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The validity and reliability of co-heating tests made on highly insulated dwellings

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Abstract

The ability of a co-heating test to accurately identify a dwelling's envelope heat-loss coefficient has been explored using dynamic thermal simulation techniques, against a number of fabric specifications ranging from 1990 UK regulation levels through to modern Passivhaus requirements.

Simple analysis methods can underestimate the heat-loss coefficient, by up to 50% for the highest performance standards considered. Using the best test and analysis methods found the envelope heat loss coefficient could be determined for current stock to better than 10% accuracy in a three week test duration. However that accuracy could not be reliably achieved in a shorter period, nor could it be achieved with a dwelling specification representing emerging standards of insulation, unless longer test periods were used.

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Keywords: Co-heating; Envelope performance; Thermal performance; Simulation; Quality assurance

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1. Introduction

The co-heating test (as described for instance by Lowe and Gibbons [1]) is a relatively simple method that uses low cost equipment to determine envelope performance. The co-heating test has been used and promoted as a viable method for the quality control of the envelope; as a test to compare design to as-built performance.

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There are few academic assessments of the co-heating test appearing in the literature; most available publications are either promotional material or project reports [2-6]. Recently there has been resurgence in interest in the test [7-9]. However it does not appear to have been established that co-heating tests provide a reliable measure of envelope performance in modern domestic buildings typified by very high levels of insulated and air-tightness. The work reported here seeks to address that gap by assessing the ability of the analysis of co-heating data to reveal the underlying envelope performance of modern specification housing envelopes.

2. Background

2.1. Co-heating tests

The co-heating test procedure has been described elsewhere [e.g. 4, 5, and 7]. The basic concept is to use a highly controlled and measureable system to achieve and maintain an elevated internal temperature through a test period, and to accurately measure the total heating power input required to do so. Over the test period, the heating power needed to maintain an inside outside temperature difference is considered as an indicator of the performance of the building envelope; the heat-loss coefficient HLC (W/K). Often the intent of the test is to compare the measured performance to the design specification in order to uncover failures in construction or detailing.

A crucial issue is that a stable control of internal temperature cannot be guaranteed, due to solar gains and varying external conditions; this issue becomes more problematic as envelope performance increases. The solar gains to a building cannot be directly measured, only ignored or inferred. Ignoring solar heat gains will lead to an underestimate of the envelope heat-loss, and so overestimate a building's performance. Our concern is that for emerging high performance envelope specifications, weaknesses in the co-heating test procedure become significant; potentially producing misleading overestimates of envelope performance, and so limiting the ability to detect common modes of envelope failures.

2.2. Co-heating Analysis Methods

While the co-heating measurement procedure is straightforward, the reliability and accuracy of the result rests with the analysis method used to account for the variation in temperatures and the existence of solar gains. Published descriptions of co-heating testing are often vague over details of analysis.

One method (termed here the "Energy Balance" method) disregards solar gains. The envelope performance is determined through the ratio of the daily average heating load and the daily average temperature difference (ΔT). The assumed response of the building is therefore;

$$E = H_{LC}.\Delta T \qquad (1)$$

where:

E is the daily average heating load (W);
H_{LC} is the envelope heat-loss coefficient (W/K); and
ΔT is the daily average temperature difference (K).

An alternative method found (the "Regression" method) assumes the daily heating response of the building to be:

$$E = H_{LC}.\Delta T - A.S \qquad (2)$$

where:

E, H_{LC} and ΔT are as defined above, and;
S is the daily average solar irradiance on a plane (W/m^2); and
A is the effective solar aperture of the envelope in that plane (m^2).

The parameters HLC and A are determined through regression of daily total or averaged S and ΔT on E.

When these test and analysis methods are tested against monitored performance in field trials [7] it has been found, unsurprisingly, that different methods produce different results, but since the true HLC of the test cases cannot be known the absolute accuracy or reliability of any method could not be determined.

3. Assessment by Simulation

We have used dynamic thermal simulation to test co-heating analysis methods. Using simulation, a specific envelope performance specification can be used to generate synthetic co-heating data. In this work we are using HTB2, a dynamic finite difference simulation model developed by one of the authors [10]. This model has been successfully validated against ASHRAE Standard 140 [11], and has in fact been used to develop recent benchmarks for that standard [12].

In the work presented here we have considered one house type, considered typical of recent practice in the UK; a detached 80m^2 two story dwelling- further information is given in table 1. To produce a worst case scenario, all glazing is south facing, with no significant site obstruction. In order to remove uncertainty due to simulation of ground contact structures, the ground floor construction was been specified as an adiabatic layer, though with a representation of appropriate internal thermal mass.

Using a consistent geometrical specification, four different envelope specifications were considered. These specifications were based on UK practice for:

- 1990's regulations, to represent existing but modern building stock;
- 2010 standards, representing good practice new stock;
- 2012 standards, to represent best practice/future stock;
- the emerging Passivhaus specification [13], to represent best future stock.

These cases are denoted as 1990, 2010, 2012 and Ph, respectively, in the text. The basic envelope performance specification for each of these is given in table 2.

In order to test the influence of thermal mass on the test performance, two cases for the Passivhaus specification were considered; lightweight and heavyweight thermal mass materials. The other cases used materials and thermal mass appropriate for the era's typical construction practice.

The co-heating tests themselves were simulated by setting a 24 hour heating setpoint for the interior zones using an idealised (e.g immediate response, perfect control) convective heating system. No cooling, internal heat sources, or occupancy patterns were specified, and no ventilation, window blinds, or curtain operations were set. The simulation algorithms chosen allowed for variations in solar gains and in longwave and convective exchanges at surfaces, as determined by the weather data, however infiltration rates were fixed at the design specification throughout. Each simulation was run for a full year; January to December, using CIBSE TMY weather data for a south UK location. As we a primarily considering the ability of an analysis method to determine an underlying performance, we do not believe the use of a single location limits our ability to draw conclusions.

Table 1 : Test case building geometry

Volume	210 m^3
Ground floor area	40 m^2
Total floor area	80 m^2
External opaque wall area	131 m^2
South facing glazing area	9 m^2
Other glazing area	0 m^2

Table 2 : Envelope specifications for the case studies.

Case:	1990	2010	2012	Ph
Wall U-value (W/m^2/K)	0.45	0.30	0.15	0.10
Roof U-value (W/m^2/K)	0.25	0.20	0.13	0.14
Ground floor U-value (W/m^2/K)	0*	0*	0*	0*
Glazing U-value (W/m^2/K)	3.00	2.00	0.80	0.80
Glazing Transmission	0.64	0.54	0.50	0.50
Infiltration rate (air changes/h)	0.75	0.50	0.30	0.03
Target HLC (W/K) **	162	110	61	33

* *Ground floor treated as an adiabatic structure*

** *as determined by steady-state simulation*

3.1. Establishing benchmark data

A successful analysis procedure must be able to produce a reliable estimate of the actual envelope heat-loss coefficient. In order to provide suitable benchmarks for comparison in each case, the simulation engine was used to estimate each case's target envelope performance through a full dynamic simulation of a steady-state design day: an external temperature of -1C; an internal (air temperature) setpoint of 22C; and zero solar gain. In essence we are simulating what might be considered the ideal co-heating test condition of a continuous winter night. As the simulation engine itself has been used to determine the target HLC, identical algorithms were in use for both the benchmark and the simulated co-heating test. Table 2 also summarises the target envelope HLC's so determined.

3.2. Comparison criteria

In order to compare different analysis methods, we set criteria for success; a relatively unadventurous error band of ±10%. That is, a method would be deemed successful if it produced an estimate of HLC within 10% of the target value for that specification, and displayed an uncertainty in that estimate of less than 10% of its value. Note that we are not considering measurement accuracy in the uncertainty of the end result.

4. Assessment of analysis methods

In order to ensure consistency between cases and building types, the shoulder-seasons (where heating load is small) for the highest performance specification are removed from all cases; we considered for analysis data only 120 days from 15-November through 15 March.

Table 3 presents the estimates of HLC resulting from the analysis methods considered. As the full data set (e.g. 120 days) is available for each analysis this represents the best possible performance of a method. The confidence in the estimate of HLC is determined from the day-to-day variance for the Energy Balance method, and from the regression statistic for the Regression methods; both represent one standard error. In this table results that fall within the 10% band of the target "truth" value are in **bold** type.

Due to vagueness in the descriptions of the methods found, two alternatives are presented for each basic method. The first energy balance method uses a full day's data; midnight–midnight average temperature and total heating energy. The second, in order to minimize the influence of solar gains, uses data only from the hour before sun-rise: 6AM. It can be seen that this latter analysis does reduce the uncertainty in the estimate, but both approaches significantly underestimate the heat loss coefficient.

Table 3: Analysis results of HLC from Energy Balance and Regression methods

Case	*Target HLC (W/K)*	Energy balance Daily (W/K)	Energy balance @6am (W/K)	Simple regression (W/K)	Limited regression (W/K)	"Best" regression method (W/K)
1990	*162*	125 ±21	143 ±11	**148 ±3**	**153 ±2**	**161 ±6**
2010	*110*	78 ±17	97 ±7	98 ±2	**101 ±1**	**109 ±4**
2012	*61*	35 ±13	49 ±6	49 ±2	53 ±1	**65 ±3**
Ph low mass	*33*	13 ±8	22 ±7	19 ±1	22 ±1	**34 ±2**
Ph high mass	*33*	13 ±8	22 ±7	19 ±1	21 ±1	**33 ±2**

Of the two regression variants the first, "Simple", uses all data available, whilst the second "Limited" analysis follows the data restriction rules described by Lowe and Gibbons [1], which remove days of high solar or low temperature difference. The regression results are marginally better that those of the energy balance methods, and the 1990 specification has now been successfully resolved. The enhanced limited data method improves results but the higher performance envelopes are still unsuccessfully identified. The regression method promises lower uncertainty in the HLC estimates, but this is misleading; accuracy has not been improved. Notably the variations in thermal mass appear to have little impact on the test results.

Due to its lower apparent uncertainty, we explored further the regression method, considering options in order to improve the method's performance. Each option was considered in isolation then the most promising options combined. The best results obtained were from a regression test and analysis that:

- used a high co-heating setpoint. Due to practical concerns (e.g. that high temperatures might cause damage such as warping wooden frames or affect the operation of design features such as PCM materials), 24C was the highest setpoint considered;
- defined the day, for temperature average and total energy, as 9AM-9AM;
- excluded days from analysis where the heating energy E was less than 10% of the design maximum load;
- excluded days from analysis where $S/\Delta T$ was greater than 2 $W/(m^2K)$.

Results from this modified method are summarized in the final column of table 3. This "best" procedure allows a good and useful identification of HLC across all the specifications, well within our required 10% accuracy.

5. Sensitivity to test length

The accuracy achieved by the "best" method identified above has been gained through the rather unrealistic and uneconomical assumption that the co-heating test can be run for a full heating season. In order to be a useful real-world procedure, the results of a co-heating test must be reliable when undertaken in a shorter timeframe.

Everett et al. [6], reporting on their development of the method, concluded that it was "... possible to establish the thermal characteristics of a house with measurements over typically only three weeks." In a service or regulatory context, time constraints may be greater. More recent reports generally indicate shorter time-scales; Lowe and Gibbons [1] suggested "... two to three weeks", while Wingfield et al. [4] suggest "... 1 to 3 weeks". Some reports appear to present results based on as little as two days of data [5].

Using the "best" method described in section 4, we investigated the optimal duration of a co-heating test. These results are illustrated in figure 1. In these results the envelope HLC is presented as the mean of the regression results obtained from each contiguous period of the stated duration possible within the heating season, and the uncertainty quoted is the standard error in that mean. The value reported is therefore the most likely result of, and the uncertainty in, any single test of that duration.

It can be seen that the duration of test is crucial to producing a reliable estimate of the envelope HLC; shorter test periods show much higher uncertainties in the result. For buildings characterised by 1990 and 2010 specifications (and we presume any older stock) the procedure can indeed produce reliable results within a three week test timeframe. However, in buildings with emerging envelope specifications, as exemplified by the 2012 and Passivhaus cases, an accurate and reliable result required significantly longer test periods; 6 and 8 weeks respectively. Should such a test be attempted in a shorter (e.g. 3 week) period, such accuracy could only be achieved within a very narrow window of opportunity; a 6 week period in mid-winter. Otherwise, once again the estimated HLC could be significantly underestimated, and so the estimate of the uncertainty in that value would be optimistic.

6. Conclusions

We have found that the envelope heat loss coefficient determined from the analysis of co-heating test data was highly dependent on the method of analysis used. We have confirmed that there was a tendency in the methods to underestimate the envelope heat-loss characteristic, and noted a tendency to imply (in the uncertainty produced by the analysis method) greater accuracy than warranted.

The most promising analysis method was based on a multiple regression using temperature difference and external solar irradiance as the independent variables. We found that the performance of the co-heating test and regression analysis methods could be improved by:

- increasing the test operating internal temperature well above normal room temperatures; 24C appears a reasonable compromise between accuracy and practicality;
- using a definition of a day as between 9AM to 9AM;
- discarding data from analysis when the heating load is less than 10% of the maximum design load;
- discarding data from analysis where $S/\Delta T > 2$ W/(m^{2}K).

Using these methods and procedures the co-heating test could identify the building's envelope heat-loss coefficient to an accuracy better than 10%, even for the most highly insulated and air-tight cases considered.

However in order to achieve these levels of accuracy in the high performance envelope cases test durations of 6 to 8 weeks were found to be necessary, or, if the test period was constrained to 3 weeks, the window of opportunity reduced to less than two months in a year.

We conclude therefore that the co-heating test (and analysis) is capable of accurately determining the heat-loss coefficient of a highly insulated dwelling, as typified by emerging low carbon dwelling specifications, when appropriate and consistent procedures are used. However, longer test durations than may be practical are necessary to achieve this. In addition, we note that without a well defined and consistent analysis method there is the potential for widely varying and misleading results to be derived.

In order to progress we feel the industry must determine the level of construction fault that must be detectable by a QA test, so as to fix the accuracy required and so help to decide whether quality assurance can be quick and low-cost, but limited, or high-quality but high cost. Unwanted accuracy may be costly, but so may unexpected uncertainty.

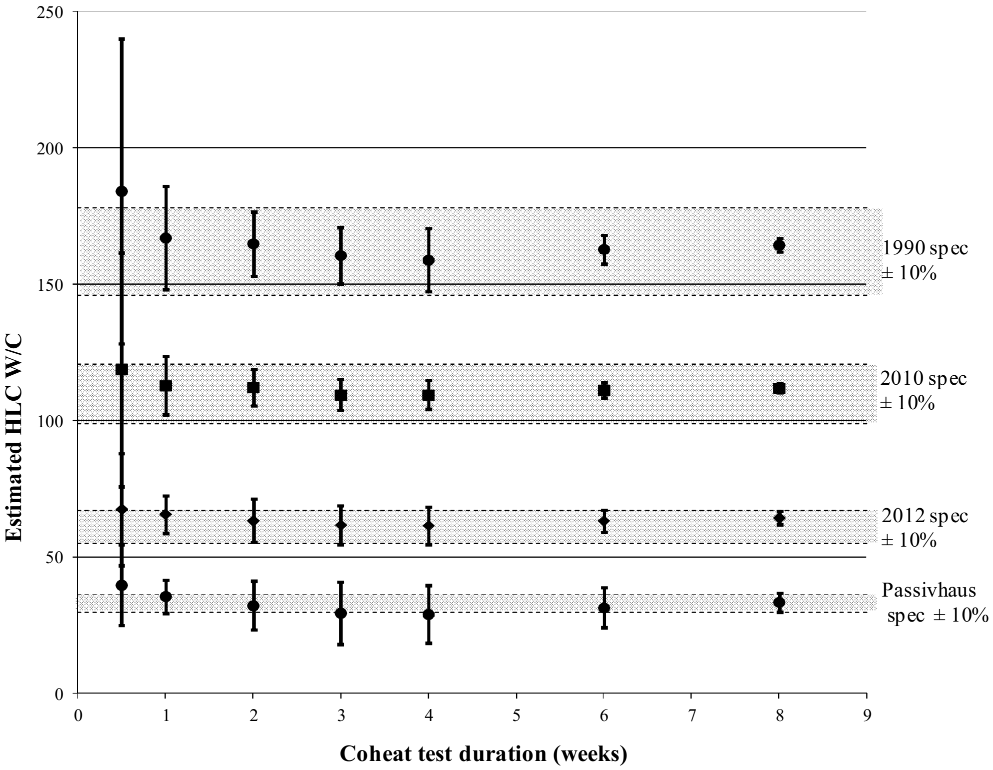

Figure 1: Sensitivity of analysis result to test duration

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