What is the impact of slab-on-ground floor losses on QUB tests in a highly insulated property?". A quantitative field based case study was used. Using empirical field based data is preferable to this study as calibrating a model to describe floor losses would be a very complex task. The work described covers the first of a two stage testing programme that will explore seasonal variation in the measurements covered. Follow up measurements to those documented are planned for 2023.

3.2. Description of the Property

The test house for the study was a certified PassivHaus in the North of England pictured in figure 1**Figure *1***. PassivHaus is a voluntary building standard characterised by high performing building fabirc often referred to as superinsulation [24]. The fabric performance characteristics of the house are listed in table 1 as per the approved PassivHaus documentation. The design heat loss is calculated following the applicable expression from equation 1 and expressed as a percentage of the total HTC.

Table 1. Test House Design Performance Characteristics

Item	Description	Design Heat Loss (W/K)
Wall	U-Value=0.097 $Wm^{-2}K^{-1}$ Brick and block with 300mm mineral wool insulation in cavity.	20.7 (30%)
Floor	U-Value=0.057 $Wm^{-2}K^{-1}$ Ceramic tiles, 150mm concrete slab and 400mm PIR insulation	5.8 (8%)
Ceiling	U-Value=0.070 $Wm^{-2}K^{-1}$ 50mm sheep wool insulation, airtightenss membrane, 406mm fibre insualtion between joists and 100mm woodfibre insulation board.	8.5 (12%)
Windows	U-Value=0.70 $Wm^{-2}K^{-1}$ Triple glazed timber and cork frame windows.	28.2 (41%)
Airtightness	Air permeability measured at 0.4air changes / hour @ 50Pa or 0.39$m^3m^{-2}hour^{-1}$ @50Pa	2.2 (3%)
Thermal bridges	Detail designed to reduce thermal bridges.	4.1 (6%)

Figure 1: External View of Property

Based on the design performance of the farbic and the measured air permeability the design HTC for the test house is 69.5WK^{-1} following calculation through equation 1. The performance of PassivHaus fabric is certified by their modelled heat demand, as calculated from PassivHouse Planning Package models, rather than HTC. Hence, equation 1 was used to determine the design HTC. To translate the result of the high pressure air permabiltiy test to a flow rate refelctive of regular conditions the n/20 calcualtion was used, as per the UK's regulatroy standard assessment precedure [10].

3.3. Measurement Campaign

From the 30th August to the 2nd of September 2022, 3 overnight QUB tests of 9 hour total duration were completed on the test house. To ensure only heat loss through infiltration was measured the mechanical ventialtion was tunred off and ventilation points sealed. A heat input (P_I) of 1750W was sized based on the forecast external temeprature at the commencment of the tests which would maintain an optimal heat input / heat loss ratio that previsous research has shown is conducive to accurate measurements [25,26].

To measure and determine the parameters to complete a QUB test (equation 2) internal and external air temperature was measured with Pt100 RTD sensors throughout the tests. To determine the internal air temperature sensors were placed in each room on a tripod to position them centrally. The external air temperature was measured at two locations on opposite sides of the property. The heat input was met with 250W heaters with their energy demand measured by Elster A100 kWh meters. To ensure the starting temperature resulted in an optimal heat input / heat loss ratio a second set of time controlled heaters paired with InstCube PID digitial temperature controllers were used. Temperature and energy measurements were recorded by Eltek SRV250 wireless data loggers with an aquisistion rate of once per minute.

To measure the floor heat loss five Huskeflux HFP01 heat flux plates logging to a DT85 DataTaker were installed on the ground floor ranging from the perimeter to the center of the ground floor seperated by approxiamtely 1m. This was done to measure a representative sample of the heat flow which is known to deviate spacially through floors [27]. The individual heat flux density measurements were multiplied by a proportion of the floor area to determine the overall heat flux (W) throughout the tests. This value was averaged over the test duration to compute equation 3. The ground temperature was measured with a Omega RDSL 12SD logger and temperature probe 340mm below surface level, approximately 1m from the external perimeter of the house.

The whole house heat loss (HTC_{raw}) was calculated through equation 2, taking average values of temperature and power for the heating and cooling phases. The floor losses were quantified through then computing equation 3 and equation 4, floor losses = HTC_{raw} - $HTC_{adj.}$ The measurement uncertianty was calculated following Taylor series for error propogation [28].

4. Results and Discussion

The HTC measurements made through the QUB method are detailed in table 2 along with the associated floor losses for each test along with their 95% confidence intervals.

Table 2. HTC and Floor Losses Measurements

Test Number	HTC_{raw} (WK^{-1})	HTC_{adj} (WK^{-1})	Measured Floor Heat "Loss" (WK^{-1})	Average Internal - External Temperature Difference (K)
1	61.9 ± 4.2	40.0 ± 4.4	21.9 ± 6.1	12.7 ± 0.4
2	75.2 ± 4.6	44.2 ± 6.1	31.0 ± 7.6	11.0 ± 0.1
3	67.0 ± 4.3	39.9 ± 6.4	27.0 ± 7.7	12.0 ± 0.3
Average Value	67.6 ± 6.6	41.2 ± 2.3	25.9 ± 4.7	11.2 ± 1.2

The average measured HTC_{raw} agrees with the design HTC with the average value differing by 2.7%. The range of measurements is $12WK^{-1}$,19% of the mean value, this is comparative with other case studies of multiple QUB tests. The test conditions of internal – external air temperature difference were comparable for all three tests.

Comparatively the measured floor heat loss is on average over 4 times the magnitude of the design value. Clearly these two observations present differing outcomes - the whole house performance (HTC) is in close agreement with the design expectations, but the floor performance is many times that of its design performance. Analysing the floor heat flux data offers some insight into this phenomena. **Figure *2*** shows the area weighted profile of the floor heat flux from test night 2.

Whilst the difference of the heating / cooling phase is somewhat distinguishable in the heat flux, the pattern appears almost unpredictable and far from the typical profile of a single decaying exponential associated with the QUB test. As this observation is apparent in the profiles from all 3 tests and all deployed heat flux plates the likelihood of an equipment failure leading to this result is considered low.

Due to the closeness of the design and measured HTC_{raw} it is unlikely that the heat flux being measured is actually reflective of the heat loss from the thermal envelope. Moreover, this heat is likely being stored in the concrete slab of floor and contributing to the temperature rise in the QUB test. As the heat flux measurements and associated calculations are spurious only HTC_{raw} remains as the valid performance measurement. The 95% confidence intervals of HTC_{raw} for tests 1 and 2 do not overlap and hence are considered statistically different. As there were no apparent differences in the test conditions the cause of this could be attributed to the floor losses introducing a systematic error into the measurements which attempts to isolate were not successful.

The QUB method is accustomed to account for thermal mass with the thermal capacitance of the test building inherently needed for the assumptions around the thermal response of the building to be valid. However, the test conditions exhibited in this case study are possibly contributing to the storage effects dwarfing the heat loss from the floor making meaningful heat loss measurement challenging.

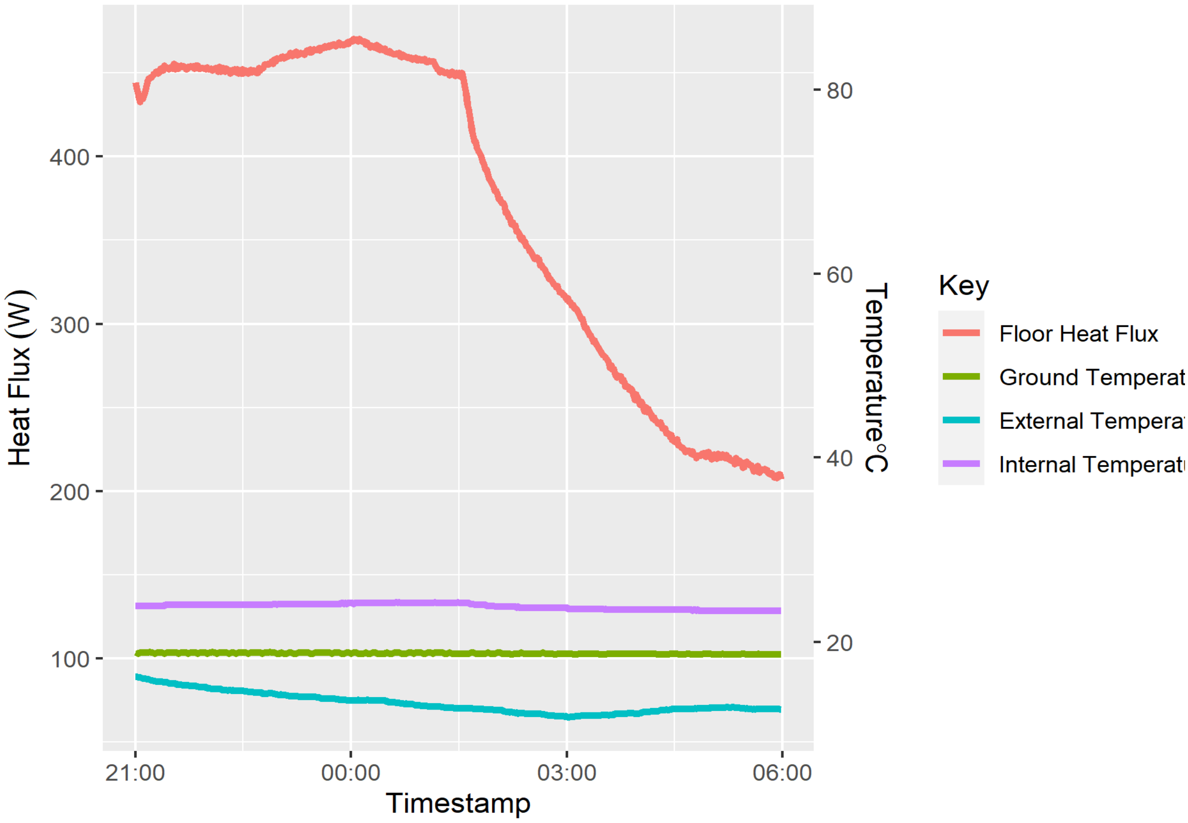

Figure 2: Example Area Weighted Heat Flux and Temperature Profiles From QUB Test

The temperature difference between the internal environment and the ground is a contributing factor in the floor heat loss. A correlation between the heat loss and the ground temperature can be observed in figure 3. The ground temperature throughout the test was relatively stable (see figure 2) so substituting this variable with the internal temperature produces a similar correlation. The temperature difference between the internal environment and the ground ranged from 5.7 – 7.2 K for the 3 tests. This temperature difference is relatively small in the context of heat loss measurement. Both the ISO 9869 for U-value measurement and the Leeds Beckett Coheating protocol require a minimum temperature difference of 10 K to promote monodirectional heat flow [21,29].

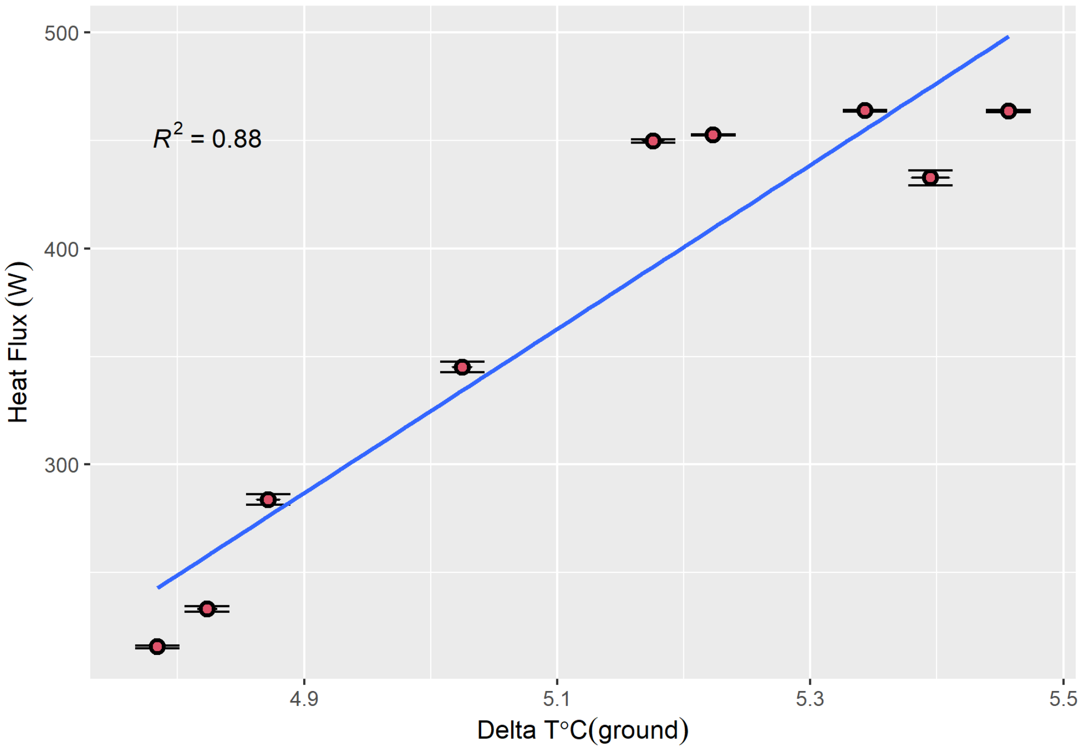

Figure 3. Example Floor Heat Loss Aggregated Hourly against Ground Temperature Difference

A further effect of the test being completed in summer is that the floor slab likely has minimal charge in it as a result of the house's heating system not being in use. The slab being heat saturated would be more appropriate for heat loss measurement as this would minimise storage effects. The planned further tests to be completed in winter will make use of surface temperature measurements of the floor to quantify this charge effect. If the issues observed in this case study are present even in more preferable conditions the performance of the floor could be verified through use of infrared thermography to confirm the continuity of insulation and absence of thermal bridges. The precursor for this would be agreement between the HTC_{raw} design and measurement.

5. Conclusions

The work presented shows promise that the QUB method can be used to measure the whole house heat loss (HTC) of a highly insulated dwelling with a slab-on-ground floor construction in summer conditions. The range of results of 12WK^{-1}, 19% relative to the mean, is reflective of existing research on the method. Despite this, not all measurements statistically agree. Spurious measurements of floor losses have introduced a systematic error which is likely contributing to this observation.

The setting in which the tests were completed create conditions that may be inhibiting meaningful heat loss measurement from the floor:

- The tests were completed in late summer and as a result had a modest temperature gradient between the ground and the internal environment (less than 10 K). This is deemed not conducive to successful heat loss measurement.
- A further issue with the tests being completed in summer / autumn is that there will be minimal thermal charge in the floor slab as no internal heating is needed. Consequently the heat flux

being measured is likely reflecting the heat being stored in the floor slab rather than heat being lost from the building.

- These issues are compounded by the superinsulated nature of the floor that will increase storage effects.

Future measurements in more preferable testing conditions are to be completed in 2023. This will reveal whether the seasonal conditions exhibited in this work are responsible for the unpredictable heat flux measurements observed. For scenarios where accurate heat flux measurements are not possible but the HTC is in agreement with design, the performance of the floor could be verified qualitatively with thermography as an alternative.

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