DEVELOPMENT AND VALIDATION OF DETAILED BUILDING, PLANT AND CONTROLLER MODELLING TO DEMONSTRATE INTERACTIVE BEHAVIOUR OF SYSTEM COMPONENTS.

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ABSTRACT

As plant modelling becomes capable of more complexity and detailed resolution, new opportunities arise for the virtual evaluation of discrete plant components such as flow control and energy conversion devices, and controllers. Such objects are conventionally developed and tested at the prototype stage in a laboratory environment. Designers now seek to use modelling technology to extend their understanding from limited laboratory test results to full building and plant system analysis. This paper describes the development of a modelling system, using ESP-r, for typical United Kingdom domestic house types with hydronic gas or oil fired central heating including radiator and underfloor heating systems, and with a variety of conventional or advanced control types. It demonstrates the ability of detailed building and plant modelling to reveal unexpected insights into how real control systems perform in combination with other plant items and in different building types, including estimation of their influence on annual energy consumption. Comparisons with measurements taken in test rooms confirm that the observed behaviour of controls is realised in practice. The authors conclude that the complex dynamic interactions that take place between the various elements that make up a real building energy system have an important influence on its overall energy performance, revealing causes of variance that cannot be identified by laboratory testing alone, or by simplistic energy assessment tools.

INTRODUCTION

The energy performance of domestic buildings is evaluated using simple tools like the UK Standard Assessment Procedure (SAP). Such tools take a very simplistic approach to assessing the impact of heating plant controls on the annual energy consumption of a house. It is known in the building controls industry that the impact of the method of control in a house can be significant, and the availability of electronic products with embedded software control algorithms creates new opportunities to reduce energy demand. However the quantitative energy use and potential savings may be influenced by the type of building construction and heating system, as well as the detailed control logic. Control product developers make use of physical test facilities, including full scale domestic room settings with simulated outdoor climate conditions. However such test facilities are not sufficient to carry out all the evaluations necessary to reliably calculate the energy reduction that should be assumed by the simplified assessment methods. Full scale testing in real houses is expensive, time consuming, and not really a practical approach given the large range of control, house, and system types that would have to be evaluated. Computer modelling and simulation, on the other hand, offers the possibility of making these calculations very rapidly, provided that the control product manufacturers and assessment procedure developers can be convinced that the simulation results from computer models do reflect accurately the performance of their real life counterparts.

There are two tasks to be completed for this to happen. First, there is a need to create a modelling capability that will capture the short term dynamics associated with a real control system and its component sensing and actuating systems. This is quite a challenge, considering that the short time scale dynamics of the control model has to be integrated into a dynamic building construction model with long time constants so that seasonal and annual energy consumption estimates can be made. The second prerequisite is to be able to make convincing comparisons with known real test results to show that the qualitative dynamics and quantitative energy consumption is being reliably replicated by the modelling system. This paper summarises the work carried out in two stages to achieve that objective, and presents some examples which demonstrate the power of the assessment approach.

DEVELOPMENT OF THE MODELLING CAPABILITY

Overview

The modelling tool used was ESP-r. ESP-r is an integrated transient energy modelling tool for the simulation of the thermal performance of buildings and the assessment of energy use. ESP-r models the energy and fluid flows within combined building and plant systems when constrained to conform to control action (Energy Systems Research Unit, 2009.) One or more zones within a building are defined in terms of geometry, construction and usage profiles. These zones are then inter-linked to form a building. Building fabric elements are defined in terms of multi-layer constructions, using material data that define thermophysical properties of conductivity, density, specific heat, solar absorptivity and emissivity for each homogenous element. Optical properties are defined for transparent elements. Internal view factors can be calculated in order to improve modelling of long wave radiation exchanges. Time-dependent internal and external convection coefficients are calculated at run time, along with casual convective and radiative gains according to the occupancy, lighting and equipment schedules. Plant models consist of thermally dynamic elements, such as heat generators and emitters, thermostat sensors and distribution pipework, and control logic elements that respond to building and plant variables by acting on actuators to control flow, or to inject heat, for example. Simulation proceeds at discrete time steps, in the case of this project one minute for the building and five seconds for the plant and controls, in order that short time constant dynamics associated with plant and controls are accurately replicated.

In order to prove the ability of ESP-r to model the control of typical UK heating systems, five house types, five heating system types and five control system types, shown in Figure 1, were selected for detailed analysis (i.e. 125 combinations).

Number	House Type	Boiler and Heat Circuit Type	Control Type
1	Detached solid wall single glazed pre-1918 100mm loft insulation. Floor area $104m^2$	Gas, non-condensing, regular boiler, non-modulating burner, radiators	Living room mechanical thermostat, no TRVs
2	Semi-detached uninsulated cavity wall, single glazed 1939-59 100mm loft insulation. Floor area $90m^2$	Gas, condensing, regular boiler, modulating burner, radiators	Living room mechanical thermostat, TRVs in other rooms
3	Semi-detached, EEC stock average, 100mm loft insulation, filled cavity. Floor area 90m2	Gas, condensing, combi boiler, modulating burner, radiators	Living room and Non-living zone mechanical thermostats
4	Semi-detached timber frame 1990 – 1999, double glazed 100mm loft insulation. Floor area $90m^2$	Oil, condensing, regular boiler, non-modulating burner, radiators	Weather (outside temperature) compensation, modulating supply water set point. Living room temperature compensation. TRVs in other rooms.
5	mid-terrace 2006 (pt L regs.) filled cavity 270mm loft insulation. Floor area $79m^2$	Gas, condensing, regular boiler, modulating burner, heavy underfloor system in living room, radiators in other rooms.	Living room sensor, modulating supply water set point. TRVs in other rooms.

Figure 1 House, boiler, heating circuit, and control type options.

House types broadly reflect typical UK housing characteristics. Only water based (hydronic) heating systems were considered. Heating system types include non-condensing and condensing boilers, regular and combi boilers, gas and oil boilers, and both radiator and underfloor heat emitters. All condensing gas boilers had the capability of modulating the firing rate. Controls range from a basic system with a single room thermostat, through to a two-zone system with two independent thermostats. Electronic controllers are also represented, both room temperature and outdoor temperature based (Cockroft et al 2007). To extend the analysis of these systems to non-simulation experts, an interface to ESP-r called ADEPT (Advanced Domestic Energy Prediction Tool) was constructed. This facilitates the set up of any desired combinations of the defined house, system and control schemes, producing standardised outputs demonstrating control behaviour and energy use (Cockroft et al 2009).

House model

All five house models contain a living room and a rest-of-house (non-living room) zone. All external fabric was modelled in detail. Figure 2 shows a typical elevation and plan for the semi-detached house types.

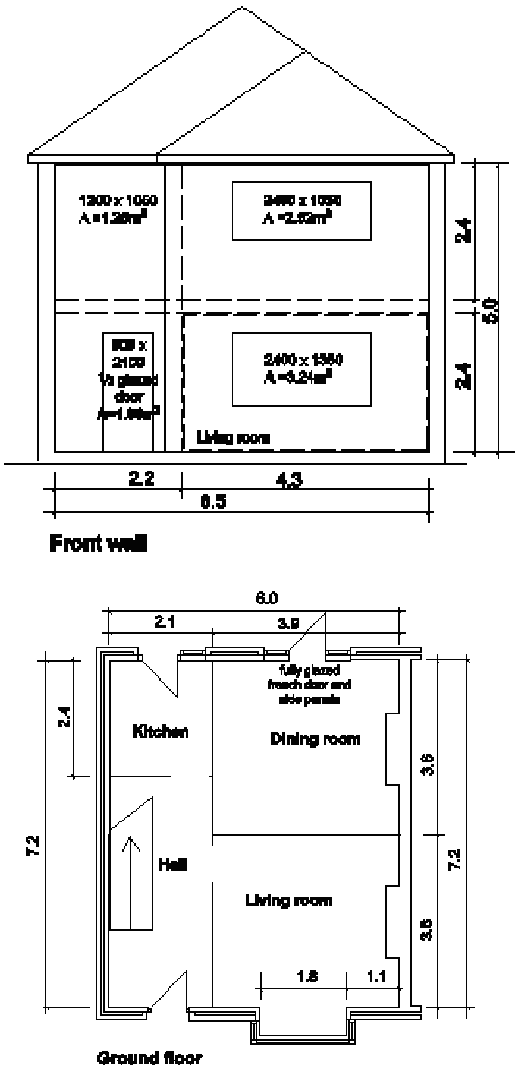

Figure 2 Elevation and ground floor plan for semi-detached house.

Boiler model

Due to the absence of detailed information to allow models of the various required boiler types to be modelled explicitly, it was decided to adopt a performance mapping approach. For each boiler, an instantaneous combustion efficiency was determined depending on return water temperature and percentage of full load gas firing rate, which is specified at the higher calorific value. Figure 3 shows an example for a gas fired condensing boiler. The boiler heat exchanger is a two-node representation which ensures that the effects of thermal mass of the boiler are simulated, and casing heat losses are calculated as a thermal input to the building zone containing the boiler. Logic was included to limit the minimum firing rate for a modulating boiler.

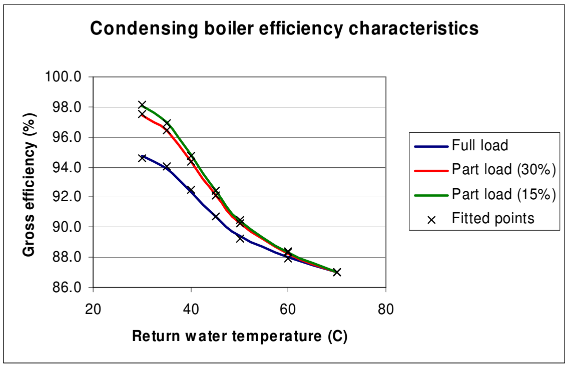

Figure 3 Efficiency characteristics for a condensing gas boiler.

At each plant time step, the boiler model calculates the ratio of actual heat output and heat output of the boiler at maximum firing rate. This determines the load, and so the gross efficiency. The gas firing rate can thus be determined. If this is less than a set proportion of maximum firing rate, the on/off control logic at minimum firing rate is invoked. The calculated heat output is injected to the boiler water nodes.

Boilers incorporate additional logic to determine action when there is a call for domestic hot water (DHW). A regular boiler will simply react to the water flow rate when the DHW zone valve is opened, on a call for heat from the cylinder thermostat. The domestic hot water storage cylinder is modelled as a separate two-node storage tank. Jacket losses are gains for the containing zone. When the domestic hot water call is satisfied (hot water temperature rises to the upper thermostat limit) the zone valve is closed.

A combi-boiler, supplying DHW instantaneously on demand, will switch to DHW service mode. In this case, the heat flux to the DHW, supplied via an internal fast response heat exchanger is known. The heat exchanger is modelled in a similar fashion to the storage cylinder, but with low thermal mass. The known heat flux to be supplied by the boiler enables the flow and return temperatures to be determined dynamically, and the boiler will modulate as necessary, mimicking the behaviour of a combi-boiler maintaining a fixed DHW supply temperature.

A variety of subtle but performance critical control routines were also incorporated; for example, pump over-run, supply – return differential temperature limiter, and modulating boiler low load cycle control.

Boilers were sized to the radiator capacity plus 3,000W to allow for DHW. The exception to this rule is the combi-boiler, which was sized at 24,000W output, being a standard size for these house types, based on the DHW rather than the heating load.

Heating system model

The heating systems each have a heat emitter in the living room zone (either a water filled radiator, or an underfloor heating system) and a radiator in the non-living room zone. Water circuits connect these heat emitters to the flow and return connections of the boiler. An on-off zone valve controls the flow of heat to each zone, depending on control action. A thermostatic radiator valve may be present on the non-living room zone radiator; this controls the flow in that radiator independently of the control system, when the respective zone valve is open, and the pump is running.

The radiator is represented by a two-node model with heat transfer expressed as a function of radiator node / room temperature difference, raised to the power of an exponent. This was judged to provide sufficient modelling accuracy without incurring excessive simulation run times. The underfloor system was modelled similarly, with appropriate thermal mass and surface area. In every case, heat emitters were sized to match the calculated design load, for each house, with a 10K flow – return temperature difference, and 20% oversize relative to the design heat loss. In the case of radiator systems an 80C maximum flow temperature was used. This is typical for UK existing domestic radiator systems, where safe surface temperature guidelines are typically not met. For the underfloor system, a 50C maximum temperature was used. The non-living room zone radiator sizing increased in this case, due to the low water temperature. Water flow from the pump was apportioned to each circuit (living room and non-living room heating, and domestic hot water) by taking into account the positions of on/off (zone) and modulating (TRV) valves.

Controls Model

Figure 4 is a schematic of a typical control configuration. In this case, an on-off room thermostat in the living room zone controls a zone valve which controls the flow of water to the radiators in both zones. Other control types modelled represent electronic controllers that can interact directly with a modulating boiler control:

- A proportional plus integral (PI) controller
- An outside temperature compensated controller, with room temperature compensation.

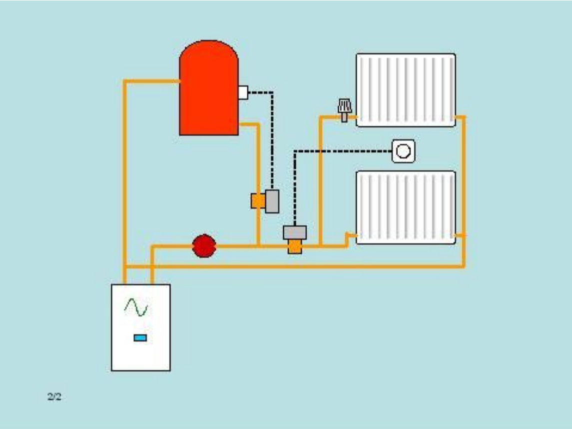

Figure 4 Schematic of a control system.

On/off room thermostat

On/off room mechanical thermostats are still the most common form of temperature control in UK housing. The dynamic aspects of the thermostat model centre around the sensor, which detects a combination of air and radiant temperatures in the zone, and also the temperature of the wall on which the thermostat is mounted. The sensor has thermal mass, and definable anticipator heating effect (the heat anticipator is a small resistor that heats the thermostat sensor while the thermostat is calling for heat, thus increasing the cycle rate of the thermostat and reducing temperature fluctuations.) The output of the dynamic model is a sensor temperature which defines the on/off status of the thermostat according to setpoint and mechanical differential settings. If the thermostat is on then the control output hot water temperature setpoint is set to the maximum. If the thermostat is off, then the control output is set to the minimum (off).

Electronic PI controller

The two advantages of this type of thermostat are:

1. the integral action removes proportional offset which other forms of control exhibit,
2. the output of the controller interfaces directly with the boiler electronics, allowing full advantage to be taken of the modulation capabilities of the burner.

The dynamic aspects of this controller are similar to those of the on/off thermostat model, but without heat anticipation. The output of the dynamic model is a sensor temperature which is input to a proportional plus integral (PI) control algorithm, the output of which is the boiler water temperature setpoint. Additional logic prevents integral wind-up, e.g. at set point changes.

Weather compensated control

Weather (or outside temperature) compensation is useful in adjusting the boiler temperature downwards during warmer weather. This provides efficiency benefits particularly when used with low temperature heat emitters, e.g. underfloor heating. The dynamic aspects of the weather compensated model relate only to the room sensor, as for the PI controller. This input provides a degree of room temperature compensation when the room temperature is far from setpoint, e.g. during morning start-up. Weather compensation uses the outside temperature to derive the water temperature setpoint according to a linear relationship which can be adjusted. The thermal mass of this sensor is not modelled, as outside temperature changes relatively slowly.

System integration

When there is no call for zone heating or DHW the boiler is turned off (boiler interlock). The combi-boiler can only service heating or hot water, not both together. Heating setpoints are 21C in the living room zone and 18C in non-living room zone. Two heating schedules are used:

1. intermittent, for weekdays: 07:00 to 09:00 and 16:00 to 23:00
2. continuous operation at weekends 07:00 to 23:00.

There are 13 calls for DHW throughout the day, with a total consumption of 122 litres.

COMPARISON WITH TEST RESULTS

Given the reliance being placed on the ESP-r controls and system modelling approach as a substitute for full scale testing in real buildings, it was necessary to provide some confidence that the ESP-r predictions were qualitatively and quantitatively in line with measured data. Measurements in two controls manufacturers' test rooms were carried out for some typical control systems. Both test rooms represented a room in a house, with a full size radiator, supplied by an external boiler. Adjacent areas were mechanically cooled to simulate external conditions. Neither room was exposed to real or simulated solar radiation. The rooms and associated plant models were set up in ESP-r and the predictions produced by models of those test rooms in ESP-r (referred to here as test room 1 and test room 2) using the modelling capability described above were compared with the measurements.

Room temperature control comparison using a mechanical thermostat.

Figure 5 shows the measured resultant room temperature close to the thermostat, compared with the simulated temperature. Through a process of successive trials, it was determined that the simulated thermostat sensor (test room 1) should sense a weighted average of room air (dry bulb) temperature (33%), temperature of wall opposite controller (33%) and temperature of wall on which sensor is mounted (33%). The heat anticipator power was 780mW.

The boiler turns off for 15 minutes just as the room temperature reaches the setpoint. This is a function of the boiler electronics, and was observed in all the measured results using this boiler. The purpose and logic of this function are unknown, and it was not included in the ESP-r boiler model. The cool down of the two curves matches well.

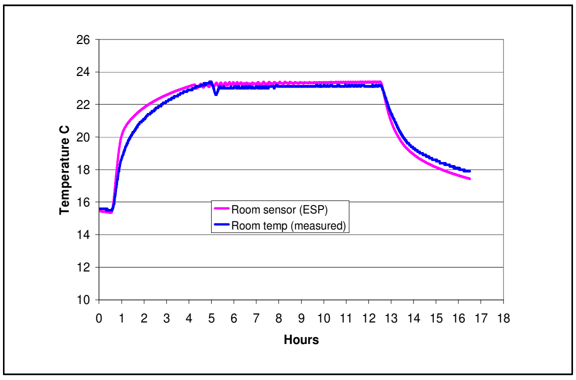

Figure 5 On/off Thermostat room temperature comparison (test room 1).

The shape of the two graphs of boiler output temperature (Figure 6) are similar, showing a rapid rise on boiler start up due to the relatively low system thermal mass and water content, a fairly steady period while the boiler runs to heat up the space, supplying water at the maximum temperature, then a period of cyclic control. The simulated temperatures are slightly higher than the measured temperatures, probably due to slight differences in setpoints and sensor characteristics.

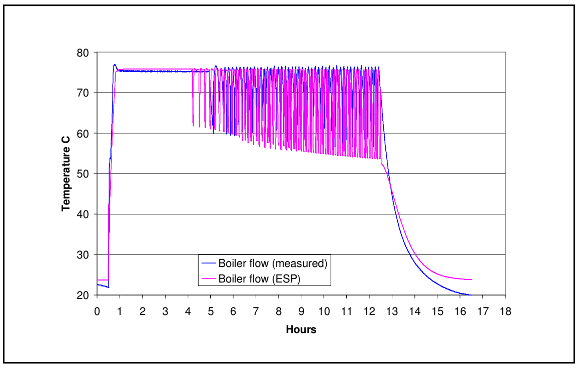

Figure 6 On/off thermostat boiler water temperature comparison.

Room temperature control comparison using a PI room controller

Figure 7 compares the simulated resultant room temperature with the measured temperature using a PI room controller. The simulated controller sensor sensed a weighted average of room dry bulb air temperature (50%), the temperature of the wall opposite the controller (25%) and the temperature of the wall on which sensor is mounted (25%). A proportional band of 8K and integral time constant of 500s were used. The rates of room temperature rise are similar for the measured and computed results. The simulated temperature then controls closely to the setpoint. The measured temperature drifts up slowly during this period. This is not explained. As before, there is a brief period when the boiler is off, after reaching room temperature setpoint. The cool down of the two curves matches well.

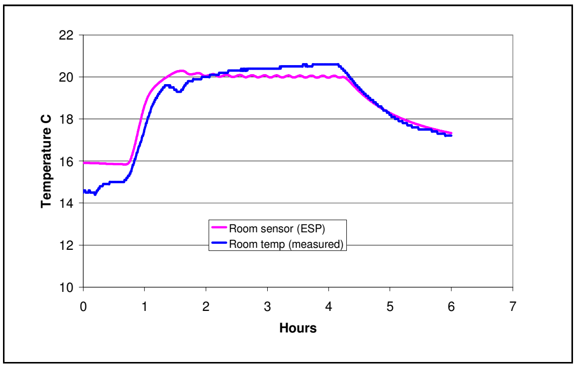

Figure 7 PI controller room temperature comparison

Figure 8 shows the boiler output temperature for the measured and simulated results. The rapid rise in boiler temperature on start up is accurately replicated by the simulation. When the room temperature has been reached, after an initial off period as noted above, the boiler firing rate reduces until it drops below the minimum of 20%. The boiler then runs in on/off mode, at minimum firing rate, in cycles of about 15 minutes, thereby delivering the required output. This behaviour, observed in the measured data, is replicated by the simulation, with a similar cycling rate of the boiler. When the system is turned off, the cool down rates are not closely matched, but

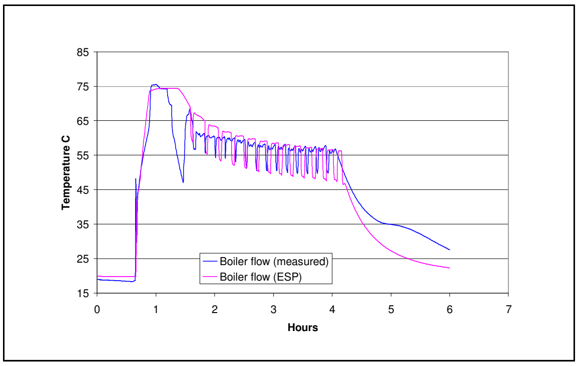

Figure 8 PI controller boiler temperature.

as the pump is turned off, this is not a significant result.

Time proportional PI controller

On/off thermostats are increasingly substituted by electronic equivalents, often incorporating time clock functions. Usually, a more sophisticated control function is possible, whereby cycle rate can be predetermined, and integral action is implemented. The output is a time proportional on/off switching action. Such a controller has been implemented in ESP-r and a test carried out in test room 2 compared its performance with measured data. The cycle rate was adjusted to six cycles per hour. The P and I terms were 4K and 2,000s respectively.
Figure 9 compares the control of room temperature, including an initial change of setpoint, control at a new setpoint, then a cool down period. There is some instability in the measured data at the lower setpoint. For both sets of data there is an overshoot of about 1K on set-up.

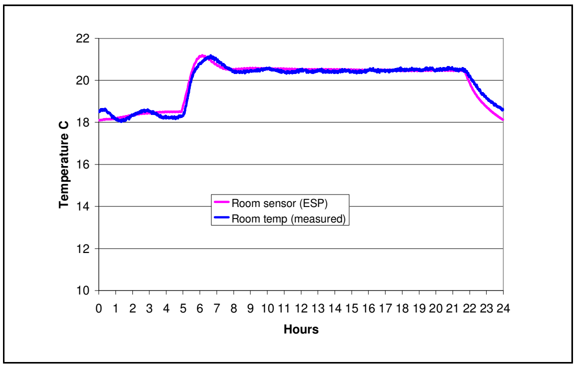

Figure 9 Time proportional PI controller room temperature comparison.

The simulated energy consumptions over the course of this and other tests in test room 1 agreed to within 5% of the measured data.

DEMONSTRATION OF ADVANCED CONTROLS ENERGY SAVINGS

Having shown that the tool can replicate advanced control behaviour in realistic UK test systems, it is possible to use the ADEPT tool to demonstrate some results in full scale buildings. Two comparisons are given where the type of plant and control system has a substantial impact on energy consumption, for the same house and boiler type.

Underfloor heating system with weather compensated controller

In this example, an average stock UK house with a typical radiator system controlled by an on/off room thermostat was compared with the same house fitted with underfloor heating in the living zone, controlled by a weather compensated control system. A regular condensing boiler with stored DHW was used. An energy saving benefit is expected, because the underfloor system operates within a lower water temperature regime, where boiler efficiency is higher (see Figure 3), due to an increase in condensing operation. The weather compensation system makes sure that the water temperature remains no higher than necessary to meet the load. Figure 10 shows the living room resultant temperatures and living room radiator/underfloor system temperatures for the two systems. The room thermostat can be seen to be cycling on/off to maintain the room at an average temperature of around 22C. The weather compensation is maintaining the underfloor water temperature at an average of 15K lower than the radiator system during the heating period, whilst maintaining a similar room temperature as the thermostat/radiator system. There are fluctuations in these temperatures during periods that the boiler is operating below its modulating range. The annual energy consumption for these two systems was calculated to be 21.2MWh and 21.9MWh respectively.

This somewhat unexpected result can be explained by observing the behaviour of the underfloor system overnight. Both the room and the water temperatures remain significantly higher overnight with the underfloor system than do the equivalent radiator system temperatures. This increases the night time heat loss, to the extent that the annual total increase in loss exceeds the savings due to the lower water temperatures during daytime.

To realise the savings due to the use of a condensing boiler, it is necessary to reduce the thermal mass of the underfloor heating system. Figure 11 shows the effect of reducing the living room underfloor heating system mass from 1,600kg to 600kg. The water cools much more rapidly overnight, but otherwise the control behaviours are similar. The annual energy consumption for the lower mass system is reduced to 19.5MWh, representing a saving of 8% compared with the standard thermostat system.

On/off thermostat and PI controller

In this case a thermostat controlled radiator system is compared with a system using a PI room controller, directly modulating the burner. A house meeting current building regulations fitted with a combi – boiler was used for this comparison. Typical energy consumption is less than half that of the previous example due to the higher insulation levels of this house. Figure 12 shows the living room temperature control and the water temperatures in these two cases. The room thermostat cycles approximately twice an hour, and has been set so that the room temperature does not fall below a setpoint of 21C. During the on period, the boiler is firing at full firing rate, as can be seen from the gas consumption shown at the bottom of the figure. The PI controller is mostly cycling on/off at the bottom of the modulating range (30%) of the boiler. Thus the PI controller is able to maintain the room temperature using a lower average water temperature, and run the boiler at a lower, and hence more efficient, firing rate. The thermostat system consumes 9.7MWh annually. The PI controller system 9.1MWh annually, a saving of 6.2%.

CONCLUSION

This paper describes the adoption of integrated dynamic modelling and simulation of domestic houses and heating systems. Verification of results in test room environments, and the establishment of an accessible interface that allows ready comparisons to be made of typical house, plant and control combinations have been described. The subtle interactions that influence the performance of different control types in domestic buildings can now be studied in detail. Developers can use this capability to develop further variations or new control schemes. The work can also be used as a basis for updated energy performance assessment procedures to accredit control types in particular system combinations that will ensure that energy savings benefits can be achieved. This is a valuable outcome, as control improvements can be readily applied to existing housing stock. Palmer et al, 2006, estimate that 70% of the 2050 housing stock already exists, so a few percent reduction due to controls can make a bigger impact on energy consumption and carbon emissions than double that percentage improvement due to new building standards.

ACKNOWLEDGEMENTS

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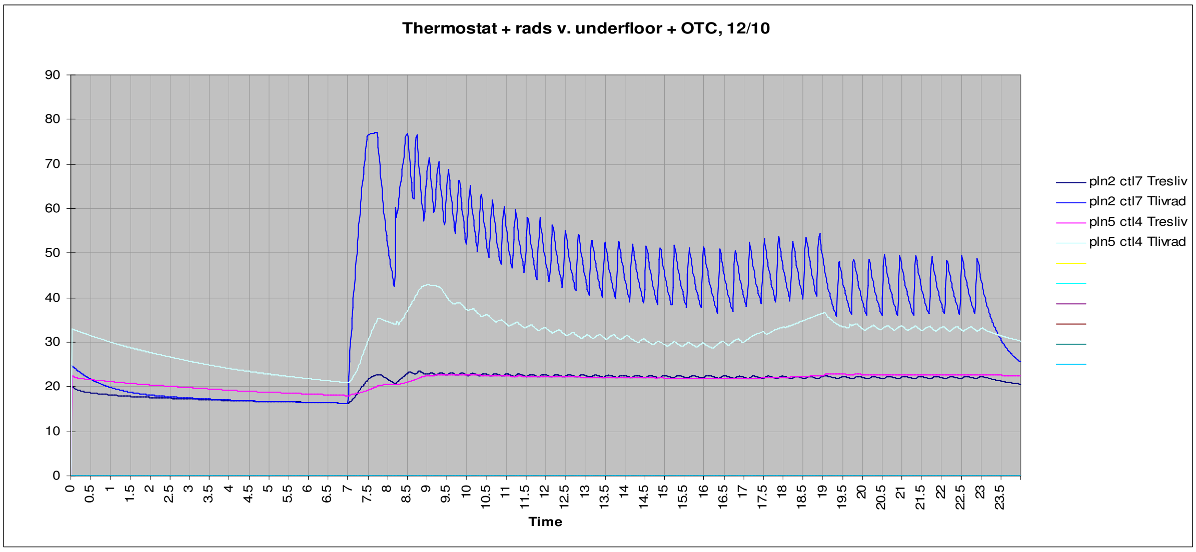

Figure 10 Comparison of thermostat and radiator system with underfloor heating and weather compensation.

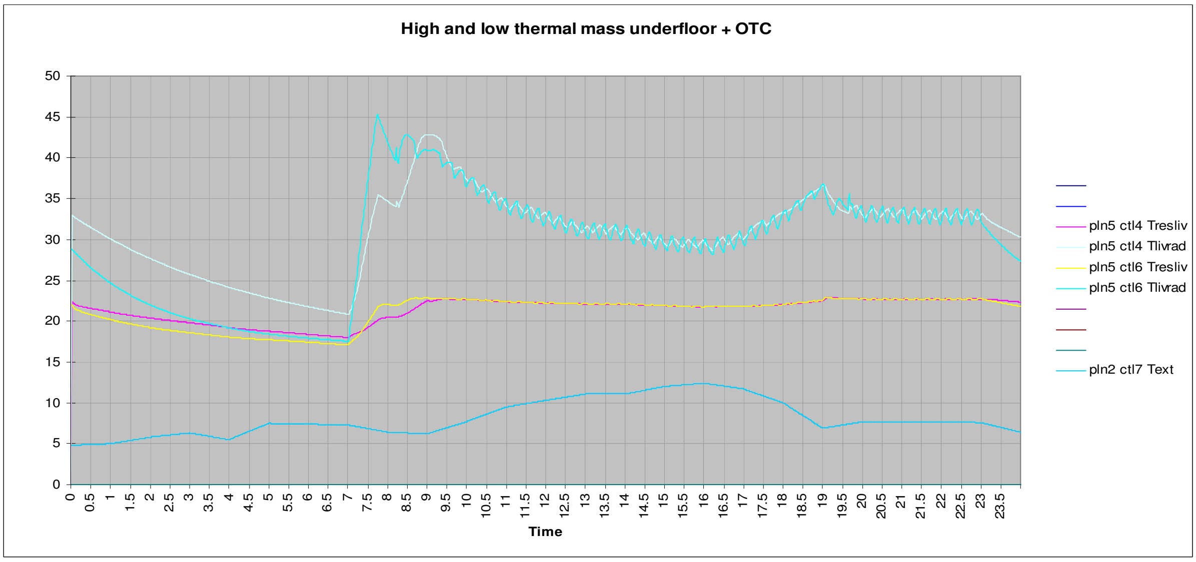

Figure 11 Comparison of high and low thermal capacity underfloor heating with weather compensation.

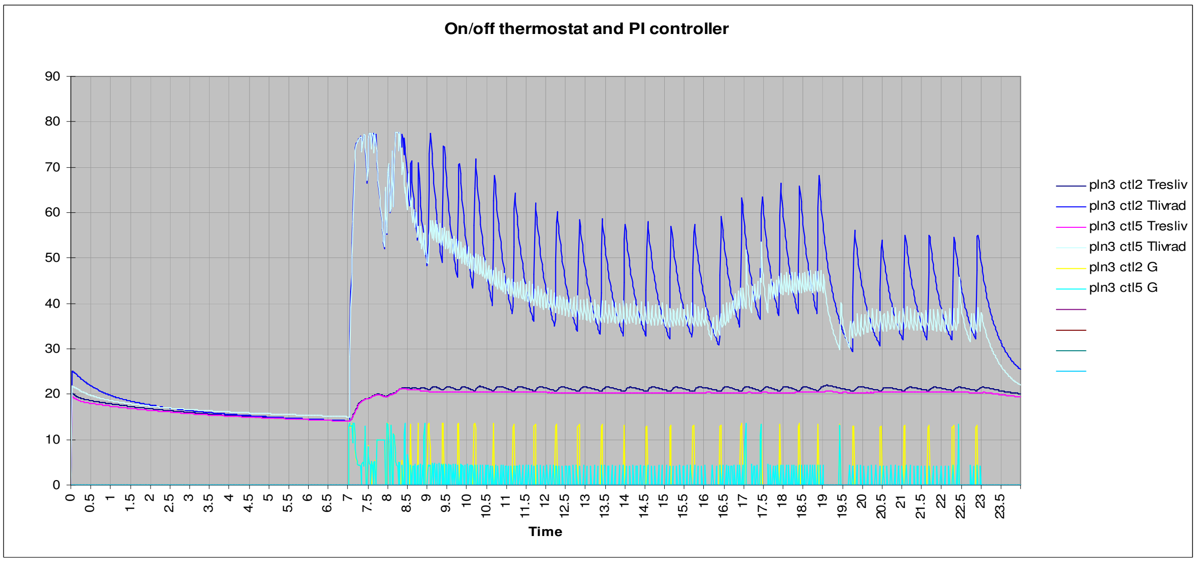

Figure 12 Comparison of on/off thermostat and PI room controller.