ELECTRIC STORAGE HEATERS
IN BUILDING SIMULATION

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ABSTRACT

This paper describes the simulation of electric storage heaters and their controls. A method for modelling manual control, inferred from transformer readings, is described. Use of the dynamic simulation language ESL compiled into a single program with an existing building simulation program, is explained. This provides a powerful and flexible tool for the evaluation and development of storage heaters and controls. Optimisation of storage heater controls has been shown to be a complex process which requires a sophisticated modelling approach. Final choice of the optimal control setting is shown to involve consideration of several parameters.

INTRODUCTION

Electric storage heaters were introduced into the UK in the 1970s in order to make better use of the load produced by the new nuclear power stations during the night, and to avoid the high daytime peaks associated with direct electric heating. While the spread of mains gas over the last 20 years has meant that many storage systems have been replaced with gas central heating, in the more rural areas storage heating is still widely used. It is also common in urban areas in high-rise flats and local authority housing, and is often an attractive option in new-build housing which are much better insulated than older stock.

While electric heating is sometimes perceived as expensive (and in the UK, domestic heating by direct electricity only is very unusual), running costs can be competitive with gas and there are other advantages of low capital and maintenance costs. Many new types of domestic tariff are appearing, and more can be expected when the market becomes fully deregulated in April 1998. This, combined with new developments in controls and communications for domestic systems, have generated a revival of interest in understanding and modelling storage systems. This paper considers some approaches to modelling such systems, describes some of the sometimes unexpected results which have emerged, and looks to future developments.

STORAGE HEATERS

Figure 1 shows a cross-section of a typical storage heater without a fan. The Feolite bricks which form the core are heated by metal heating elements, similar to the type used in kettles. The special insulation reduces heat loss from the bricks. Heat is emitted radiatively from the case, and by convection through the bricks as shown. The flap at the top, usually operated on a simple thermostat consisting of a bi-metallic strip, opens when the room temperature falls to the set level to increase the convective heat emission. There are various methods of charge control, described below. Some heaters do not allow convective loss by natural convection, but have fans which drive the air through the core; these have better heat retention and greater control.

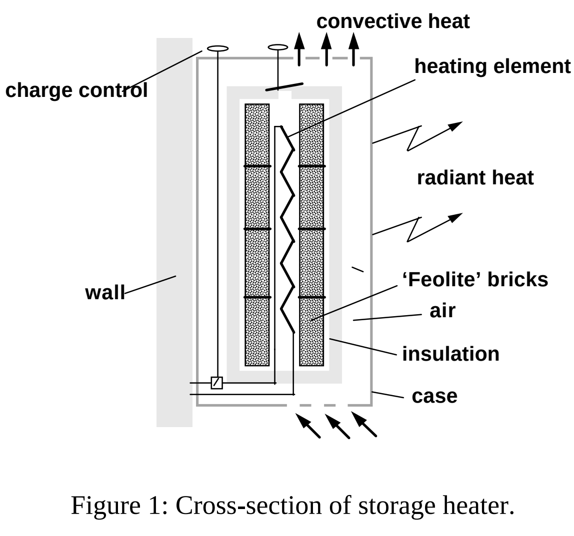

Figure 1: Cross-section of storage heater.

CONTROLS

There are four main types of storage heater control:

- Manual control setting of core thermostat
- Control of charge time using outside night temperature

- Thermostatic control to a room temperature set point during charge period
- Programmed control to optimise internal conditions at minimal cost of supply

Manual control

Manually-controlled heaters have a knob which sets the core temperature, typically between about 200 °C on a low setting and 650°C on the maximum setting. From the start of the charge period the elements will heat the core until this temperature is reached, then cycle on and off until the end of the charge period. This 'forward charging' means that on low settings (i.e. typically mild weather), heat is wasted during the latter part of the charge period. Because the core temperature is so much higher than the room temperature, heat loss is fairly insensitive to internal conditions and manual adjustment is necessary as the weather varies to maintain comfort.

Temperature-compensated local control

This type of controller provides backward charge control periods to all of the heaters in a house based on outside local temperature sensing via operation of a contactor at the meter. The start of the charge period is delayed until a time determined by the outside temperature, measured by a sensor attached to the outside of the building. The higher the outside temperature, the longer the delay. A typical range for the UK is 16°C between full charge and no charge.

Weather-compensated radio-teleswitch control

Another type of weather-compensated control uses current and forecast temperature and wind data to calculate charge times. The heating circuits are then switched on and off via a radio teleswitch in each dwelling. There is still individual control of the heaters which may be of any type.

Automatic control

Several manufacturers produce heaters with controls which are generally known as 'automatic', which go under various trade names. A sensor measures either the room temperature a little distance from the heater, or the temperature at the base of the heater which is a combination of room and core temperature. Charging continues until a set point (with dead-band) is reached when heat input is turned off. Charging is then restarted if the temperature falls below the dead-band, and this continues until the end of the charge period.

'Intelligent' Controls

Various new control systems are being developed which use optimisation algorithms to minimise the cost of heating for the consumer or the supplier, while achieving close control of room temperatures during occupied times set by the consumer. They do this by taking an optimal amount of electricity when the price of units is low, and minimising the amount used when the price is high. This applies to both charging the storage heater and direct heating. Unit prices can be taken from a tariff, or using cost reflective messages sent via radio signals which vary over the day. An example of this technology is the CELECT system developed at EA Technology. Development of this system made extensive use of simulation.

SIMULATING STORAGE HEATERS

Storage heaters in the UK were originally developed for a single 7 or 8 hour charge starting at about midnight, followed by a 17 or 16 hour discharge period, repeated every 24 hours. At the end of the discharge period the heater is not fully discharged (the bricks are still warm); capacity is quoted as the number of kWh available on a cyclic charge. This might seem a simple system to model, and indeed using simple exponential decay is a very good approximation to reality for an isolated heater on a cyclic charge. However, the heater is also interacting with the building fabric with a time constant of about one to three days, the effect of casual gains and other heating systems (which do not affect heat discharge very much but can have large effects on the heater controls), variations in weather, and variations in control setting whether manual or automatic. Before privatisation, the Electricity Council carried out several field trials of various storage systems which yielded valuable information about use of controls and occupant behaviour. However, field trials are very expensive to set up and often, because of the variability between households and lack of control, lead to difficulty in interpreting results and making precise comparisons.

Therefore, to account for all factors over a heating season, and be able to control inputs, a detailed building simulation is often the best option. Storage heater models are not generally available in simulation programs. There are a number of reasons for this:

- Storage heaters are not used much, or at all, in the country where the program was developed
- They require a special module which must interact with the building fabric, unlike the treatment of plant in many programs which is a post-processing of instantaneous loads calculated in the building part of the model.
- Storage heaters are not used much in large non-domestic buildings which is the main market for

building simulations because of the costs and one-off design problems involved

However, in recent years some storage heater models have appeared, for example in the TAS program developed by EDSL in the UK and the HTB2 v2.01 program [UWCC 96].

MODELLING HEATER CONTROLS

For all except the manual control, controls can be modelled in the usual way by representing the real control algorithms in the simulation. However, no defined algorithm exists for manual control. It is known that people with manually-controlled heaters do not leave them on a fixed setting over the heating season, which would result in very poor comfort, but actively vary the control settings. Research work [ECRC 85] and anecdotal evidence show that there is a wide spectrum of ways in which customers control the charge of storage heaters. Some consumers appear to alter the setting in response to internal conditions while others do so on a seasonal basis. There is no doubt that manual heaters are usually under active control by the consumer.

Half-hourly data from transformers serving areas with a large amount of manual storage heating were used to obtain the consumption during the night period over the heating season. From this, linear regression equations were developed expressing consumption as a function of the exponential-decay weighted-average temperatures over three days - this recognises that consumption is related to temperature and the thermal inertia of the property.

It was found that the relationships was different between spring, winter and autumn. From plots of the transformer loads and external temperature, it seems that consumers will turn the heaters on and the charge setting up in response to feeling cold during the autumn, and only turn the control down and/or heaters off in the spring when they feel uncomfortably hot after the first warm spell. This suggests some underheating in the autumn and considerable overheating in the spring. Over the winter there is some adjustment of control setting as the temperature fluctuates. Therefore the heating season was split into three periods - autumn (up to the first cold snap), winter (up to the first warm spring spell) and spring (subsequently).

The regression equations resulting are for transformer consumption of economy rate electricity. To convert this function to manual charge control settings, the loads are scaled from zero in mild weather to a maximum, equivalent to maximum charge, at a time of peak demand in very cold weather, typically when the average daily temperature is around -1 to 0°C. This is consistent with storage heater sizing which is typically for an outside temperature of about -1°C in the UK.

Figure 2 illustrates the seasonal differences in response to outside temperature, taken from the transformer data regression equations. There are three lines of control setting corresponding to the three periods. In the autumn, settings are generally lower (colder houses) and respond fairly strongly to temperature. The spring has similar slope but is offset higher (warmer houses). The winter responds less strongly to temperature with a flatter slope. Note this is illustrative - in practice some of the temperatures would rarely if ever be experienced in all seasons - but does show the inconsistency of response over the heating season.

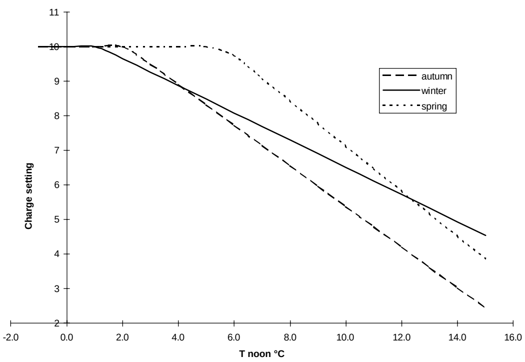

Figure 2: Control setting (1-10) against outside temperature for manual control.

LINKING HEATER AND BUILDING MODELS

In 1995 researchers at EA Technology Ltd, carrying out studies for the UK Electricity Industry and storage heater manufacturers, developed standalone, detailed models of storage heaters. These models used the European Simulation Language (ESL), developed originally for the European Space Agency [ISL 92]. This language allows differential equations to be encoded explicitly for dynamic systems, which are then solved automatically. Comparison of results with measurements from a number of storage heaters in a calorimeter room showed very good agreement, as shown in Figure 3. The effect of the top damper opening as the room temperature drops is clearly shown. In addition to using ESL for modelling the heaters, the HTB2 program v1.10 was being explored for use in the building side of simulations; this version did not contain a storage heater model

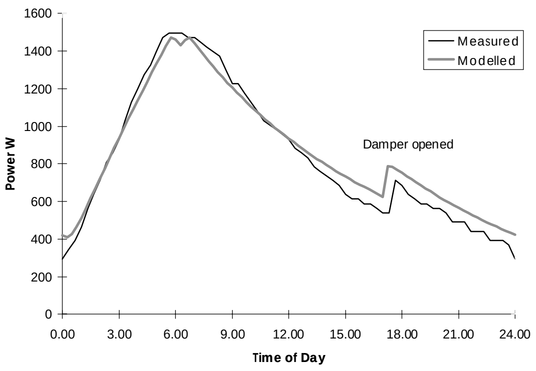

Figure 3: Graph of measured and modelled heat output from storage heater.

However, the problem remained of how to link these models to a building model. The ESL language is based on FORTRAN and it is possible to translate it to FORTRAN as an intermediate step during the compilation process. Although this machine-generated code looks fairly meaningless, it can be compiled together with the HTB2 code (also FORTRAN) into a single hybrid program in which the HTB2 building model is, in effect, called as a subroutine of an ESL program. It would probably be possible to do the reverse but that would have been technically more difficult since ESL has some unusual features - in either case the net result is the same.

At each time step, data on heat output from the heaters is passed to the HTB2 program, which returns room temperatures. The temperatures in turn feed back to heat transfer mechanisms and are used in control. The ESL program was also used to total electrical consumption (on and off peak) by heaters and appliances. Fortunately, both programs require similar time steps to maintain stability, of about 2 minutes or less.

There are certain practical limitations to this approach. The ESL language requires that the 'dynamic' part of the code uses separate variables, and it is not possible to have an array of heaters simulating only those required. Although 'dummy' heaters which have no thermal interaction with the building can be specified, these still take up some simulation time. Therefore code has to be altered to change the number of heaters being modelled for minimal run times.

It was found that modelling heaters using ESL and HTB2, compared to a normal HTB2 simulation, typically doubled simulation time. To model a house with up to 11 heaters for 245 days (a heating season) required about 40 minutes on a Pentium 133MHz machine - acceptable but requiring multiple runs to be done overnight using a batch file. The graphing facility of ESL, which allows on-screen plots of user-defined variables with time during the simulation, proved very useful during development and to follow progress.

ASSESSMENT

In assessing the performance of any heating system, there are three main indices of interest: comfort, energy and cost. Most heating systems supply heat on demand, and comfort is usually 'guaranteed' by a thermostat. Also, because most energy tariffs are flat-rate, the cost is directly proportional to the amount of energy used. Therefore the assessment of different systems and conditions of use becomes a matter of comparing energy use, ensuring that the plant is adequately sized, and thermostatic control works correctly.

Assessing storage systems is more difficult because all three indices depend on the storage of heat *before* the occupied period. Storing insufficient heat during the charge period results in a large shortfall in stored heat remaining towards the end of the discharge period, requiring an excessive amount of expensive direct heating 'top up' to achieve adequate comfort. Too much stored heat results in overheating during the start of the discharge period and higher energy use, although the proportion of direct heating will be smaller.

Furthermore, because some stored heat is lost during unoccupied periods (including, in most cases, the charge period itself), stored heat is used less efficiently than direct heat in providing comfort. Without exception, a thermostatically controlled direct electric heating system for a given building, which has a very fast response time and 100% conversion efficiency, will result in the best comfort and lowest delivered energy use (typically around 35% less energy than a typical storage + direct system), but at a much higher cost.

Sometimes the ratio of storage to total heating energy, or 'split' as it is known in the UK industry, is considered an important index in its own right, with splits of 0.9 for non-fan storage systems and 0.95 for fan storage systems being quoted as optimal for the UK. However, concern about the split is misleading; to the consumer what matters is achieving acceptable comfort and control at the lowest achievable cost (and not, therefore, the lowest energy consumption).

Sizing the heaters correctly is important. Usually they are designed so that in the coldest weather, there is a higher proportion of direct heating used; otherwise they would be oversized for most of the heating season. Simulation can be very effective in investigating different sizing strategies.

COMFORT

In simulations omfort was measured as the number of degree hours above and below a comfort band around the set point temperature, during heated period only. Conditions outside heated periods were ignored. The house was divided into three zones:

Zone 1: Living room
Zone 2: Kitchen, hall and landing
Zone 3: Bedrooms and bathroom

The comfort bands are shown in Figure 4.

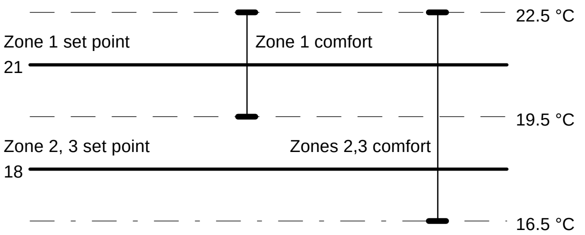

Figure 4: Comfort bands for zones

The comfort band for zone 1 is the conventional comfort range applied in most situations and corresponds to a Predicted Percentage Dissatisfied (PPD) < 10%, based on Fanger's comfort equation. For zones 2 and 3, a wider upper band, up to the zone 1 upper limit, is allowed on the basis that people wouldn't mind these zones being warmer up to the zone 1 limit.

Degree hours 'under' are the integral of ($T_{set\ point}$ - T_{actual}) over time, where T_{actual} is the zone average temperature if below $T_{set\ point}$, otherwise zero. For example, three hours at 15°C during a heated period in zone 2 counts as 4.5°C h under.

Similarly, degree hours 'over' are the integral of (T_{actual} - $T_{set\ point}$) over time, where T_{actual} is the zone average temperature if above $T_{set\ point}$, otherwise zero. Total discomfort is simply the sum of all degree hours under and over, across all zones.

VARIATION IN PARAMETERS WITH CONTROL

Figure 5 shows the variation of various parameters as a function of control setting for manually-controlled heaters. It is particularly interesting to note that cost remains almost constant throughout. Although it is not easy to see the variation on the graph because it is so slight, the normalised figures are: 100.0 99.3 98.5 98.5 98.8 99.0

Therefore there is a minimum cost which in this case happens to coincide approximately with minimum total discomfort. Clearly both of these are valued by the consumer. Energy increases monotonically with increasing control setting; this makes sense because the lowest energy will be for direct-only heating, while increasing the amount of storage will inevitably mean increased energy use.

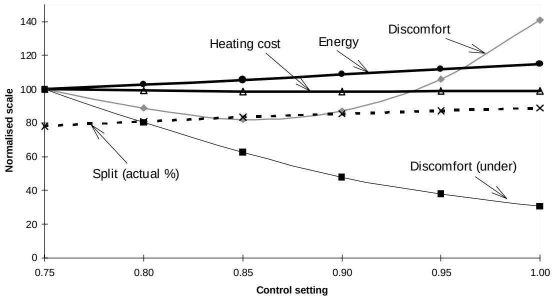

Figure 5: Variation in comfort, energy, heating cost and storage/total split as a function of control setting for manual heaters in a brick terraced house.

OPTIMISATION OF CONTROL SETTING

Optimising control settings for different permutations of dwelling type and controller could not be done on a single parameter. It was felt that using total discomfort, which would be simple, was not ideal because it can lead to significant underheating at times which is compensated by overheating at other times; in practice people are likely to prefer to be too warm rather than too cold, and also overheating can usually be overcome by opening windows (not modelled) whereas underheating is more difficult or expensive to overcome. Therefore a pragmatic balance of overall comfort , avoidance of serious underheating, and cost was chosen, designed to reflect what a consumer would do in practice.

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CONCLUSIONS

Modelling storage heaters presents many unique problems compared to other heating systems, associated with controlling use of stored heat, varying prices of electrical units, and the need for assessment on a number of parameters.

The ESL language provides a powerful tool for modelling dynamic systems such as storage heaters, which can be linked directly into a full building simulation program for other thermal processes. This approach could be used to model any device with complex dynamics (e.g. an active solar system) interacting with a building.

There is likely to be a large increase in the use of more sophisticated storage heater controls at all levels as consumers demand better comfort at low cost, and electricity suppliers act to gain greater control over the times at which heaters are charged through use of radio tele-switching and 'intelligent' controllers. New fan storage models are being developed with greater heat retention than existing models, resulting in more efficient use of stored energy. There are large potential markets in areas such as South Africa, Spain and Canada which have serious problems with direct heating loads in peak winter conditions. Storage heating remains competitive in new, low-energy housing with its low capital and maintenance costs, where the low heat loss of the fabric means that storage heat lasts a long time and the direct heating requirements are small.

In all of these developments, computer simulation of the heaters, controllers and buildings will play an increasing role. As building simulation programs develop with greater emphasis on plant modelling, more are likely to include storage heater models. In the UK, lack of resources to run large and very expensive field trials, combined with the availability of improved modelling tools and hardware, has meant a much greater reliance on simulation to provide data on storage systems than in the past.

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