ADDRESSING THE THERMAL PERFORMANCE GAP: POSSIBLE PERFORMANCE CONTROL TOOLS FOR THE CONSTRUCTION MANAGER

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Construction practice has failed to deliver buildings that consistently meet their expected thermal performance; however, examples of good practice do exist. Buildings can be designed and built within acceptable tolerances and meet nearly zero carbon standards. Unfortunately, due to the negative implications associated with the performance gap there have been attempts to divert attention from measurement, with some being critical of methods that were used to identify the variance in building performance. However, the tools have proven reliable and the practice of thermal measurement which was once limited to scientists is finding its place in industry. Measurement is becoming more accepted and different tools are being used to assess thermal performance. The tools can add value to inspections, building surveys and assist with quality control. Construction professionals, not least construction managers, are gaining valuable insights through research undertaken and observations gained. The tests reviewed provide new methods of capturing evidence on building performance, thus allowing valuable information on the quality of design, workmanship and process to be gained. Use of thermal measurement and analysis tools should result in further improvements to building performance. The data from major performance evaluation projects are reviewed and presented.

Keywords: building performance, quality assurance, zero-carbon buildings.

INTRODUCTION

Approximately 34% of man-made emissions come from the built environment representing 45% of the UK’s total carbon footprint, with space heating loads accounting for the greatest proportion of emissions (Palmer and Cooper, 2013). Heating loads make up 62% of the total energy used in homes (DECC, 2013; 2014). Thus, the construction industry carries a significant burden, being responsible for the largest share of emissions by some way. Thus, there is pressure to improve the thermal performance of buildings and make substantial reductions in the energy required to heat and condition them.

The European Energy Performance of Buildings Directive (2010) and the demand for a nearly zero standard for dwellings by 2018, represents a significant challenge to the construction industry. The UK's aspirations to achieve nearly zero energy buildings during a tighter timeframe (by 2016) is ambitious, especially since there are relatively few studies that have measured thermal performance and understand how buildings behave when heated. Due to the lack of measurement, most professionals do not know when energy efficiency targets have been achieved. To achieve the reduction in

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carbon emissions required, improvements in thermal performance must be real, achieved in practice and not limited to aspirational designs. Unfortunately, differences between the designed thermal performance and that actually achieved have been found. Regardless of the aspirational design standard, research has revealed a considerable discrepancy; some buildings tested in the field can be double that expected (Stafford *et al*., 2012a; 2012b), it is not uncommon for dwellings to experience 60% greater heat loss than designed (Gorse *et al*., 2013; 2014).

The findings do not provide an example of an industry that is in control of performance. The range of performance across the dwellings is dispersed and requires process improvements to ensure buildings are delivered within acceptable levels of thermal performance. Before construction managers can achieve the degree of process control needed, they need the tools to measure and monitor the performance of the buildings being assembled. Where discrepancy from designed performance is large, remedial action will be necessary to bring performance back on track. However, as there is little agreed practice with regard thermal measurement and performance, acceptable levels of tolerance have not been established. Work is required to understand the discrepancy that is acceptable for construction practice so that a workable tolerance can be set.

UK specific targets will not be achieved unless tolerances are understood and buildings are designed with a suitable safety margin. The errors in design and construction should be removed by measurement and use of systems that eliminate assembly problems. Processes to prevent substandard materials being used and unauthorised product switching, should also be addressed. There are tools are being developed which can help alleviate such practice. An examples of real time process tool being applied to capture design, survey and performance data include the VRM technology system being tested through the BRE S-Impler Innovate UK project (BRE, 2015). The process issues can be overcome if the processes that lead to the desired performance can be recognised. Unfortunately there is limited use of the tools that actually measure and establish how the building performs.

Method

An overview of the methods used for assessing thermal performance, their reliability and possible applications are discussed. The observations are taken from the findings of a number of research projects undertaken at Leeds Beckett University. To provide examples of the findings, the discussion uses some primary data to demonstrate the performance of the tools. Further detail on the research methods can be found within the following research reports:

16. Joseph Rowntree Housing Trust Temple Avenue Projects (CeBE, 2012)
17. Coheating methodology (Johnston *et al*., 2013)
18. Technical Reports (CeBE, 2014)
19. Stamford Brook reports (CeBE 2014; Gorse *et al*., 2014)
20. DECC Core Cities reports (Gorse *et al*., 2014)
21. Saint Gobain Energy House (Farmer *et al*., 2014)

Measuring thermal building performance: Reliability, validity

The methods used for measuring a building’s thermal performance have become a topic of debate. The coheating test (Johnston *et al*., 2013) has been influential in recognising that many dwellings were not achieving their expected performance (Stafford *et al*., 2012; Gorse *et al*., 2014). However, following Butler and Dengle’s

(2013) investigation of whole building test methods, some doubts were raised over the reliability of the test. However, the research brought into focus what can go wrong where research methods are not applied correctly. The heat loss measurements at the heart of this debate are often difficult to capture, and with so many influencing variables, which need to be accounted for within the analysis, the current methods are largely limited to academic study. The field tests are exposed to naturally occurring phenomena, variable test conditions are expected and the reliability of results must be considered against the environmental changes that take place. Amongst other observable conditions, analysis of heat loss needs to take account of irradiation, humidity, moisture, temperature, wind etc. In some instances, the external test conditions may be so variable that tests are not applicable nor the results reliable. When external conditions cause significant changes to the internal conditions, such that they affect the ability to measure fabric performance all is not lost. Such results are often indicative of fabric failure. For tests to be undertaken on the building fabric, the fabric must offer a level of resistance and provide some effective envelope seal. Where thermal bypasses of the fabric and air changes are high, the thermal resistance offered by the fabric can be so poor that energy assessments monitor the changes in the weather rather than the building fabric resistance. Initial results of the DECC research found some properties experienced air change rates exceeding 20 changes per hour, meaning that any heat in the building was flushed out with changes in the wind every few minutes (Gorse, 2014). In the same study some buildings were found to be so leaky that the test could not obtain reliable results. Where the envelope does not offer an effective fabric enclosure the fabric cannot be tested. As with all methods there are limitations, those affecting coheating are identified in the method (Johnston *et al.*, 2013).

Tests have been conducted to explore the reliability and validity of the coheating test. In January 2010 a research team undertook a coheating test on a 2 ½ storey detached dwelling using the Whole House Heat Loss Test Method (Wingfield *et al.*, 2010). The test was undertaken as part of a project designed to test the thermal performance of prototype dwellings in situ for the Derwenthorpe housing development. The Heat Loss Coefficient (HLC) resulting from the January 2010 coheating test was 132.9 (± 1.5) W/K. In December 2012 a different research team undertook a coheating test on the same dwelling in accordance with the 2012 iteration of the Coheating Test Method (Johnston *et al*, 2012). The HLC resulting from the December 2012 coheating test was 133.8 (± 1.9) W/K. The two test results obtained 35 months apart with differing research teams differed by < 1%. An independent sample T-test of the 24 hour solar corrected HLCs obtained from both tests showed no statistically significant difference ($P = 0.432$) between the HLCs obtained in each test, this suggests a reasonable level of repeatability in the coheating test in this instance.

Alternative approaches to whole house heat loss

In addition to checking the repeatability of the coheating method on the same dwelling in the field, opportunity also presented itself to cross check alternative methods through the Saint Gobain Energy House project (Farmer *et al.*, 2014; Weaver and Gibson, 2014). At each of the six stages of the retrofit project, blind tests were undertaken independently by the Leeds Beckett University research team and Saint Gobain Reserché. The Saint Gobain team used their QUB (Quick U-value of Buildings) method (Pandraud *et al.*, 2014) and the Leeds team used the coheating test. Due to the unique facility offered by the Salford Energy House, it was possible to perform each test separately and sequentially, under the same controlled external conditions, something which is not possible to achieve in the field. QUB is a very simple diagnostic method that enables the heat loss coefficient to be calculated over one or two nights. It measures the temperature response during a heating and free cooling period. A level of uncertainty is estimated to be ± 15% when performed on a single night which becomes less as the test period is extended (Pandraud *et al*., 2014). Cross checking of the methods at the energy house showed a much closer fit than expected. Good agreement was found between the results of both testing methods (Farmer *et al*., 2014). The blind nature of the tests, showed that both methods were able to reliably identify the heat energy transferred through the fabric. The results of the QUB tests suggest there is merit in developing a commercially viable alternative to the coheating test which may encourage more widespread performance checks in the industry.

Other methods, based on in-use monitoring data have also been cross checked with the coheating tests and show comparable results. The Integrated coheating, currently being developed by Leeds Beckett University is of interest if integrated with smart monitoring (Farmer, 2015). The test is a variation on electric coheating that uses the test dwelling's own heating system to provide the heat input, and control of internal temperature, throughout the test. A heat meter is used to measure the space heating energy delivered to the test dwelling; this allows the efficiency of the heating system during the test to be measured. This means that an integrated test has the potential to quantify both fabric and system performance, hence it assesses the dwelling as an integrated system. Initial tests show a reasonable agreement between the heat loss coefficient (HLC) obtained from integrated coheating and the HLC obtained from electrical coheating. Integrated coheating type test will experience many of the same variations as current coheating tests. However, as the provision of heat to the test house during an integrated coheating test is more likely to resemble what is experienced during the dwellings operation, the HLC estimate obtained from integrated tests is more likely to be representative of how the dwelling will perform in-use. As integrated coheating is less resource intensive and can utilise cheaper forms of heating, it has greater potential than electric coheating to be used as a viable commissioning and monitoring test. The importance of measuring the energy delivered for space heating, was something that was previously missing from similar work that did not show the same capability in providing HLC (see earlier work by Sutton *et al*., 2014). The Integrated coheating, utilising heat meters, represents a considerable change in the potential data that can be extracted during in-use monitoring.

Validity: Aggregating and disaggregating data

Whilst alternative methods of measuring the HLC of a building might hold commercial advantage the real power of using a coheating test to determine thermal performance and disaggregate the building's heat transfer for elements. In particular, to perform an analysis of the empirical heat loss data using the standard definitions of heat transfer coefficients defined in ISO 13789 (ISO, 2007), separating ventilation heat loss as an independent factor.

The prolonged steady state internal environment demanded for the coheating test provides ideal conditions for accurate heat flux measurement to ISO 9869 (ISO, 1994) and detailed thermographic analysis. This disaggregation of the results is crucial when it comes to assessing the performance gap. Rather than simply listing how much the whole house HLC measured exceeds the predicted figure, by splitting both measured and predicted figures into these component values the tests can provide quantitative information for each building element identifying the specific elements that are responsible for the performance gap. Such work is essential to ensure efforts are concentrated when attempting to minimise the gap. In conjunction with thermal bridging computation, the measured elemental and whole house heat loss values provide a comprehensive assessment of heat exchange and help to close the loop.

Air leakage

Initial tests on a small and varied sample of existing buildings in the UK (Gorse et el., 2014), found some buildings to be so leaky that it would not be possible to perform tests using standard electrical heating equipment. The power required to elevate the whole house to a sufficient temperature above its surroundings would overload and fuse the property's electric supply. This has important implications as structures of this nature cannot be accurately tested using portable electrical heating. In relatively small buildings, air changes rates of ≈16 – 29 h-1 @ 50 Pa were found in properties that had been previously occupied. Very leaky buildings, such as those with the conditions observed suggest that it would not be possible to adequately heat the whole building during winter without excessive heat input. Aside from the testing discussion, Santamouri *et al*. (2014) suggest that we are freezing the poor in Athens, however, the initial results reported here are a clear indication of the same problem in the UK's colder climates.

Air testing in retrofit properties can be particularly revealing. In similar properties with similar retrofit measure air permeability results can be surprisingly different. In recent studies where floor and edge seals were overlooked improvements were limited (24 – 20 m3/ (h.m2)@50Pa). In properties, where attention was given to detail design and workmanship stepped changes from around 19 to 4.73 (m3/ (h.m2)@50Pa and 16.77 to 6.43 (m3/ (h.m2)@50Pa were achieved (Gorse *et al*., 2015). Understanding the level of airtightness achieved is a relatively straightforward commercial test. Furthermore, the introduction of a thermal survey during the heating season under depressurisation provides valuable information on the building's behaviour.

Addressing the challenge: Interventions and effects

The tools used to measure the performance are of limited use if not applied in a systematic way. Those that can readily assist with quality assurance can be accommodated within all forms of construction, the more scientific studies should be applied in a manner that suits the situation and care given to the testing regime so that the key issues can be properly measured. There are some notable examples of research that clearly show the step change in behaviour.

The Temple Avenue project (CeBE, 2010) is a typical example of staged intervention demonstrating how improvements can be made to new developments and retrofit projects. At the same time as undertaking the refurbishment of an existing 1930's property to the same thermal and energy performance as two highly energy efficient new-build prototype dwellings the Joseph Rowntree Housing Trust also developed and tested prototypes before producing the final designs for a new 540 home development (CeBE, 2010). This scale of the research does not need to be applied to whole buildings, often it is possible to examine elements in some detail. Work with Knauf Insulation on the effectiveness of different products has offered a lead in this area. An example from a recent study focusing on party wall interventions is shown below. The results clearly show how the intervention of retro-fill blown mineral fibre significantly changes the thermal behaviour of a masonry cavity party wall.

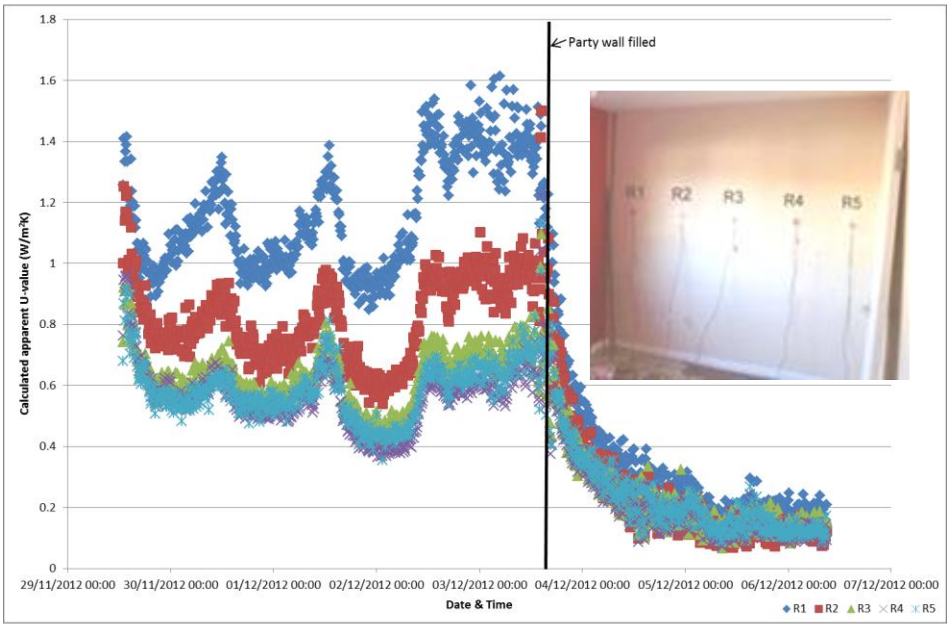

Figure 1: An unfilled cavity party wall exhibiting characteristic signs of thermal bypass and air movement, the full-fill intervention creates a fabric that controls movement and significantly reduces heat loss.

The results show significant improvements to the thermal performance of the wall. Prior to the intervention of full-fill insulation the wall failed to provide an effective barrier to the outside elements. The variability of the heat flow before the insulation fill was introduced suggests that the wall was not effectively sealed and experienced problems due to air infiltration, bypasses and other breaches of the building fabric. The graph (Figure 1) shows how insulation added to existing walls can provide a consistent and performing fabric, offering the desired thermal resistance and creating a separation between internal and external environment conditions.

The Saint Gobain Energy House Project (Farmer *et al*., 2014) provided a full-scale and staged retrofit to the replica Victorian Terrace. In the Energy House Project, the whole building, which is constructed within a controlled environment, enables the temperature and environmental conditions surrounding the property to be controlled. Different retrofit upgrades were added to the property and three expert teams using multiple methods of measurement analysed the results. The project represents an important point in building performance research; in most other retrofit trials the full retrofit is applied and it is difficult to investigate the individual contribution of the systems that make up the whole. Specifically, the Energy House project provides an example of a systematic and staged approach to the measurement of thermal upgrades. The knowledge gained on the elements and whole building's performance provides a key step forward in understanding the behaviour of a building that is representative of a significant proportion of the building stock in the

The staged elemental changes confirms the interventions contribution to the reduction in the building's heat loss. Under the facility's test conditions greater certainty was achieved and ambiguity, which has previously resulted from trying to compare different houses and house types in variable climatic conditions, was removed. There remain limitations of the test environment, as the conditions are not real, but the approach has advantages. Thus, it was possible to focus more thoroughly on the building changes introduced and measure their impact, and validate the methods.

The Energy House laboratory allowed each thermal upgrade to be exposed to a range of conditions, the same exposure being repeated for each upgrade allowing direct comparison of six upgrades. Standardising the test environment and removing the uncontrollable conditions experienced in the field allowed the research teams to concentrate on the improvements made and the accuracy of the methods used.

Test and measures: Using the tools to improve the construction process
Tools often used during field work are listed (table 1 and 2) and from observations made during their application suggestions are provided on their ability to inform the construction process. In many of the studies reported, detailed photographic and documentary evidence was collected during the construction process. Such information proved useful during building forensics, when attempting to uncover why problems occurred and performance differed from that expected. Such process and construction data is clearly important when identifying the root cause a problem and making improvements to the construction process.

Clearly all the tools discussed are of benefit to understanding building performance, however, for small scale developments, many, such as coheating, are too resource intensive to be economically feasible. Contractors are benefitting from the findings of performance evaluation work and, although it is not yet possible to integrate all of the test methods into the construction process, there are benefits in using some of the simpler tools that have fewer resource constraints.

Table 1: Inspection methods: thermal performance

Field tests and measures	Information gained and suitability to inform the construction process
Photographic and video records (with meta data, for example: date, time, position, elevation, altitude, weather data links)	Chronological record of construction work, identification of materials installed and assembly. Log to ensure material fit as spec and design. Possible to use the information, record in real time using systems such as vrm technology
Survey data temperature, humidity, surface temperature	Identification of consistent and irregularities. Identification of moisture and thermal patterns. Quick laser guided temperature sensors can be used to inspect properties during winter heating. These can be easily accommodated within inspection processes.
Air tightness and smoke tests.	Air change, permeability and leakage detection. Relatively inexpensive, should be used to assess air tightness in new buildings, mandatory for a sample, however there is benefit for greater application.
Thermography (without pressurisation)	Identification of hot and cold spots, indication of cold bridge, moisture and bypass. With the intervention of thermal cameras linked to mobile phone technology the cost of the equipment has reduced drastically and can be used during inspections during winter heating periods
Thermography with air tests, smoke test, bypass detection.	Cold bridging, air leakage, bypass, air circulation paths

Within the research projects already discussed, the performance measurement tools have proved informative in recognising where performance has been achieved and where further work is required. The use of simple tests such as blower doors, supported with thermal cameras or smoke guns to identify air leakage proved useful in identifying problems (Table 1). The blower door, smoke and thermal surveys can be used in all domestic projects. Problems, recognised through simple tests, may be a result of design failures or poor workmanship. Once the cause of the faults are recognised, through forensic investigation, including the review of design documents, site photographs and site records, the aspect of the construction or design process that requires change can be addressed, becoming the focus of further monitoring.

The heat loss tests and measure remain resource intensive and are economically limited to large scale projects. However, the results of the tests have proved invaluable in recognising performance differences and where buildings have met their design targets. Table 2 identifies the information that can be gained from different tests.

Table 2: Thermal performance tests: heat loss and thermal resistance

Test method	Information gained and suitability to inform the construction process
Integrated coheating: In use whole building fabric and system monitoring.	In-use feedback of building performance – potential constant feedback if integrated with smart technology (HLC), suitable for fabric and service commissioning and in-use efficiency. Potential to provide dynamic, steady state signatures, thermal response and behaviour. Could be used for end of line commissioning test.
QUB Quick U-value of buildings: dynamic energy signature and building response.	Overnight test (HLC), suitable for commissioning test at the end of the build period. Still exploratory, but early indications suggest that this test will be useful in providing a rapid indication of thermal building performance.
Coheating: Heat loss coefficient, also the heated building lends itself to thermography, building survey and forensics	Whole building diagnostics (HLC), element and whole building investigation and prototype fabric testing. Very useful as the base line test to investigate prototypes and new systems. Due to high resource requirements it is economically limited to large scale developments. Beneficial for prototype and product testing, provides ideal conditions for further building forensics.
Heat flux measurements and surface temperature measurement (performed concurrently with coheating)	Elemental performance . The heat flux measurements require the similar controlled conditions to the coheating tests. It is expected that such tests would be used on small samples and prototypes, being too resource demanding for testing all buildings.

CONCLUSIONS

Attempting to close the loop between designed and actual energy consumption in buildings is not an easy challenge; the multifaceted approaches outlined in this paper provide an indication of a sample of tests and methods for measuring thermal building performance. The use of such tools within the practice of construction needs to be better understood. It is clear that there are merits in pursuing methodologies like the coheating test to gain detailed understanding of issues at the same time as ensuring commercially viable tests are developed that can support performance checks. Some tests are resource intensive and there use would be economically prohibitive in the testing of all new homes and retrofits. For prototypes it is essential that developers and contractors understand the performance achieved and reasons for not achieving performance. Once an understanding of what works is gained, then simple checks can be made to ensure that performance conforms with design expectations. The quicker tests such as blower door, thermal surveys and smart energy monitoring provide relatively inexpensive feedback. Further work needs to be undertaken to see how these can be adapted for use as part of process and conformance checks.

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