Obtaining the heat loss coefficient of a dwelling using its heating system (integrated coheating)

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Abstract

This paper presents the methodology, along with some of the initial findings and observations from tests performed on two dwellings, of differing construction and form, in which a coheating test was performed using the dwelling's central heating system; this method is referred to as *integrated* coheating. Data obtained during the integrated coheating tests using a dwelling's heating system have been compared with data obtained during electric coheating of the same dwelling. In one instance, integrated coheating test data from one dwelling was compared to a similar adjoining control dwelling that was simultaneously subject to an electric coheating test. The results show a good agreement between the heat loss coefficients (HLC) obtained using a dwelling's own heating system and those obtained through electrical coheating. Initial analysis suggests the HLC estimate obtained from integrated coheating is likely to be more representative of how a dwelling performs in-use. The findings question the appropriateness of comparing current steady-state HLC predictions to those derived from in-use monitoring data. Integrated coheating has the potential to provide a more cost-effective and informative indication of whole house heat loss than electric coheating, as it enables *in situ* quantification of both fabric and heating system performance.

Keywords

Coheating; Heat loss coefficient; Thermal performance; Energy signature; Heating system; Performance gap; Heat meter; Energy efficiency; Building fabric; Whole house heat loss.

Table 1: Nomenclature

Term	Symbol	Unit
Heat loss coefficient	HLC	W/K
Indoor-outdoor air temperature difference	ΔT	K
Total measured power input from space heating	Q	W
Solar aperture coefficient	R	m^2
Solar irradiance	S	W/m^2
Total transmission heat loss	$\Sigma U.A$	W
Background ventilation heat loss	C_v	W
Density of the heat transfer medium	ρ	kg/m^3
Volume flow rate	V	m^3/s
Specific heat capacity at constant pressure	c_p	kJ/kgK
Temperature of the liquid in the flow pipework	t_f	K
Temperature of the liquid in the return pipework	t_r	K
Heat input to the dwelling measured by the heat meter	Q_{hm}	W
Heat gain from the heat generation plant	Q_p	W

1 Introduction

EU [1] and UK [2] regulations are progressively increasing the building fabric energy efficiency standard of new and existing dwellings driven by the requirement to reduce CO_2 emissions and the increasing cost of the energy required to heat dwellings. A body of evidence has been amassed which highlights a discrepancy between the predicted and as-built thermal performance of the building fabric which threatens to reduce the desired impact of these regulatory measures (Stafford *et al.* [3] and Johnston *et al.* [4]). This underperformance is commonly referred to as the '*performance gap*'. In order for the thermal performance of buildings to be quantified a metric is required: the heat loss coefficient (HLC) is one such metric. The HLC is the rate of heat loss in Watts from the entire thermal envelope of a building per Kelvin of temperature differential between the internal and external environments (ΔT) and is expressed in W/K. Obtaining an estimate of a building's HLC *in situ* enables a comparison to be made between the realised performance and predicted performance and enables feedback to the occupier, building management system and to other stakeholders regarding the thermal performance of the dwelling.

Comparable metrics to the HLC can be obtained from in-use monitoring data using linear regression based energy signature analysis techniques (Hammarsten [5], Sjogren *et al.* [6]). As many of these models rely on assumptions regarding occupant behaviours, their accuracy must be questioned. Complex dynamic statistical models are also being identified which aim to isolate the effect of occupant behaviour, enabling identification of the HLC and other parameters from in-use monitoring data (Bacher and Madsen [7]). Although these methods could enable a HLC to be isolated from smart metering of an occupied dwelling; validation of their output parameters against measured baseline values is required to establish their reliability.

The uncertainties associated with occupant behaviour when estimating the HLC *in situ* can be removed by physical measurement of an unoccupied dwelling. Physical measurement techniques can be separated into two distinct categories: disaggregate and aggregate. To estimate the HLC of a building using disaggregate techniques, the U-value of all thermal elements must be measured (commonly using heat flux plates), along with the background ventilation rate of the building (pressurisation testing or tracer gas methods), and linear thermal bridging (Taylor *et al.* [8]). Estimating the HLC using a combination of disaggregate methods has the advantage of providing multiple parameters relating to the building fabric which can potentially isolate the cause of any potential performance gap. However the veracity of the HLC estimate is questionable as it is difficult to ensure that the U-values measured *in situ* are representative of the entire element (especially ground floors and bridging layers), and measurement of linear thermal bridging is highly complex in a dynamic environment. Although aggregate methods yield less information regarding individual parameters of the building envelope, they capture the thermal bridging component of the HLC and can obtain an estimate of the HLC with a lower level of complexity; one such method is electric coheating.

Electric coheating is a recognised test method for obtaining an estimate of the *in situ* HLC of a building. A coheating test involves heating the internal environment of a building to an elevated, homogenous, and constant temperature with electric resistance heaters and then maintaining that temperature over a number of days (typically 10-21 days). The power input to the dwelling, as well as the internal and external environmental conditions, is monitored throughout the test.

Electric coheating has existed in various forms since the late 1970s. It was originally performed overnight as a test to measure the efficiency of heating systems that cannot be measured directly, such as fireplaces and furnaces (Sonderegger and Modera [9] and Sonderegger *et al.* [10]). These early tests found that heating a building solely with electric resistance heaters meant that the building's HLC could also be measured. Future development of the coheating test in the 1980s in the UK (Siviour [11], Everett *et al*. [12] and Everett [13]) focused upon measurement of the HLC. These works increased the length and complexity of the test and analysis to better accommodate for the dynamic external environment in which coheating tests take place.

The use of coheating increased in the UK following its uptake and development by Leeds Metropolitan University (now known as Leeds Beckett University); notably during the Stamford Brook Project. Coheating tests during the Stamford Brook Project identified a substantial performance gap in new dwellings, and helped quantify the party wall bypass heat loss mechanism (Lowe *et al.* [14]). Following the Stamford Brook Project, the electric coheating test method was further refined and developed by Leeds Metropolitan University, resulting in the 2010 version of LeedsMet's Whole House Heat Loss Test Method (Wingfield *et al*. [15]). This version became recognised as an established test method in the UK when it was incorporated within the Post Construction and Initial Occupation studies undertaken under the Technology Strategy Boards (now Innovate

UK's) Building Performance Evaluation Programme [16]. The 2010 version of the test method was significantly revised in 2013 (Johnston *et al.* [17]).

In recent years, research efforts have primarily been concentrated on coheating test data analysis and the identification of sources of uncertainty, rather than the experimental setup or the testing methodology. *In situ* coheating tests and computer simulations found measurement uncertainty to be greatest during periods of high solar gain and also for dwellings with high thermal mass (Bauwens *et al*. [18] and Stamp *et al.* [19]). Most recently, a state-of-the-art review of the coheating test and the methods used to analyse test data proposes that the most sensible analysis method to adopt is multiple linear regression (Bauwens and Roels [20]).

Unlike the fan pressurisation test method, which is used to establish the air permeability of dwellings, the coheating test has not been widely-adopted as a procedure for either regulatory compliance or quality control purposes. Instead, it remains the preserve of a few academic institutions and specialist consultancy services (Zero Carbon Hub [21]). There are numerous reasons why the coheating test has seen limited application, which include: reluctance from the construction industry to acknowledge and research the performance gap; criticism regarding the precision and accuracy of the coheating test (Butler and Dengle [22]); the duration of the test with no guarantee of obtaining a confident estimate of the HLC in the limited time available; the test's restriction to the heating season (October – March in the UK); the lack of a recognised, standardised test and analysis method; a lack of experienced testers; and, the time and financial costs associated with undertaking the test (Taylor *et al.* [8]).

The financial cost of a coheating test can be disaggregated into costs associated with the time for which a dwelling must remain unoccupied, as well as the personnel, equipment and energy costs. Dynamic whole house heat loss test methods exist that are far shorter in duration than the coheating test. These include: ISABELE (Bouchié *et al.* [23]), the Quick U-value of Buildings (QUB) method (Mangematin *et al.* [24]) and the Primary and Secondary Terms-Analysis and Renormalization (PSTAR) method (Subbaro [25], Subbaro *et al.* [26]). However, the nature of the HLC estimation obtained by PSTAR was questioned when compared with that measured by a coheating test on the same dwelling (Palmer *et al*. [27]). The robustness of methods currently under development (the QUB and the ISABELE method) is yet to be established for dwellings in the field. Other financial costs could be significantly reduced by substituting the dwelling's heating system for the portable electric heaters that are commonly used to provide the heat input during whole house heat loss tests.

This paper provides details of the methodology and early analysis of the data obtained from experiments performed on two dwellings where coheating tests were undertaken using the dwelling's own hydronic central heating system to provide heat input; a method referred to as *integrated* coheating. It also compares the results obtained to the same dwellings undergoing electric coheating in accordance with LeedsMet's 2010 coheating method (referred to henceforth as LeedsMet coheating).

2 Estimation of the HLC from a coheating test

Following an initial period during which the building fabric reaches thermal capacitance, a coheating test assumes the following whole house energy balance (adapted from Siviour [11]):

$$Q + R.S = (\Sigma U.A + C_v).\Delta T \tag{1}$$

Where: Q is the total measured power input from space heating (W), R is the solar aperture of the house (m^2), S is the Solar irradiance (W/m^2), $\Sigma U.A$ is the total fabric transmission heat loss (W), C_v is the background ventilation heat loss (W) and ΔT is the temperature difference between the internal and external environment.

The whole house energy balance equation can be rearranged to show that:

$$HLC = (Q + R.S) / \Delta T \tag{2}$$

The HLC is typically estimated using a linear regression-based quasi-steady-state analysis of the data obtained during the test period. The raw HLC can be obtained from the slope of a simple linear regression analysis in which Q is the dependent variable and ΔT is the independent variable, though this does not account for the effect of solar radiation. The power provided by solar radiation to the dwelling during a coheating test (R.S) is not measured directly, rather its effect is observed in a measured reduction in the power required to maintain a constant internal temperature, which is manifested in a reduction in the raw HLC. Solar radiation not only results in solar transmittance through glazed elements which is absorbed within the building, but it is also absorbed by the opaque exterior surfaces of the building, causing a reduction (or temporary net reversal) of heat flow through external elements. It is therefore not advisable to calculate the solar aperture (R) of a dwelling based solely on the glazed properties of a dwelling, as in the SAP 2009 methodology (BRE [28]). A more appropriate method is to introduce solar irradiance into a multiple regression analysis in which ΔT and S are independent variables and Q the dependent variable (Bauwens and Roels [20]). The multiple regression analysis produces regression coefficients for ΔT (the HLC) and for S (the solar aperture). It is then possible to correct Q for R.S, which can be plotted in a simple linear regression with solar corrected power (Q + R.S) as the dependent variable and ΔT as the independent variable. The resulting slope is the HLC estimate. Wind speed can also be included in the multiple regression analysis, with the HLC estimate being corrected to include the wind speed regression coefficient. It is common for the constant to be excluded (regression through origin), as the model assumes that at zero ΔT with zero solar irradiance and no wind, there is no heat transfer from the dwelling. All estimates of the HLC in this paper have been obtained using the multiple regression based methods detailed in this section with the constant omitted.

Although the appropriateness of a simple linear model and the application of steady-state analysis to a dynamic system has been questioned (Baker and van Dijk [29]), in practice the coheating tests are undertaken over a sufficient length of time to minimise or smooth out some of the dynamic effects, such as thermal storage and inertia.

Data used in the regression analysis comprise 24 hour mean values for each variable to account for the diurnal cycle. A 6 a.m. – 6 a.m. 24 hour interval is often used as this provides the greatest opportunity for daytime solar radiation absorbed by the building fabric to be released within each period, thus reducing errors attributable to solar thermal storage from one 24 hour period influencing the results from another and increasing the reliability of the regression analysis.

3 Method

In order to establish whether the integrated method can produce a useful estimate of the HLC, a confident baseline estimate of the *in situ* HLC of each test dwelling is required. In the absence of an international standard for coheating, the LeedsMet coheating method was selected for the electric coheating tests. HLC estimates obtained using the integrated method can then be validated against the baseline HLC estimate.

3.1 Comparison of LeedsMet and integrated coheating test methods

Table 2 lists the principal considerations when conducting a LeedsMet coheating test and compares these against the approach taken in experiments undertaken using the integrated method.

Table 2: Comparison of the LeedsMet and integrated coheating methods

	LeedsMet coheating	**Integrated method**
Internal space heating	Portable electrical direct resistance heaters (100% efficient as all electrical energy consumed is ultimately liberated as heat)	Dwelling's own installed heating system. Typically in the UK, hydronic gas central heating system with condensing gas boiler (~90% efficient) feeding radiators as the heat emitters. District heating, electric heaters and heat pumps are also suitable
Power measurement of internal space heating	Energy meters (uncertainty +/- 1%)	Heat metering of boiler output (uncertainty +/- 5%), gas meter with correction applied, heat metering of district heating or heat pumps at point of entry to the

		thermal envelope. Minimum heat meter resolution of 100 Wh recommended.
Homogenised internal temperature	Use of air circulation fans	Natural convection
Internal temperature control	Thermostatic temperature controller for each heater	Dwelling's heating control. Typically in the UK, wall mounted thermostat(s) and thermostatic radiator valves (TRVs)
Internal temperature measurement	Temperature sensors in each zone	Temperature sensors in each zone. Potentially, a building management system
External environmental conditions	External weather station with vertical south facing pyranometer	External weather station with vertical south facing pyranometer or local weather station data

From Table 2, it can be seen that the notable differences between the two approaches relates to the provision and distribution of heat within the dwelling and the measurement of power input from space heating (Q); these will be explored in greater detail.

The significant difference in the two methods is the use of the dwelling's own heating system to provide space heating in lieu of the electric resistance heaters. The integrated method shares similarities with a coheating test undertaken on a school, in which for practical reasons, a proportion of the building was heated using the heating system, with other areas heated electrically (Zabot *et al.* [30]). Electric resistance heaters are used in the LeedsMet coheating tests because they are effectively 100% efficient at the point of use; this enables a reliable measure of Q to be obtained using an energy meter. Portable electric resistance heaters can be strategically placed throughout the dwelling to ensure heat input into all areas of the dwelling.

The efficiency of modern condensing gas boilers is in the region of 90%; operational efficiency can vary depending upon the boiler load and climate conditions. It is therefore not possible to obtain a reliable measure of Q using gas metering alone and this has prevented its use in coheating tests. However, the heat output of gas boilers can be measured using a heat meter, and these are becoming more affordable and prevalent. A heat meter comprises a flow sensor, a pair of temperature sensors, and an integrator which calculates the heat dissipated into the dwelling using the heat transmission formula:

$$Q = \rho.V.c_p.(t_f - t_r) \quad (3)$$

Where: Q is the quantity of heat given up or absorbed (W), ρ is the density of the heat transfer medium (kg/m^3), V is the volume flow rate (m^3/s), c_p is the specific heat capacity at constant pressure (kJ/kgK), t_f is the temperature of the liquid in the flow pipework (K) and t_r is the temperature of the liquid in the return pipework (K).

A shortcoming of measuring Q with a heat meter is that measurement error is greatest at lower flow rates, which creates more uncertainty about the value of Q at smaller temperature differentials. In addition, heat meters do not account for the additional heat input from boiler casings housed within the thermal envelope (though this is likely to be a small proportion of total heat input). Heat metering could provide a better measurement of Q in dwellings where the heat input was metered on entry to the dwelling, such as where a district or communal heating system is used, or some heat pump configurations. In situations where the plant used to generate heat is contained within the thermal envelope, the value of Q is more likely to be:

$$Q = Q_{hm} + Q_p \quad (4)$$

Where: Q is the total measured power input from space heating (W), Q_{hm} is the heat input to the dwelling measured by the heat meter (W), Q_p is the heat gain from the heat generation plant (W).

During LeedsMet coheating tests a relatively homogenous air temperature throughout the test dwelling is facilitated by the use of air circulation fans, ensuring a similar ΔT throughout the building envelope. The integrated method of coheating relies upon natural convection from the heating system radiators to obtain a homogenous temperature throughout the dwelling. However, some stratification within a test dwelling will inevitably occur and some areas of a test dwelling might not contain any, or sufficient, heat emitters to produce a homogenous internal temperature. If the test dwelling has a complex internal arrangement, this may also hinder heat distribution throughout the internal environment. A lack of homogeneity in internal temperature will complicate the calculation of the mean internal temperature and could also result in some areas of the building fabric experiencing differing patterns of thermal storage and release than others.

The internal temperature during LeedsMet coheating is controlled by thermostatic temperature controls connected to each heater, which facilitates a homogenous internal environment. The modern fuzzy logic thermostatic temperature controllers increasingly used in coheating maintain an almost constant internal temperature, which minimises dynamic fluctuations within the building fabric emanating from the internal environment. As the energy balance is based upon steady state assumptions, this is an important factor.

The level of internal temperature control during integrated coheating will largely be dictated by the control system of the test dwelling. In the UK, it is common practice to have a wall mounted thermostat which controls the flow of heat from the boiler to all radiators within a particular heating zone. Heat delivery to each zone is dictated by this thermostat and TRVs are usually fitted on all radiators within each zone, except for the radiator closest to the control thermostat. The low accuracy and sensitivity of TRVs, compared to the control thermostat, means there will be less control of temperature in rooms where these are fitted. In addition, no heat will be delivered to these radiators if the thermostat controlling flow from the boiler is satisfied. More advanced digital zoning and radiator control valves should increase the level of temperature control within a dwelling.

3.2 Test dwellings

Obtaining empty test dwellings is consistently a problem in field studies of this nature. For these experiments three test dwellings were made available by Joseph Rowntree Housing Trust (JRHT). Although two of the dwellings are of a common construction type found in the UK, the sample size is small and the dwellings are in a similar geographical area, therefore the sample cannot be considered truly representative of the UK housing stock. The test dwellings are illustrated in Fig. 1 and a summary of their characteristics is provided in Table 3.

Fig. 1: Test dwelling A (left) and test dwellings B and C (right)

Table 3: Test dwelling characteristics

	Dwelling A	**Dwellings B and C**
Heating system	Hydronic central heating system with radiators as heat emitters. 24 kW gas-fired condensing gas boiler	Hydronic central heating system with radiators as heat emitters. 24 kW gas-fired condensing gas boiler

Heating controls	One zone with bimetallic thermostat in the hall on the ground floor. TRVs on all radiators except bathroom	Two zone, with bimetallic thermostats in living room on the ground floor and main bedroom on the first floor. TRVs on radiators in all other rooms
Build form	Detached. 2 storey plus room in roof. South facing winter garden	Semi-detached. 2 storey
Internal arrangement	Irregular	Regular
Total floor area	155 m^2	90 m^2
Dwelling volume	411 m^3	225 m^3
External wall area	186 m^2	84 m^2
Glazing area	30 m^2	12 m^2
Orientation (Front/rear)	North/South	South/North
Building completion date	November 2009	May 2012
External wall construction	Structural insulated panel (SIP) system containing rigid foam insulation. Design U-value: 0.15 W/m^2K	Masonry with fully-filled mineral wool cavity. Design U-value: 0.26 W/m^2K
Floor construction	Suspended beam and block concrete. Design U-value: 0.16 W/m^2K	Suspended beam and block concrete floor. Design U-value: 0.23 W/m^2K
Roof construction	SIP warm roof. Design U-value: 0.15 W/m^2K	Cold roof. Design U-value: 0.11 W/m^2K
Glazing	Double. Centre pane U-value: 0.93 W/m^2K	Double. Centre pane U-value: 1.40 W/m^2K
Thermal Mass Parameter (SAP 2009)	Medium	Medium
Predicted heat loss	120.1 W/K	92.6 W/K (B) 90.1 W/K (C)
Measured air permeability	3.43 $m^3/h.m^2$	9.86 $m^3/h.m^2$ (B) 9.05 $m^3/h.m^2$ (C)

3.3 Experimental procedure

Each test dwelling was subject to three tests:

1. LeedsMet coheating to obtain a baseline HLC estimate.
2. Integrated coheating using gas-fired central heating system with air circulation fans.
3. Integrated coheating using gas-fired central heating system only.

The rationale for performing the integrated coheating test with the use of air circulation fans is that it could yield further understanding of the effects of air circulation during coheating tests, as well as potentially isolating differences caused by the variation in the measurement of Q between coheating methods.

A party wall separates test Dwellings B and C. Dwelling C was subject to LeedsMet coheating throughout the experimentation period and acted as a control dwelling which enables the response of similar dwellings using different coheating methods to be compared. Any anomalies in the estimate of the HLC that might be caused by the external environmental conditions, by inherent problems with the analysis method, or by unidentified factors are therefore not attributable to the variation in the test method. Maintaining the internal temperature of Dwelling C isothermal to Dwelling B also minimises heat transfer between the party elements of these dwellings.

The set-point temperature for the fuzzy logic thermostatic temperature controllers in the LeedsMet tests was 25°C. The same set-point temperature was selected for the integrated test, which involved setting the control thermostat(s) to 25°C and the (TRVs) on each radiator to a setting which the manufacturers' data sheet suggested would maintain a local temperature of 25°C. The programmer for the central heating system was set to manual override (always on) so that boiler output was controlled by the zone thermostats only.

Prior to the experiment, the flow and return pipework from the boiler of Dwelling B was fitted with a heat meter. Dwelling A had previously been fitted with a heat meter as part of a previous in-use monitoring project. Both the heat meters used were Sontex Supercal 539 (uncertainty ≤ ± 5%) that had a pulse output registering one pulse per 100 Wh of energy delivered.

Energy consumption, along with internal and external environmental data in all tests, was logged at ten minute intervals throughout the experiments using an Eltek Squirrel RX250AL data logger. Missing data was corrected using linear interpolation. The gas consumption of Dwelling A was also logged at ten minute intervals. Electrical energy consumption was measured using an using an Elster A100C energy meter (uncertainty ± 1%) with pulse output, registering one pulse per 1 Wh. Internal temperatures were measured in each room using shielded RTD temperature sensors (uncertainty ± 0.1 K), whilst the external environmental conditions were measured using a Vaisala WXT520 weather station containing a thermistor (uncertainty ± 0.3 K). Irradiance was measured using a vertically mounted south-facing Kipp and Zonen CMP 11 pyranometer. The internal and external environmental monitoring systems remained the same between experiments to reduce the number of variables changing between tests.

During the experiment measurements of heat flux were undertaken using Hukseflux HFP01 heat flux plates in accordance with ISO 9869:1994 [31] to provide greater insight into the behaviour of the dwellings between tests. *In situ* U-values were calculated using the averaging method contained within ISO 9869.

4 <u>**Results and discussion**</u>

4.1 HLC estimates

4.1.1 Dwelling A

Fig. 2 illustrates the linear regression-based solar corrected HLC estimation of Dwelling A from the coheating test scenarios. HLCs from all test scenarios are shown in Table 4.The baseline HLC estimate of 133.7 W/K differs by <1% from the HLC estimate of 132.9 W/K obtained from a previous coheating test undertaken on this dwelling in 2010, almost 3 years earlier (Miles-Shenton *et al.* [32]). This increases confidence in the baseline value and suggests that LeedsMet coheating may be reasonably precise.

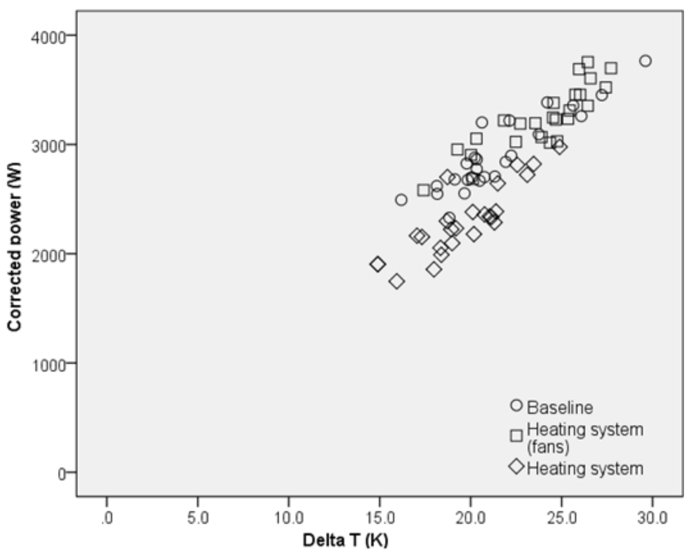

Fig. 2: Linear regression estimation of Dwelling A HLC from each coheating test scenario

Table 4: Summary of the estimations of the HLC of Dwelling A obtained from the three test scenarios

Test scenario	Analysis period	HLC (W/K)	Standard error (W/K)	Variation from baseline

LeedsMet (baseline)	05/12/12 - 10/01/13	133.7	1.9	n/a
Integrated (fans)	20/01/13 – 13/02/13	134.8	2.3	+0.8%
Integrated	27/10/12 – 03/12/12	117.1	2.1	-12.4%

A one-way ANOVA was used to test for differences in the HLC estimates obtained from the three tests. Data comprises 24 hour solar corrected HLCs. There was a statistically significant difference between the three tests, $F(2,97) = 52.79$ $p = <0.001$. Gabriel post-hoc comparisons of the three groups indicate that the integrated test ($M = 117.3$, 95% CI [114.5, 120]) resulted in a significantly lower estimate of the HLC than the integrated test using air circulation fans ($M = 135.9$, 95% CI [132.4, 139.3]), $p = <0.001$ and baseline test ($M = 134.8$, 95% CI [131.9, 137.7]), $p=<0001$. The analysis also revealed that there was no statistically significant difference between the baseline test and integrated with fans test ($p = 0.946$).

The HLC estimate obtained from the integrated test is below the predicted HLC of 120.1 W/K, however the LeedsMet and integrated with fans tests both produced an estimate greater than the predicted HLC. Some of the decrease in HLC estimate obtained from the integrated method could be attributed to a reduction in convective heat transfer resulting from the absence of fans. However, it is thought the internal arrangement of the dwelling on the second floor prevented some areas of the thermal envelope from reaching the same temperature as the living areas (principally the loft and the space behind the knee walls on the second floor, all of which were contained within the thermal envelope – hatches to these areas remained open during all tests). Thermography and temperature measurements undertaken during the integrated coheating test revealed these spaces to be approximately 1-2 K cooler than adjacent rooms. These spaces were primarily heated by TRV controlled radiators in adjacent rooms which ceased providing heat input once the room air temperature reached the set-point. This resulted in under heating of the dwelling, which was not accounted for in the ΔT calculation. The limited air exchange between these areas and the living areas effectively reduced the size of the thermal envelope, as they were providing additional thermal resistance between the external environment and heated living areas.

During the LeedsMet coheating test, a thermostatically controlled portable electric heater and fan was placed in the loft, which maintained a constant and homogenous temperature in this space. In addition, air circulation fans were used to provide heated air to the knee wall voids. The location of all circulation fans was not changed for the integrated coheating with fans test, although a slight adjustment was made to the master bedroom fan position to direct air into the loft space. The provision of heat to all areas of the thermal envelope may be responsible for the higher HLC estimates obtained during the LeedsMet coheating test.

4.1.2 Dwellings B and C

4.1.2.1 Dwelling B

Fig. 3 illustrates the linear regression-based solar and wind corrected HLC estimation of Dwelling B from the coheating test scenarios, HLCs from all test scenarios are shown in Table 5. The largest discrepancy occurs between the baseline test HLC estimate and the integrated (fans) test estimate.

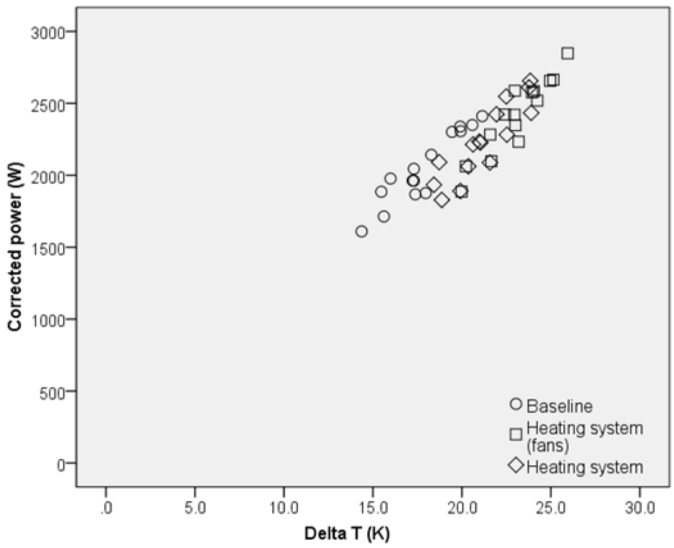

Fig. 3: Linear regression estimation of Dwelling B HLC from each coheating test scenario

Table 5: Summary of the estimations of the HLC of Dwelling B obtained from the three test scenarios

Test scenario	Analysis period	HLC (W/K)	Standard error (W/K)	Variation from baseline
LeedsMet (baseline)	21/12/12 – 10/01/13	114.5	2.3	n/a
Integrated (fans)	09/03/12 – 24/03/12	104.5	2.8	-8.7%
Integrated	21/02/13 – 07/03/13	105.2	1.5	-8.1%

A one-way ANOVA was used to test for differences in the HLC estimates obtained from the three tests. Data comprises 24 hour corrected HLCs. There was a statistically significant difference between the three tests, F (2,49) = 22.866 p = <0.001. Gabriel post-hoc comparisons of the three groups indicate that the baseline test (M = 114.4, 95% CI [112.3, 116.5]) resulted in a significantly higher estimate of the HLC than the integrated test using air circulation fans (M = 104.1, 95% CI [101.5, 106.8]), p = <0.001 and integrated test (M = 105, 95% CI [101.7, 108.2]), p=<0001. There was no statistically significant difference between either of the integrated tests (p = 0.96).

The use of circulation fans appeared to have no statistically significant impact on the HLC estimate for the dwelling. The comparatively low impact of circulations fans in Dwelling B compared with Dwelling A could be explained by the regular internal arrangement of Dwelling B and the provision of heat to all areas within the thermal envelope, aided by a multi-zone central heating system providing control of the internal temperature.

4.1.2.2 Dwelling C (control)

Table 6 provides the solar and wind corrected HLC estimations of control Dwelling C during the period in which the baseline test and integrated coheating tests were being undertaken in Dwelling B.

Table 6: Summary of control Dwelling C HLC estimations obtained using LeedsMet coheating

Test scenario	**Analysis period**	**HLC (W/K)**	**Standard error (W/K)**	**Variation from baseline**
Baseline	21/12/12 – 10/01/13	105.5	2.2	n/a

Integrated (fans)	09/03/12 – 24/03/12	99.2	2.5	-6.0%
Integrated	21/02/13 – 07/03/13	102.9	1.0	-2.5%

A one-way ANOVA was used to test for differences in the HLC estimates obtained from LeedsMet coheating of the control dwelling during the three tests. Data comprises 24 hour solar corrected HLCs. There was a statistically significant difference between the three tests, $F(2,49) = 10.68$ $p = <0.001$. Gabriel post-hoc comparisons of the three tests indicate that the integrated test using air circulation fans (M = 98.9, 95% CI [96.6, 101.2]) resulted in a significantly lower estimate of the HLC than the baseline test (M = 105.5, 95% CI [103.5, 107.6]), p = <0.001 and integrated test period (M = 102.8, 95% CI [100.5, 105.1]), p=0.042. There was no statistically significant difference between the baseline test and integrated test (p = 0.197).

4.1.2.3 Comparison between test Dwelling B with control Dwelling C

From Fig. 4 it can be seen that both dwellings' 24 hour HLC estimates tend to respond in similar fashion to dynamic factors present during the baseline LeedsMet coheating test ($R^2 = 0.816$). The outlier near the top right of the regression line represents the 24 hour period following the greatest change in external temperature during the test, which is symptomatic of the steady-state coheating analysis. This strong relationship enables Dwelling C to be used as a control dwelling with a reasonable degree of confidence. A paired-samples t-test was conducted to compare the 24 hour HLC estimates of Dwelling B and Dwelling C during the baseline measurement test. This revealed that there is a significant difference in the HLC estimates for Dwelling B (M=114.4, SD=4.7) and Dwelling C (M=105.5, SD=4.5); $t(40)= 6.259$, $p = <0.001$; thus the control dwelling will only be used to compare relative change in the HLC estimates.

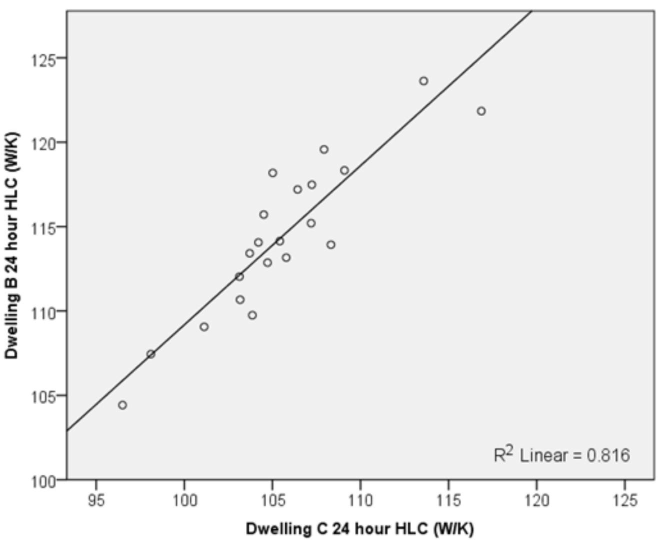

Fig. 4: Correlation between 24 hour HLC estimates of Dwelling B (test) and Dwelling C (control) during the baseline HLC estimation period

Fig. 5 shows a reasonable correlation ($R^2 = 0.624$) between 24 hour HLC estimates during the integrated test in which air circulation fans were used. In Fig. 6 it can be seen that the correlation was weaker ($R^2 = 0.468$) during the integrated test without air circulation fans. The lower correlation evident during the integrated tests could highlight the comparative weakness of a dwelling's heating system to respond quickly to changes in ΔT, compared to the heating equipment installed during a LeedsMet coheating test. This could be due to the lower thermal inertia of the electric resistance heaters used in LeedsMet coheating compared to the central heating system. Further analysis is required to establish if this is the case.

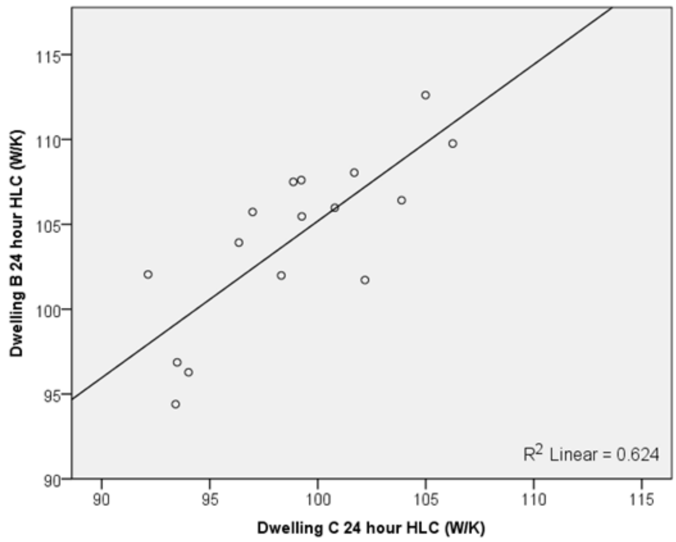

Fig. 5: Correlation between 24 hour HLC estimates of Dwelling B (test) and Dwelling C (control) obtained during the integrated test with fans

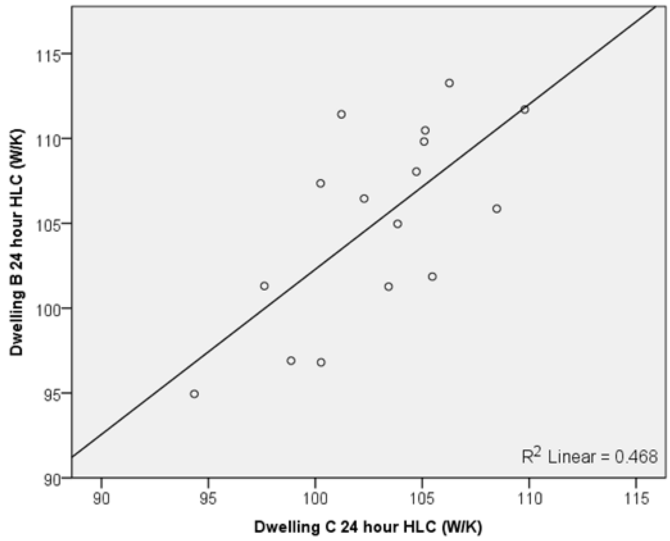

Fig. 6: Correlation between 24 hour HLC estimates of Dwelling B (test) and Dwelling C (control) obtained during the integrated test

The HLC estimates derived from the integrated tests in Dwelling B were significantly lower than the baseline estimate. The HLC estimate from LeedsMet coheating of control Dwelling C during the integrated test with fans was also significantly lower than the baseline estimate.

In situ measurements of heat flux on the external walls of the control and test dwellings showed a reduction in thermal transmittance from the baseline test period to the integrated (fans) test period, see Table 7. The reduction in external wall thermal transmittance accounts for 49% of the total reduction in HLC estimate of the control dwelling and 43% of the test dwelling.

Table 7: Reduction in the thermal transmittance of the external walls of the test dwellings from the baseline test to the integrated test with fans

Dwelling	Baseline test external wall *in situ* U-value (W/m^2K)	Integrated (fans) test external wall *in situ* U-value (W/m^2K)	External wall area (m^2)	Reduction in external wall heat loss (W/K)
B (test)	0.33 (± 0.01)	0.28 (± 0.01)	84.28	3.9
C (control)	0.34 (± 0.02)	0.30 (± 0.01)	84.28	3.1

The reduction in thermal transmittance is attributed to a continual decrease in the moisture content of the building fabric resulting from prolonged heating during the testing programme. Both dwellings were continually heated from October 2012 to April 2013. Hygrothermal simulations have shown that the thermal transmission of the building fabric reduces during the first years of a dwellings operation as heating drives residual construction moisture from the fabric (Holm *et al.* [33]). It is probable that other thermal elements also experienced a reduction in thermal transmittance. Hence, it is thought that a significant proportion of the discrepancy between the baseline test and integrated tests HLC estimates can be attributed to a reduction in the thermal transmittance of the test dwelling. It is therefore probable that if the thermal transmission of the building fabric had remained stable across the test programme, the discrepancy between the baseline and integrated tests HLC estimations would have been less.

4.2 Internal temperature control

It can be seen from Fig. 7 and Fig. 8 that the LeedsMet coheating maintains a closer control over internal temperature compared to the integrated test methods. The temperature remained within a generally stable range (amplitude 0.1 K) in each zone of the test dwellings, except for periods of high solar gain which are denoted as outliers.

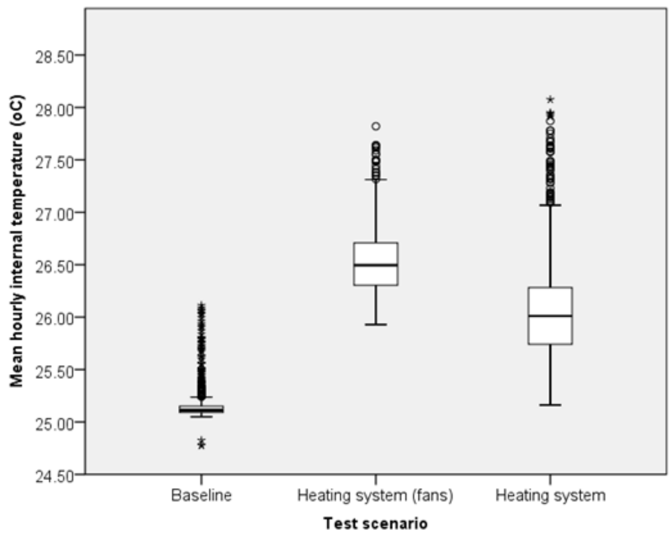

Fig. 7: Box plot of the mean hourly internal temperature in Dwelling A during the three test scenarios

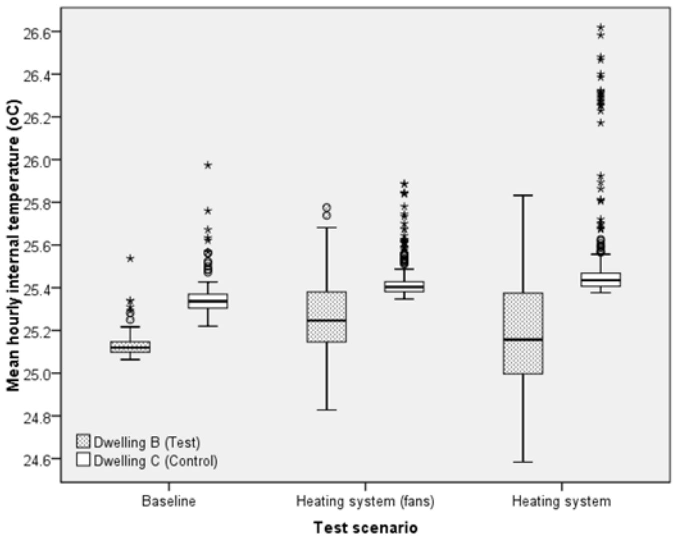

Fig. 8: Box plot of the mean hourly internal temperature in Dwelling B (test) and Dwelling C (control) during the three test scenarios

The reason for the lower positive skew and number of outliers during the integrated test scenarios in Dwelling B compared to Dwelling A is thought to be due to under-heating occurring in the north facing rooms in Dwelling B during periods of high solar radiation. High solar gains resulted in overheating in the south-facing rooms containing the wall mounted thermostats; this caused the boiler to cease supplying heat to the rest of the dwelling. The ΔT between the north and south rooms of Dwelling B meant that the mean internal temperature of Dwelling B remained close to the thermostat set point.

Individual zone temperatures during integrated coheating were characterised by an oscillating pattern around the mean temperature, with amplitude of ~ 0.5 K in Dwelling A and 1 K in Dwelling B. The mean internal temperature in Dwelling B was maintained closer to the thermostat set point of 25°C and remained more stable and homogenous throughout the integrated test periods than in Dwelling A. The closer control in Dwelling B was probably due to its zoned heating configuration, radiator distribution and dwelling form. The use of air circulation fans reduced the interquartile range of the mean internal temperature in both test dwellings. This suggests that the use of air circulation fans can facilitate greater control of internal temperatures.

The small HLC estimate discrepancy between the integrated test involving fans and the baseline test in Dwelling A would suggest that the higher amplitude of the oscillation in internal temperatures has a low impact on the HLC estimate. However, the LeedsMet approach facilitates a stable and homogenous temperature throughout a test dwelling and ensures greater precision between tests. The experiments undertaken highlight the variation in heating characteristics that can be experienced between differing dwellings.

4.3 Other findings

The test programme also highlighted issues with the installation of the central heating systems. In Dwelling A, a TRV was fitted to the hall radiator which was close to the main control thermostat. This resulted in problems with overheating in other areas of the as the TRV was restricting the supply of heat to the hall causing the boiler to cycle excessively (causing the loss of 8 days data). This was resolved by setting the hall TRV to maximum. In all three dwellings the TRVs were incorrectly positioned, vertically at the top of the radiator, which will have reduced their effectiveness in heating the dwelling. The zone thermostats controlling the boiler interlock in Dwelling B were wired to the wrong actuator valves, resulting in the ground floor thermostat controlling the first floor heating and *vice versa*; this issue was responsible for the hiatus period prior to rectification.

Dwelling A's boiler efficiency was calculated by dividing the energy output of the boiler measured by the heat meter (Q) by the energy supplied to the boiler, calculated from the metered gas supply. The calculated boiler efficiency of 84% during the integrated tests was lower than the boiler's SEDBUK rating of 90.1%. An additional advantage of using the dwellings own gas-fired central heating system to undertake an integrated rather than a LeedsMet coheating test, is a reduction in the energy costs and CO_2e emissions. If an 84% efficient gas boiler is used to provide the heat input during a coheating test, a 54.7% CO_2e emission reduction[1] and 63.4% cost reduction[2] can be achieved compared to mains electric heat input[3].

5 Conclusions

The initial findings show good agreement between the LeedsMet coheating and the integrated method, though further tests will need to be conducted to enable any firm conclusions to be drawn about the precision or accuracy of the integrated method. Although the LeedsMet coheating method is likely to be the more precise, such precision might not be required for basic compliance or quality assurance procedures. Instead, it may be more appropriate in the academic sphere or in dwellings that have been designed to have a very low HLC, such as Passivhaus.

The findings presented suggest that using the dwelling's own heating system to deliver heat during a coheating test is acceptable and that a heat meter measuring boiler output is a suitable device for obtaining a reasonable estimate of the power input from the space heating system. The discrepancy between the boiler efficiency stated by the manufacturer and that measured *in situ* means that calculating heat input to a dwelling from metered gas consumption cannot provide an accurate estimate of heat input into a dwelling.

The effect of introducing air circulation fans in Dwelling A suggests that the movement of air, and thus heat, within the dwelling could be the greatest source of discrepancy in the HLC estimates observed between the LeedsMet coheating test and the integrated coheating test. This implies that the integrated coheating method is more appropriate for use in dwellings without a complex internal arrangement, or large areas without heat provision. However, the integrated method may produce an estimate of a dwelling's HLC that is more representative of how a dwelling performs in-use. The use of portable electric heaters and air circulation fans in LeedsMet coheating is effective at creating a homogenous internal temperature, which ensures consistency between tests and a more valid comparison with steady-state HLC predictions. However, it is unlikely that a dwelling's heating system and occupant behaviour will replicate these conditions in the field. Therefore it can be assumed that the HLC derived from an energy signature analysis of an occupied dwelling will be closer to that obtained from integrated coheating rather than LeedsMet coheating. Thus, in the case of Dwelling A, both the integrated coheating test and energy signature analysis may fail to identify the fabric performance gap, or may underestimate the scale of the gap. This brings into the question the legitimacy of comparing a HLC obtained from in-use monitored data to HLC predictions using current steady-state models. As a consequence, a more complex HLC prediction model, which accounts for the provision and movement of heat within a dwelling, may be required to enable the accurate quantification of a fabric performance gap from in-use monitoring data.

The information provided by an integrated coheating test reveals more than just an estimate of the HLC of a dwelling and fabric performance; it also provides information relating to the performance and characteristics of the space heating system, as it tests the dwelling as an entire system. Experiments involving the integrated coheating test identified significant issues with the heating systems in the test dwellings. An integrated coheating test performed after dwelling completion could be undertaken as part of a holistic whole house commissioning process. The procedure could be used to identify issues relating to the heating system, such as

[1] Based upon UK 2013 values for natural gas of 0.18404 kgCO_2e and mains electricity (including transmission losses) of 0.48357 kgCO_2e (DEFRA [34]).
[2] Based upon the mean UK 2012 price per kWh for mains natural gas of £0.0475 and mains electricity of £0.1544 (DECC [35]).
[3] Based upon a mean internal temperature of 25ºC, and the mean 2011 – 2013 heating season (November – February) external temperature for York, UK of 4.5ºC (BizEE [36]).

inappropriate delivery and control of heat and could highlight issues of space heating system efficiency. Thus, integrated coheating has the potential to identify fabric and heating system performance gaps.

The reduction in energy cost and labour required to transport and distribute coheating equipment means that integrated coheating should be a more financially viable whole house heat loss test than electric coheating. However, the period required to perform the test could be the greatest barrier preventing its use as a widely used regulatory compliance tool. Conducting an integrated coheating test in combination with a dynamic test to reveal characteristics of a building which relate to thermal mass properties could provide useful parameters which inform the building management system as to the behaviour of the whole house as a system, as well as assisting with the identification of a dwelling's energy signature from statistical analysis of future in-use data.

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