1 Introduction

Room space heating is a major source of energy use in the EU, accounting for approximately one third of energy use when considering both domestic and non-domestic buildings[1]. In England, approximately 90% of homes use central heating[2], usually fired by gas. Gas fired boilers are used for space heating, generally using a *wet* system of wall mounted radiators, also providing hot water for cleaning and washing. These types of systems are the predominant heating system in the UK and their performance has a major impact on the amount of energy used for domestic space heating. Domestic energy demand in 2013 was 29% of the total UK final consumption of energy, with space heating accounting for more than 60% of this figure[3]. This means that approximately one fifth of the energy consumed in the UK is by central heating boiler systems, making their effective performance an important part of UK energy policy. The English Housing Survey[2] indicates that 24% of homes in England (approximately 5 million) could benefit through the installation of improved heating controls.

Shipworth et al.[4] highlighted the shortage of data regarding the effectiveness of heating controls other than the existing models outlined in the Standard Assessment Procedure (SAP)[5]. The Standard Assessment Procedure is the UK regulatory assessment model to establish the projected energy performance of domestic properties. Shipworth et al. conducted a study of 427 homes, and questioned the performance of controls in terms of energy saving. The study relied, to some degree, on householders to report information and install two temperature sensors. This resulted in a number of data collection risks that Shipworth et al. clearly identified. A more recent study by the Building Research Establishment (BRE)[6] used a larger sample of 823 homes. Three temperature sensors and Energy Performance Certificate ratings based on a model known as RdSAP (Reduced Data SAP)[5] were used to understand the properties. However, the focus of the BRE study was concerned with internal temperatures rather than controls. A record of the presence of wall thermostats and timers was taken, rather than a full description of the control system. While the BRE study is useful in challenging assumptions about internal temperatures held within the SAP model, its usefulness in the understanding of controls is more limited. It should be noted that, while closely aligned, internal temperatures are only be a loose proxy for actual energy consumption, as shown by Summerfield[7]. It is possible that other control methods may be used to manage the temperature in a property, such as building users opening windows. This can give rise to situations where the temperature declines while energy continues to be consumed[8]. The gap in current knowledge with regards to the performance of controls is also addressed in Munton et al.[9].

The British Electrotechnical and Allied Manufacturers Association (BEAMA) Heating Controls Study[10], was funded by the BEAMA Heating Controls Group that represents the association of controls manufacturing companies. This is of a different order of granularity to the large-scale studies previously discussed. It investigated the performance of controls in a highly monitored single test property within an environmentally controlled space, removing the impact of the additional variables such as external weather, solar radiation and occupant behaviour, which makes data analysis for individual measures in field trials difficult to isolate[11]. It should also be noted that through the control of the variables it does not directly reflect what may occur in an individual home. The control of variables to create benchmark testing in order to isolate the differences between control regimes does mean that findings may not be directly translated to consumer savings under a wider variety of conditions.

Understanding the performance of heating controls requires a detailed knowledge of internal and external environmental performance, the building and heat loads[12]. It also requires information about the interaction of the building, systems and controls with the occupants comfort objectives, habits and practices. While recognising that issues of housing and heating are socio-technical in nature[13], by removing the variables of occupants and weather differentials, we can begin to unpick the potential factors underlying the results from field trials such as Shipworth et al.[4] and Heubner et al.[14], as well as Heubner et al.'s[15] mixed methods study with a smaller sample. It also serves as a counterpoint to the social science studies on heating controls such as Peffer et al.[16], Meier et al.[17,18], Crosbie and Baker[19] and Chetty[20].

2 Relevant UK regulations relevant to heating and controls

The standard installation of heating system and controls is well described by Munton et al.[9] and identifies key elements such as boilers, tanks, emitters, controls and ancillary pumps and valves.

There are a number of boiler controls available, specified within the UK regulations. New dwellings in England are controlled by the requirements of Part L1A of the Building Regulations, which came into effect on 6 April 2014, covering the installation of heating controls. Schedule 1 highlights the regulatory requirement for new homes to be fitted with effective controls.

Part L1A of the Building Regulations[21] requires an assessment of the carbon dioxide emissions at an early stage of the design of homes. This is done using the Standard Assessment Procedure (SAP 2012)[5] identified earlier as the standard regulatory modelling framework for UK domestic properties. The 2014 Building Regulations identify that a Target Emission Rate (TER) is produced, which is referred to as a *notional dwelling*. This is a fully specified property in terms of the main energy parameters, including factors such as the fabric performance, the heating system and its controls. In terms of controls, the notional dwelling includes time and temperature zone control and a weather compensator, which is a sensor located externally that controls the performance of the boiler, and a modulating boiler with interlock.

The Domestic Building Services Compliance Guide[22] identifies minimum standards for the efficiency of boilers and other heating appliances, as well as the controls of heating and hot water systems.

The current UK Building Regulations identify that a set of controls is now a regulatory requirement. However, many properties have been built prior to the introduction of these more stringent building regulations, or may not have been effectively upgraded with new controls when heating systems have been replaced. The English Housing Survey: Energy Efficiency of English Housing Report[23] identified that 24% of 20.2 million English Homes lack full heating controls, based on a study sample of 12 763 properties. It should also be noted that this was higher in the private rented (29%) and owner occupier sectors (26%), than in social housing (16%), probably due to renovation and energy efficiency programmes such as the Carbon Emissions Reduction Target, the Communities Energy Saving Programme[24], Decent Homes[25] and Warm Front [26, 27], which were aimed at fuel poor homes. Currently, heating controls are supported through the Green Deal[28] and the Home Heating Cost Reduction element of the Energy Company Obligation[29], which is the supplier obligation that replaced CERT and CESP.

3 The Salford Energy House test facility

The Salford Energy House, Figure 1, is a full sized test house, built within an environmental chamber. It is a test facility that bridges the gap between laboratory-based materials and product testing and outdoor field trials, which may or may not include occupants[30].

The house is a traditionally constructed Victorian end-terraced building, with a conditioning void to represent a neighbouring property. It has solid brick walls, suspended timber floors, lath and plaster ceilings and single glazed windows. In its base state it is un-insulated. It has a wet central heating system fired by a gas condensing combination boiler. All of this can be changed to suit the testing requirements. The conditioning void uses the same construction techniques and can be environmentally controlled to reflect different heating behaviours. Solid wall properties such as those represented by the Energy house currently number approximately 6.6 million in the UK.

Figure 1. The Salford Energy House.

The house is a traditional UK “two-up, two-down” Victorian property, with the floor layout shown in Figures 2 and 3.

Figure 2. Ground floor layout.

Figure 3. First floor layout.

The external environment surrounding a dwelling can potentially make a significant difference to how much energy is required to heat the building. The chamber can recreate a range of external weather conditions: Temperature can be controlled from -12°C to +30°C (with an accuracy of +/-0.5°C). Wind, both localised and chamber wide, of up to 10 m/s, and rain of up to 200mm each hour can be applied. This controlled environment allows for consistent temperatures to be used. This is particularly useful for validating approaches such as co-heating, or whole house heat tests, and in-situ U-Values. Dynamic and random heating patterns can also be used which is valuable for research into transient effects in the structure or reflecting repeatable real world conditions.

4 Test methods

4.1 Overall Energy House Set Up

The study was split into three separate tests, described in Section 5. Each test involved a single 24-hour period of heating following a standard SAP heating pattern[5]. The property was heated from 7am until 9am in the morning and 4pm until 11pm in the evening. The target temperatures were 21°C for the main living area and 18°C in the other parts of the house. The experiment used 3 heating control configurations.

- Test 1 - Boiler thermostat at factory setting.
- Test 2- Wall thermostat in main living area.
- Test 3 - Wall thermostat and TRVs on all radiators except living room.

Each test was run with the same experimental setup, described in more detail below. The only variables introduced were the changes to the controls in the building and the addition of setpoints for those controls. The environmental chamber temperature setpoint was an average of 5°C, with a variation of +/- 0.5°C during the study. The neighbouring property was not heated and designed to reflect a building that had no occupancy. This ruled out the variable of heat gain from a neighbouring property.

The heating system was a standard condensing boiler rated at 26kW, a Veissman Vitodens V200W. The heating system was designed and installed to the standards laid out in the CIBSE Domestic Heating Design Guide to remove the variable of different system sizing. The loads for each of the radiators and their outputs are shown in table 1.

Table 1. Loads and outputs for heat emitters.

The system was re-commissioned and balanced by a heating engineer, both prior to initial testing and the installation of the TRVs. The room thermostat and TRVs were selected by BEAMA, the brand of which was not revealed to either the BEAMA members or the research team. The selected controls represent a mid-range set of *dumb* controls as might be found in a standard home. They were considered representative by the panel, which included members from BEAMA and the research team. They have not been identified in any part of the study published by BEAMA[10] or within this study.

Before each test was carried out, the building was allowed to settle for a period of one week, to acclimatise and avoid a cold start situation. This created a steady test environment, removing the impact of the building's thermal mass. Each phase consisted of a 48-hour test, with the second day being used for data analysis. The 24-hour period prior to the test was used as a settling day.

The chamber was sealed and no personnel entered the chamber during the test. All external windows and doors were closed and latched in the main house and the neighbouring property. The curtains remained open for the entire period. All internal doors were closed. It is recognised this reduces air exchange – however for accuracy of temperatures and to accurate allow benchmarking between different scenarios, this was deemed to be appropriate. It should be noted that occupants may have any combination of open and closed doors in their homes, but this issue was not addressed by this test. It is recognised that this will lead to higher savings than an open door scenario. Appliances in the property were switched off to minimise incidental gains, again something that would not be found in the field. The heating pattern during the test was set according to the times laid out in the SAP guidance issued by BRE (from 7am until 9am in the morning and 4pm until 11pm in the evening)[5]. A half hour heat up time was used before each heating period commenced, to bring the building up to heat before the period began.

4.2 Sensors and data collection

A Resistance Temperature Detector sensor, in a reflective housing, was used to measure the air temperature at the geometric centre of each room recording at 1-minute intervals. The sensors perform to a resolution of 0.1 °C and are accurate to ±0.5 °C. The type T thermocouple temperature sensors are used to measure the feed and return temperature of the boiler. These have a range of -200 to 350°C, with a resolution of 0.1 °C, with an accuracy of ±0.5 °C. These are used to measure the temperature of the water coming in and out of the boiler.

The gas meter used in the energy house was with a pulsed output. The gas consumption was monitored using a pulse data logger, reading the pulse output from the gas meter with 1-minute intervals every 0.01m^3, with an accuracy of ±1%. The electricity meter used to monitor the electricity consumption of the boiler is a single phase kWh meter with pulse output, with an accuracy of ±2%.

5 Description of the Tests

While section 4 described the common test conditions and data collection for each test, this section covers the variable elements, which were concerned with the changing of control arrangements for the property,

5.1 Test 1 – boiler thermostat only

Test 1 was designed to mimic the installation of a boiler into a home with no controls other than the boiler programmer, to maintain the heating pattern, and the boiler thermostat. The settings of the boiler were unchanged from factory setting, giving a 74°C flow temperature. No hot water was drawn off during the course of the test. The heating time schedule was set following the standard pattern as defined earlier. The boiler flow temperature remained at 74°C for all following tests. The room thermostat was disconnected and TRV's in all room were placed to the fully on position to ensure they did not impact the study.

5.2 Test 2 – living room thermostat

The base scenario for Test 2 remained the same as Test 1, but with a room thermostat added to the system. This device was a thermo mechanical thermostat representative of a mid-range of widely available domestic room thermostats. This was wired into the boiler in accordance with the manufacturers instructions. The thermostat was located on an internal wall of the living room at the height recommended by the manufacturer (1200mm). This thermostat was set to reach a setpoint of 21°C to reflect the standard SAP heating setpoints[5]. This could not be done using the device itself as the accuracy was not of an experimental quality so a calibrated air temperature gauge was used to ensure the thermostat reflected its actual setpoint rather than the numeric set point on the display. This is due to the fact that, whilst setting up the experiment, it was found that the device would give start signals to the boiler when at set points some considerable distance from the measured air temperature directly adjacent to the device. This gave more accurate control over the house. It also raises questions around how we might understand set points in the context of user behaviour, as highlighted by Peffer[15] and Meier[16], and also how modelling assumptions of setpoints might need to be reconsidered[31]. This does not necessarily mean we need more accurate thermostats, because as both Shipworth[4] and Nicol et al.[32] identify, the relationship between the individual, thermostats and comfort can be complex.

5.3 Test 3 – living room thermostat and TRVs

In the final scenario TRVs were added in all rooms apart from the living room, as this room already contained the room thermostat. As with the wall thermostat, the TRVs were initially set at steady state to 18°C. This was done using air temperature monitors to achieve the desired setpoint. All other factors remained the same. The TRVs were set at steady state, as this, under cycling or heating pattern conditions, is extremely difficult.

6 Results

The results describe the two main issues that were under consideration. The first is control of the internal temperatures and the second is the energy and cost savings made due the system being under different control regimes.

6.1 Control

For the purposes of the study, the internal temperatures were considered to be under control if they were within the boundaries described by SAP, 21°C in the main living area and 18°C in all other rooms.

During Test 1 the house exceeded the setpoint in most rooms, with the air temperatures at the geometric centre reaching up to 31°C in the bedrooms, as illustrated in Figure 4. The chamber temperature is shown in the bottom of the graph indicating a stable environment was achieved for the test. This was repeated for all of the subsequent tests.

Figure 4. Room and chamber temperatures during Test 1.

Table 2 shows the maximum, minimum and mean air temperatures for each of the rooms during the test during the morning and evening periods.

Table 2. Temperatures during Test 1.

The temperature passing the desired setpoint was caused by the heating system relying only on the boiler thermostat to control the heating system in the house. The boiler thermostat controls the temperature of the hot water fed to the radiators, rather than the air temperature as might be experienced by the occupant. This was set to 74°C as illustrated in the feed temperature graph in Figure 5.

Figure 5. Test 1 feed and return temperatures.

It is also clear from the results that the flow feed temperature (Figure 5) reached maximum after a very short period, and did not reduce in any significant way for the entire duration of the period. The same can be said of the radiator surface temperatures, as shown in Figure 6.

Figure 6. Test 1 radiator surface temperatures.

However there are two exceptions; in both of the heating periods the radiator in the bathroom begins to come under control, as does the radiator in bedroom 2. The temperature at the surface of the radiator, and therefore the room temperature dropped. This may be due to an overheating fail-safe built into the TRV head itself, which according to the manufacturer's instructions, is engaged at around 26°C.   It is not fully understood why this fail-safe did not activate in the other areas. One reason for this could be the limited amount of airflow around the TRV heads, meaning that the increase in air temperature at the valve head that was far quicker than in the other areas.

The test shows that the lack of control in the property may lead to comfort issues from the perspective of occupants. Again, it is likely that the occupant would intervene through the use of heating controls or window opening, which would greatly influence the consumption figures. The maximum temperatures shown in Table 2, show that all of the rooms exceeded their setpoints. Due to the limited time of the heating periods (maximum duration of 7 hours and 30 minutes) it is felt that these maximum room temperatures could reach even higher over a longer period, as the trend of the graphs appear to represent a significant rate of rise even at the end of the heating period. This could exacerbate overheating in buildings that are heated constantly, however, in a field scenario, it is likely that the occupants would intervene to address this issue.

During Test 2, as shown in Figure 7, the living room thermostat takes some control of the whole house, as indicated by the appearance of fluctuations in all of the room temperatures. This is due to the fact that the living room is now acting as a proxy for the rest of the dwelling. An oscillating cycle induced by the room thermostat has an influence on the rest of the building because the entire heating system is dictated by one room thermostat. This cycle is both very regular, and in certain rooms, very broad, with a +/- 1°C (a 2 degree swing) taking in place in the living room, which was also reflected in the other rooms. However, this only occurs during the longer evening heating cycle, as the morning cycle only just enters the control band of the room thermostat as the heating cycle is drawing to an end.

Figure 7. Room and chamber temperatures during Test 2.

The increased degree of control makes an impact on the flow and return temperatures (Figure 8) as would be expected.

Figure 8. Test 2 flow and return data.

Table 3. shows that during Test 2 the setpoint was exceeded in all of the rooms apart from the living room when both average temperatures and maximum temperatures were taken, during both morning and evening heating periods.

Table 3. Temperatures during Test 2.

In Test 3 the building was under full control and it was expected that the set point would be effectively maintained. This, however, was not the case. The setpoint was still exceeded, albeit by much smaller margins and for shorter durations (Figure 9).

Figure 9. Room and chamber temperatures Test 3.

Again, the increased degree of control makes an even greater impact on the flow and return temperatures (Figure 10) in Test 3.

Figure 10. Test 3 flow and return data.

The rooms that did exceed the setpoint did so for a shorter period of time than in the previous tests, as seen in the maximum room temperatures (Table 4), and can be seen to maintain the setpoint when the room temperatures are averaged over the period of heating.

Table 4. Temperatures during Test 3.

During the experiments it was found that the TRV was difficult to set to maintain constant temperatures. The TRVs varied widely in setpoints from room to room despite all being set up to meet the required 18°C setpoint. It was also found that the valves were unpredictable in terms of how they reacted to the setpoints. Some would run at the setpoint for a short period and then lose accuracy, while others would consistently run accurately. Some valves were changed to rule out faults, but the same issues persisted. Bedroom 2 provides an example of the unpredictable nature of these devices, the temperature reached 21°C rather than the 18 °C setpoint. This proved to be a problem in the experiment, but it was felt that this resulted in an overestimation of energy usage rather than an underestimate. It was also found that the living room did not reach its setpoint during the morning heating period.

6.2 Energy consumption and boiler condensing

The overall energy consumption during each of the tests is shown in Table 5. Due to the significant in control in Test 3 compared to Test 1 and 2, it is clear that in this scenario less energy was used. While the removal of occupant factors does mean that results may not directly be comparable with occupied properties, a unique aspect of this research is the capacity to quantify the level of improvement between the three scenarios. Table 4 shows combine gas and electricity consumption. Gas consumption has a measurement error of +/- 1%, while electricity has a measurement error of +/- 2%.

In terms of gas consumption, highlighted in Table 5, it is clear that although the introduction of a thermostat in Test 2 did make some improvements resulting in a 12% reduction in consumption, the major savings are gained with the introduction of the TRVs in Tests 3, which resulted in a 42% reduction in overall gas consumption.

Table 5. Gas and electricity consumption during the tests.

When gas consumption is combined with the electricity used to control the system, the savings in terms of total energy consumed, costs and carbon emissions are approximately 40% for Test 3 compared to Test 1 (Table 5). The savings resulting from Test 3 can be attributed to the system achieving the desired setpoints without wasting additional energy that results from exceeding the setpoint. In terms of boiler efficiency, these tests also highlight the fact that a boiler running with little or no control rarely engages the condensing mode, which is effectively only active during the heat up cycle of the heating schedule, as shown in Figure 4. This represents 11% in the morning period and 4% in the afternoon period for Test 1, as shown in Table 6. This is considerably lower than observed in Test 2 and 3.

Table 6. Condensing mode %.

It can be seen from Table 6 that, under the conditions of Test 3, the boiler is in condensing mode for 28% of the time in the morning period, and 54% of the time during the evening cycle.

7 Conclusions

This study set out to question whether controls work effectively in a whole house test under fixed weather conditions, with standard installation. As stated previously, the impact of interventions by occupants are not directly addressed in this study. However, the resulting data suggests that even the basic set of controls suggested under UK building regulations may have a significant impact on the energy used in the heating of the building, as well as the potential comfort of the occupant, when compared with a no control scenario. It should be noted that the intervention of occupants in response to elevated temperatures has a major potential to influence the savings figures. Occupants may respond by engaging with their controls or opening windows in response to a wide range of comfort needs – this is difficult to predict. This, however, is not the direct purpose of the study, but the influence of these factors should be recognised when considering the results. We should also recognise that the issue of control would play out differently in house with different insulation levels, which presents an opportunity for potential further work.

It is apparent that the introduction of heating controls improves the control of temperatures within the property. Here, we have quantified the level of that saving within a free running house without occupants and external weather variations. Savings of 40% in terms of energy, CO_2, and costs have been achieved in this experiment, and this area of research warrants further investigation, particularly in terms of introducing more dynamic variables such as internal door opening, occupant interventions and other factors that would quite probably reduce these savings figures.

This study is not designed to address the savings of controls regimes in field based occupied properties, meaning the savings figures cannot at this stage be directly compared given the experimental design. The control of variables, such as door shutting and the removal of the occupants means that the savings described here are higher than may be found in homes. The work represents an exercise in isolating the variables in a way that would not be possible in the field. The extent of data collection undertaken in the house would be untenable across a statistically reliable sample in the field, as well as introducing a high number of dynamic variables making analysis difficult, which explains the lack of field work in this area. However, the main outcome of the study is to allow us to consider a range of heating system controls against this benchmark study. The tests conducted here used a set of mid range dumb controls, but could be compared against more complex and/or expensive devices.

Further work will be undertaken to investigate different control arrangements and this work represents a real opportunity to explore the impacts on energy efficiency of alternative control approaches, such as weather compensation and intelligent controls. In addition, the future collection of comfort data, such as radiant temperature and air velocity, will allow a clearer understanding of the occupant experience under various controls regimes.

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