STUDY ON OPTIMAL START/STOP OPERATION OF HYDRONIC HEATING SYSTEMS

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ABSTRACT

The study is focussed on the sensibility of optimal start/stop control of hydronic heating systems on boiler and radiator sizing, supply temperature lift, and the building occupancy pattern. For the prediction of optimal start/stop times the recursive least squares method and the gradient method are evaluated. Computer simulation is applied on the example of an office building equipped with an hydronic heating system.

1 INTRODUCTION

The occupancy pattern of a particular building depends on the building users and functions. Room air temperature requirements vary with the occupancy pattern. During the occupied period a certain comfort temperature is required. Outside the occupied period there is either no limit to the temperature or the temperature is limited by condensation or freezing. The purpose of heating and control systems is to maintain room air temperature at the level specified by these limits. Intermittent heating can be applied to accomodate the consumption of the heating energy to the building occupancy pattern and thus it offers an effective and technically simple means of reducing energy consumption in periodically occupied buildings, eg. offices, schools etc.

One of the main problems of realizing optimal intermittent heating is how to accurately estimate the preheat time. This is important for both the energy conservation and thermal comfort aspects of intermittent heating: overestimation of the preheat time leads to unnecessary energy use whereas underestimation leads to "cold mornings".

This paper presents results from the studies concerning optimal start/stop operation of hydronic heating systems carried out within a subproject of the IEA Energy Conservation in Buildings and Community Systems - programme Annex 17 BEMS (Building Energy Management Systems). Several research institutes share the tasks of this project, mainly working on the development of methodologies for the evaluation of performance and energy saving potential of building energy management systems.

The study is focussed on the sensibility of optimal start/stop control for different parameters, like boiler and radiator sizing, variation of the control function for the supply temperature, and the duration of the shut down period.

By detailed computer simulations energy saving and comfort are evaluated on the example of an office building equipped with a hydronic heating system. The adaptive algorithms of two different start/stop controllers are also tested by investigation of a heating period of four weeks, using measured weather data with a wide range of outdoor temperatures.

2 ALGORITHMS FOR OPTIMAL START/STOP CONTROL

In this Chapter two different control algorithms are introduced: The recursive least squares method (RLS), (Chapter 2.1, evaluation in Chapter 4.1) and the gradient method (Chapter 2.2, evaluation in Chapter 4.2).

2.1 The Recursive Least Squares Method (RLS)

It can be shown /1,2/ that the preaheat time τ_p of a particular building can be approximated by

$$\tau_p'(n) = k_1 + k_2(T_d - T_r(n)) + k_3((T_d - T_r(n))(T_r(n) - T_0(n)) + k_4\epsilon(n-1) \qquad (1)$$

where T_d is the desired room temperature at the beginning of the occupied period, $T_r(n)$ and $T_0(n)$ are the room temperature and ambient temperature at instant n, respectively, and $\epsilon(n-1)$ is the error of the previous preheat time estimate. Writing the equation in vector form we obtain

$$\tau_p'(n) = \theta(n)\chi^T(n) \qquad (2)$$

where $\theta^T(n) = \{ k_i \}$ and $\chi^T(n) = \{ 1, (T_d - T_r(n)), ...\}$. The parameters k_i are functions of the thermal properties of the building and heating system and thus application dependent. An estimate θ' of the parameter vector can however be computed using the recursive least squares identification (RLS) algorithm

$$\theta'(n) = \theta'(n-1) + K(n)\epsilon(n) \qquad (3)$$

$$K(n) = P(n-1)\chi(n)/\alpha \qquad (4)$$

$$\alpha = \chi^T(n)P(n-1)\chi(n) + \lambda(n) \qquad (5)$$

$$P(n) = [P(n-1) - K(n)\chi^T(n) P(n-1)]/\lambda(n) \qquad (6)$$

$$\lambda(n) = [\lambda(n-1) - 1]\lambda_{up} + 1 \qquad (7)$$

where λ is the forgetting factor which is used to track changes in the dynamics of the system /3/. The next preheat time estimate is given by the equation

$$\tau_p'(n+1) = \theta'^T(n)\chi(n+1) \qquad (8)$$

Initially all parameters of the algorithm are in this work set to zero, except for k_1 which is set to an assumed preheat time. The values of the diagonal of covariance matrix $P(4 \times 4)$ are set to 1000 and other values to zero. Initial value of the forgetting facor λ_0 is set to 0.95 and the value of the update coefficient of the forgetting factor (λ_{up}) is set to 0.75.

2.2 The Gradient Method

The gradient method /6/ assumes the increase of room temperatures at the beginning and the decrease of room temperatures after the end of heating to be linear. Although the two dimensional gradient method (with a memory matrix for measured data) is not adaptive (in the classical sense of the control theory), it can give a controller the ability of self learning. A gradient method controller renounces optimal start/stop for the first days of heating, starts with a fixed heating time, watches the reaction by measuring and memorizing the temperature of a reference room in discrete time steps, calculates the gradients of heating and cooling with memorized temperature profiles and finally uses these stored gradients to calculate the new start/stop times. In the following section this method is described only for the case of optimal start.

The start gradient for the day D is defined as

$$G_s(D) = \frac{\tau_r(D) - \tau_s(D)}{T_c - T_{s,i}(D)} \qquad (9)$$

with τ_s as the time the heating system is started, τ_r as the time the required comfort condition is reached, T_c as the required comfort temperature and $T_{s,i}$ as the indoor temperature at the time of start.

The optimal start controller consists of a clock, sensors for the actual indoor and outdoor temperature, a memory mainly for the gradient data bank, and a processor for the estimation of the start times of the heating plant. The memory should give the controller the ability of self learning. When the heating system is shut down ($\gamma = 0$) the processor calculates in small time intervals the predicted room temperature T_p by using equation 10 for the case that the heating system will be just started. If the predicted room temperature is equal to or smaller than the required comfort temperature, than the heating system is started by the controller ($\gamma = 1$) and the actual time and indoor/outdoor temperatures will be memorized. The predicted room temperature is

$$T_p = T_i + \frac{\tau_c - \tau}{G_s} \qquad (10)$$

where T_i is the actual indoor temperature, which is an effective temperature to be composed of the air temperature T_a and the radiant temperature T_{rad} as

$$T_i = \frac{1}{2} \cdot (T_a + T_{rad}) \qquad (11)$$

$$T_{rad} = \sum_{j=1}^{n} \frac{A_j}{\sum_{j=1}^{n} A_j} \cdot T_{rad,j} \qquad (12)$$

For the first days the value of the start gradient in equation 10 has to be estimated as good as possible. After the comfort temperature is reached, the processor calculates the real start gradient for the actual day and stores it to the memory. The memory is organized as a two dimensional field (IKE example: 5x5), in which the value of the start gradient is related to the two dimensions indoor temperature and outdoor temperature $G_s = f(T_{s,i}, T_{s,o})$. After some days of operation a sufficient number of values should have been stored to make the controller able to guess (interpolate) the shape of the G_s curve. Then the daily optimal start times can be predicted by using computed gradient values for equation 10. Our first simulation results show that the method mentioned above does not consider the thermal inertia of the building correctly. It can be demonstrated that if the method is applied, the influence of the structure temperatures, weakly represented by the radiant temperatures (see equation (12)), will be nearly neglected. This fact can introduce problems especially in buildings with big thermal inertia and in periods with big changes in the outdoor conditions. In order to avoid these problems two additional devices are implemented in the optimal start controller : First, if the outdoor temperature is less than - 8°C the optimal start control will be frozen and the heating system operates continuously. Second, if the controller measures gradients which have an unlogical relation to other values in the memory (e.g. if gradient for lower temperatures is bigger than the gradient for higher temperatures) then the value of the previous day will be kept.

3 Specification of the Example

Computer simulations were carrioed out on the example of an office building equipped with a hydronic heating system /5/.

3.1 Building

The building is modelled as a set of equal units (office rooms) and has a north-south orientation (see Figure 1). The nominal heat demand of the rooms is calculated

for -12°C outdoor temperature. The insulation of fasade, roof and ceiling is chosen as proposed in a german energy saving order. Typical internal loads (lighting, equipment and people) of a commercial building are chosen.
The building is occupied from 8 am to 5 pm. Only the two middle sections of the whole building are simulated.

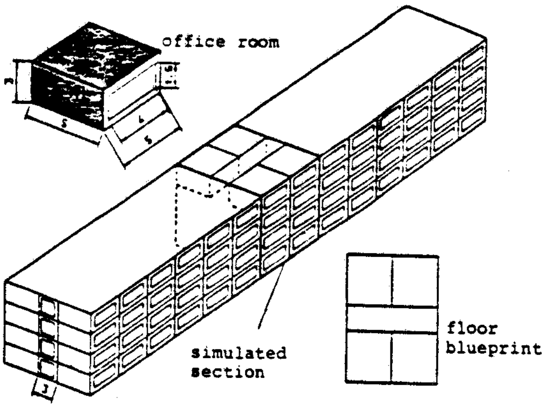

Figure 1: Office building, dimensions in meters

3.2 Heating System

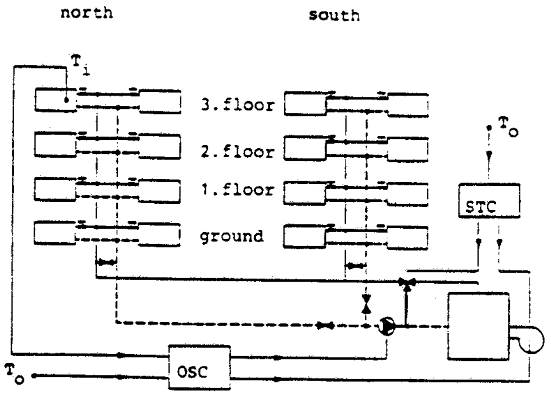

Figure 2: Radiator heating system of the office building, OSC: optimal start controller, STC: supply temperature controller

The heating system is assumed to be a " low temperature heating system " (design temperatures 70/60°C) (see Figure 2). It consists of flat plate radiators (nominal power between 986 W and 1366 W) in each of the office rooms controlled by ordinary thermostatic valves (set point temperature 23°C). A modern high efficiency boiler is chosen (nominal useful power 130 kW). Weather compensation control is applied on the boiler and the three way mixing valve.

3.3 Weather

The evaluation of optimal start/stop strategies require long weather periods. The period of 4 weeks from February 1st to 28th is simulated, using the meteorological data of the german test reference year /7/.

3.4 Mathematical Models

The building and the plant are simulated by mathematical models mainly developed within the IEA projects Annex 10 " System Simulation " and Annex 17 " Building Energy Management Systems ".

The boiler model is the steady state model of the IEA Annex 10 project. Losses are functions of the operation conditions. Two heat exchangers are considered : the gas to water heat transfer and the enviromental heat losses.

The radiator model is a multi-element dynamic model based on the energy balance on the exhaust water temperature for each element. The water and metal capacitance of a radiator element is concentrated in one node.

A simplified building model is used. Each zone is represented by a second order lumped parameter model. A zone has only one temperature. Five parameters have to be determined for each zone: thermal resistance of light structures in connection with the ambience, resistance of heavy structures, capacitance of heavy structures, internal capacitance of the zone (indoor air) and the global accessibility of structural capacitance.

IKE uses in addition the simulation program GERALT /6/ in which the transient heat transfer through walls is simulated by a finite difference method and the heat and mass balance is considered for every wall surface and room air node.

In both simulation models it is assumed that only the two middle sections of the whole building (on each floor only 4 rooms and one corridor section) are simulated. Furthermore it is assumed that no doors and no air exchanges between the rooms exist. The constant ventilation rate of 0.5 h^{-1} is only required in the office rooms but not in the corridors. The cellar and roof influence is considered with constant temperatures in the cellar (15.0°C) and in the heating room (25.0°C).

VTT simulations on the RLS-algorithm were carried out using PIBNET, a program package developed at VTT for dynamic thermo-hydraulic simulation of water radiator heating plants /4/.

4 ALGORITHM EVALUATION

4.1 Evaluation of the Recursive Least Squares Algorithm

This chapter includes the evaluation of the RLS-algorithm which has been implemented by VTT. For the evaluation of the RLS-algorithm simulations were carried out for the office building comparing continuous heating, intermittent heating with fixed operation times and intermittent heating controlled by the RLS-algorithm. For intermittent heating a northern office room on the third floor is chosen as the reference room (see Figure 1) and supply water temperature during the preheat period is set constant (75°C). Figures 4,5 and 6 present the results of the evaluation.

Continuous heating in this case produces an offset of 1 - 2°C from the set pont in the office room temperatures. This is due to the P-control charactersistics of thermostatic radiator valves. Assuming that 20°C is the optimal temperature for the occupants and the use of the building, it can be said that continuous heating does not provide comfortable thermal conditions. The room temperature offset also indicates unnecessary energy use.

In the case of intermittent heating with fixed operation times the fixed preheat time (2 hours) is not even close to enough on the cold days at the beginning of the period but on the rest of the days the error is +/− 30 minutes. However, the temperature distribution in the office rooms during the occupied period is quite wide and the lowest temperatures reach as low as 17°C. Energy savings compared to continuous heating are about 25%.

The RLS-algorithm shows similar problems on the cold days at the beginning of the simulation period as the previous case. The available preheat power is not enough to justify the assumptions made in the construction of preheat time estimate. This can be seen as variation the preheat time prediction error and slight divergence of the parameters k_1 and k_2. The temperature distribution is quite the same as in the case with fixed operation times. The energy savings obtained by the RLS-algorithm are almost the same as with intermittent heating with fixed operation times.

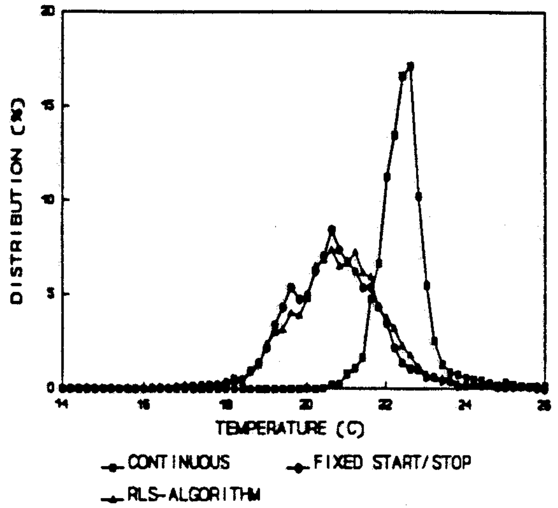

Figure 3: RLS vs. continuous heating and fixed operation times: room air temperature distribution

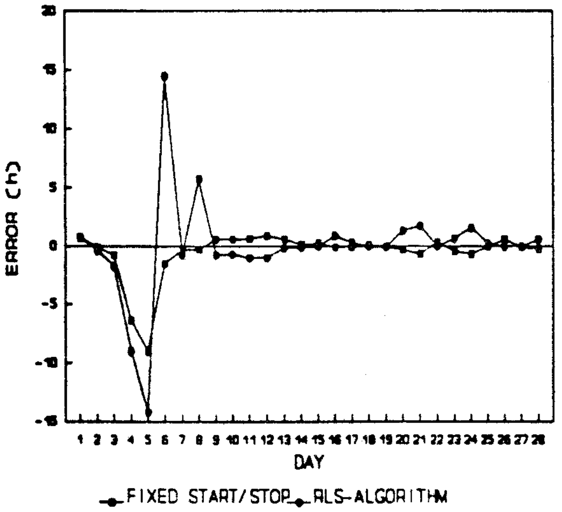

Figure 4: RLS vs. fixed operation: preheat time prediction error

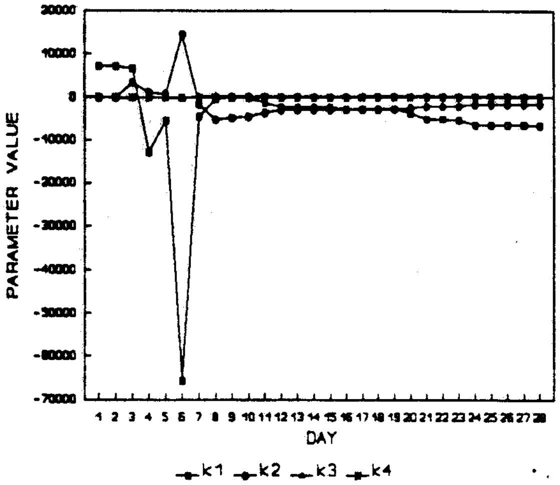

Figure 5: RLS parameter identification

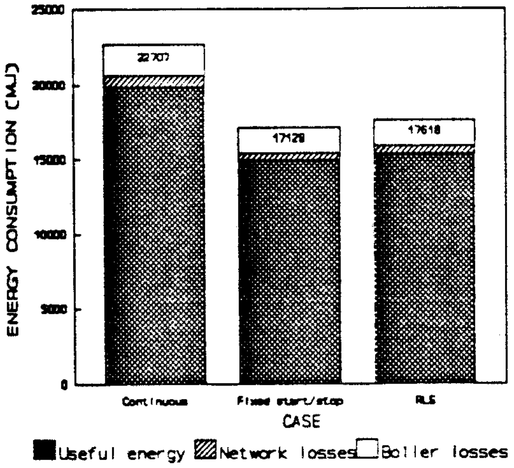

Figure 6: RLS vs. continuous heating and fixed operation times: energy consumption

4.2 Evaluation of the Gradient Method Algorithm

This chapter includes the evaluation of the gradient method which has been implemented by IKE. The evaluation is done by comparison between a fictitious perfect controller and a real algorithm based controller.

The perfect controller has been simulated by iteration: The simulations are repeated several times, until comfort temperature is reached every day at 7 am (one hour before the occupants return). After each simulation run these values are corrected by looking at the plots for the temperature in the reference room. After 4 to 6 repetitions the optimal start times are found.

The building should be occupied from 8 am to 5 pm. The comfort temperature is 20°C and already required at 7 am. For the evaluation of optimal start a northern office room on the third floor is chosen as the reference room (see Figure 1). Test runs have shown that the northern rooms on the last floor are the coldest rooms.

In Figure 7 the evolution of the gradient memory is shown The values for the first day are free chosen by considering the simulation results with the perfect controller. It can be seen that the developement is very slow, especially because of the additional functions which compensate the lack of consideration of the thermal inertia of the building.

The very cold period in the first week provides bad estimations of the real controller up to three days after the event. But thereafter, a long period with good estimations (good agreements of real and perfect control) follows. An overview of the daily start times obtained with both contollers and the error made by the real controller is given in Figure 8. The other smaller errors of the real controller should be explained by the long learning time to be required for this controller.

As already mentioned, if the gradient method is applied for the prediction of optimal start times, the influence of the structure temperatures should not be neglected. The optimal start times, found by the repetition of the simulations, and the daily indoor temperatures at the moment of start can be used to calculate the daily gradients of start by using equation 9. These values are plotted by relating them to their indoor/outdoor temperatures in a 3 dimensional field. The result is shown in the right part of Figure 9. The Finite Difference Method for the modelling of the building allows to investigate the layer temperatures in all walls, too. By examining the layer temperatures it can be seen that the irregular peaks in the right part of Figure 9 are the gradients of the days after cold periods. On these days the building structure is still cold although the outside air temperature has risen. If the gradients of these days are not considered in the plot, the picture of a much smoother plane will be achieved (see Figure 9, left part). The gradient method with only two dependences ($G_s = f(T_{s,i}, T_{s,o})$) will not provide good forecasts, if the effect mentioned above is neglected.

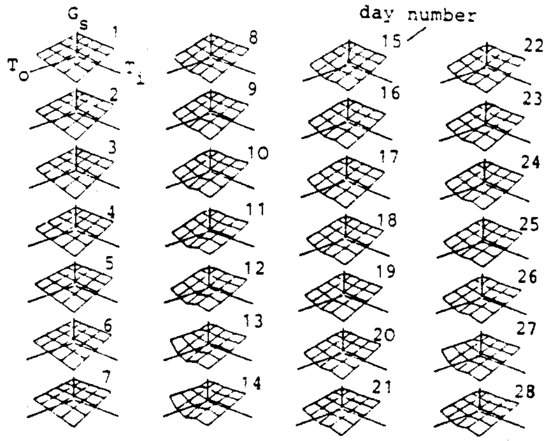

Figure 7: Evolution of the memory matrix (5x5 field for $T_i = 16°C....20°C$ and $T_o = -4°C....20°C$)

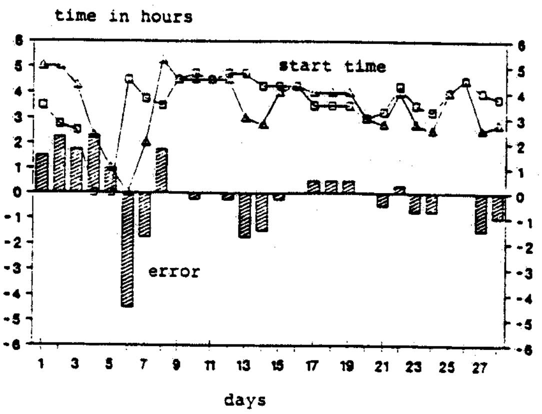

Figure 8: Daily start-up times (triangle: perfect controller, square: real controller) and error of the real controller (beams: +: soon, -: late)

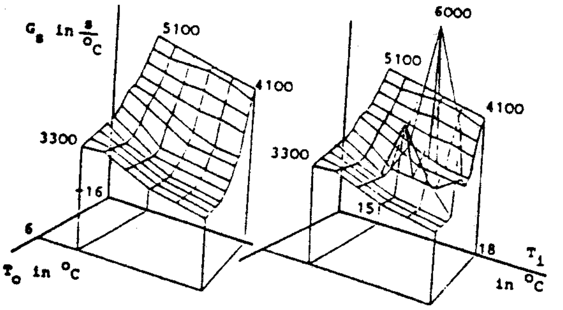

Figure 9: Dependences of the start gradient ($G_s = f(T_{s,i}, T_{s,o})$); left side: the gradients of the days, on which the outdoor temperatures have returned from a cold season back to warmer days are not considered; right side: the gradient of all days are considered

5 PARAMETER STUDIES

5.1 Influence of Component Sizing on the Optimal Start Operation

The objective of this chapter is to demonstrate the influence of the sizing of heating system components when optimal start is applied in an office building equipped with a radiator heating system. To avoid different comfort conditions during the occupation time continuous heating is selected as the reference case.(Fixed Start/Stop would not achieve the required comfort condition on cold days.)

The influence of the sizing of the heating system components is shown by the combination of 4 sizes of boilers (100, 130 (nominal), 200, 260 kW useful power) and two sizes of radiators (100% and 200% nominal performance). Furthermore, in combination with thermostatic valves the big radiators cause higher room temperatures. This provides higher transmission losses of the building. To investigate this influence, a special case with 1 K reduction in the set point temperature of the thermostatic valves is simulated for the oversized plant (200% radiator and 200% boiler power).

Figure 10 shows the room temperatures of the reference room in the case of nominal sized boiler and radiators and 200% oversized boiler and radiators. The daily evaluation of the room temperatures is plotted for the period between Februray 15th and Februray 21th (3rd week). It can be seen that the larger plant allows to start the heating system later than the nominal plant. The total energy consumptions for all simulated cases is given in Figure 11. There are only small differences between the various boilers, if optimal start is applied. Furthermore, oversizing of the radiators leads to higher energy consumptions caused by higher room temperatures. For both control modes the consumption falls, if the set point temperature of the thermostatic valves is reduced 1 K .

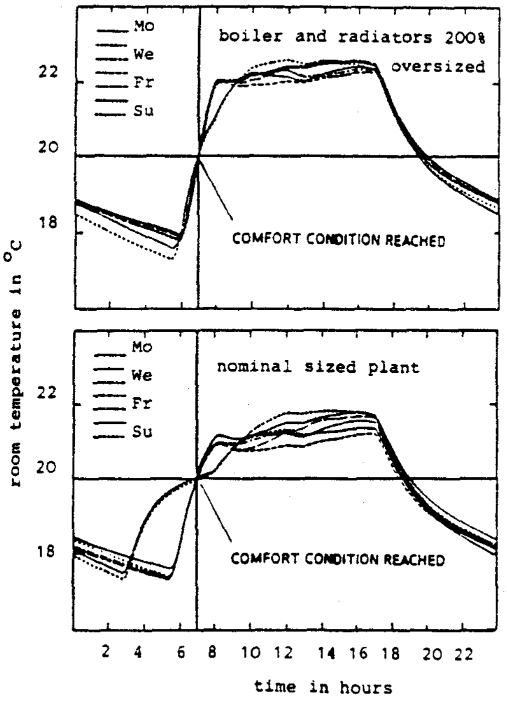

Figure 10: Room temperatures of the reference room during the 3rd simulated week (Februray 15th to 21th)

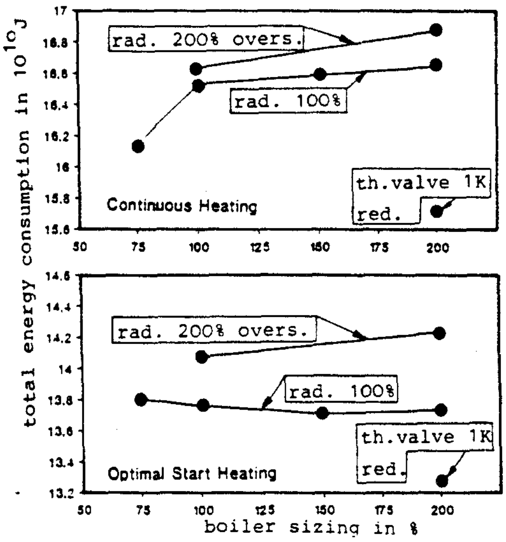

Figure 11: Total energy consumption for the period February 1st to 28th

5.2 Influence of Supply Temperature Lift on the RLS Algorithm

Figures 12, 13 and 14 present the results of simulations of intermittent heating controlled by the RLS-algorithm in which the supply water temperature during the preheat period is set to 90°C. The supply temperature lift is obviously beneficial as far as only the operation of the RLS-algorithm is used as criteria. Preheat time prediction error converges close to zero and also the parameters k_i reach almost constant values.

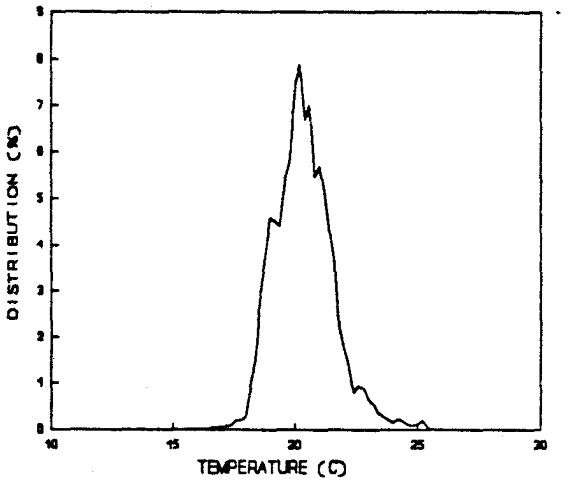

Figure 12: RLS supply temperature lift, room air temperature distribution

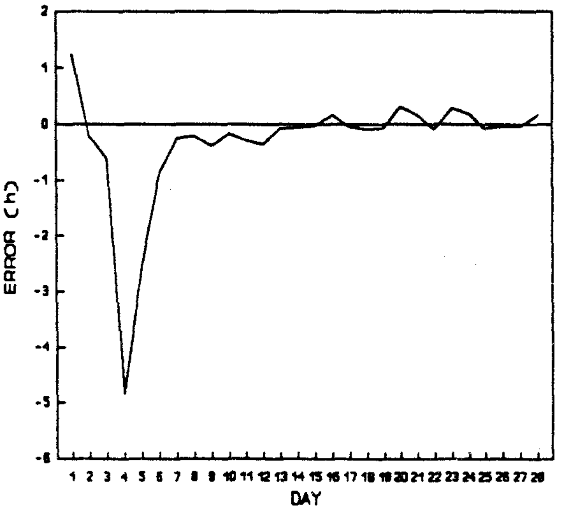

Figure 13: RLS supply temperature lift, preheat time prediction error

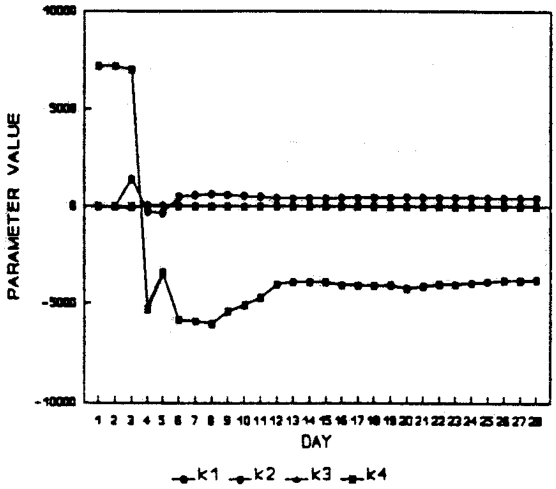

Figure 14: RLS supply temperature lift, parameter identification

5.3 Influence of Occupancy Pattern on the RLS Algorithm

Figures 15, 16 and 17 present the operation of the RLS-algorithm with three different building occupancy pattern: (1) daily occupation from 6 am to 10 pm, (2) occupation from 8 am to 5 pm on working days with no occupation on weekends, and (3) occupation from 8 am to 5 pm on working days with no occupation and no heating on weekends.

When the building is occupied daily from 6 am to 10 pm the operation of the RLS-algorithm is very stabile. The reason for this is quite obvious. Due to the short cooling period (about 7.5 hours during most of the calculation period) the room temperature range inside which the algorithm has to operate stays quite narrow. This stabilizes the operation because of assumptions made in the linearization of preheat time approximation equation (eq. 1).//

When the office building is not occupied during weekends the absence of heat-loads causes considerable problems: the approximation preheat time is almost one hour too short during weekends. Changes can also be seen in the identification procedure. The parameters of preheat time prediction model converge to new values each week. This demonstrates the fact that the identified parameters k_i have in fact no physical meaning but they merely represent a "best fit line" of the analytical preheat time solution. It has to be noticed, however, that the weekend preheat time prediction error has practically no effect on the temperature distribution of the occupied period.

In the case where the building is not occupied and the heating system is switched off during weekends the algorithm shows similar behaviour as in the previous case: estimated preheat time is much too short on monday mornings. As the building is allowed to cool down with no lower temperature limit during weekends the operation range of the algorithm on monday mornings is quite different from the rest of the week. In this particular case the monday morning error causes observable oscillations in the preheat time prediction and the parameteres converge to new values each week. An error of this magnitude also causes significant deviation from the desired temperature at the beginning of the occupied period.

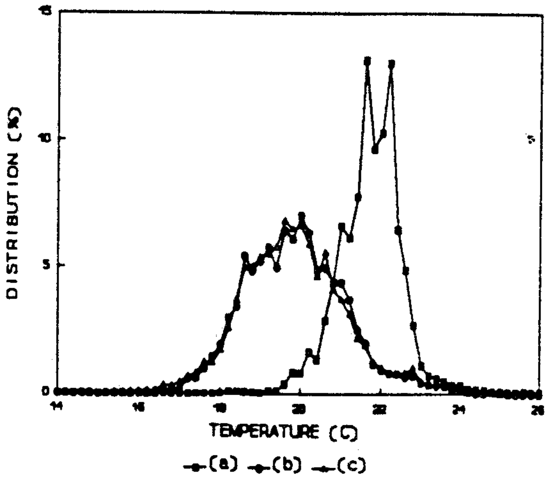

Figure 15: RLS, (a) 6 am 10 pm, (b) no occupation on weekends, (c) no occupation and no heating on weekends: temperature distribution

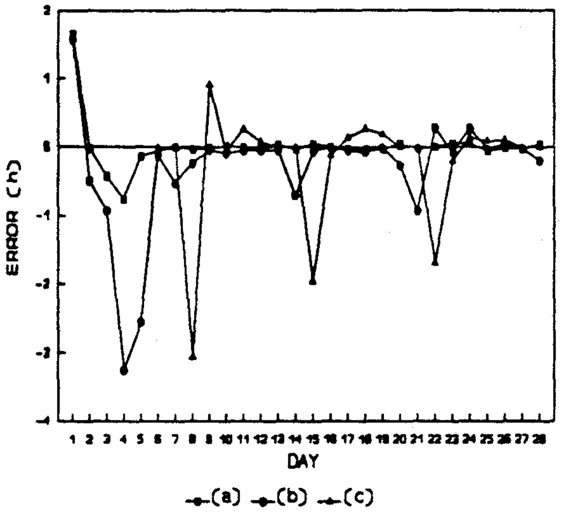

Figure 16: RLS, (a) 6 am 10 pm, (b) no occupation on weekends, (c) no occupation and no heating on weekends: preheat time error

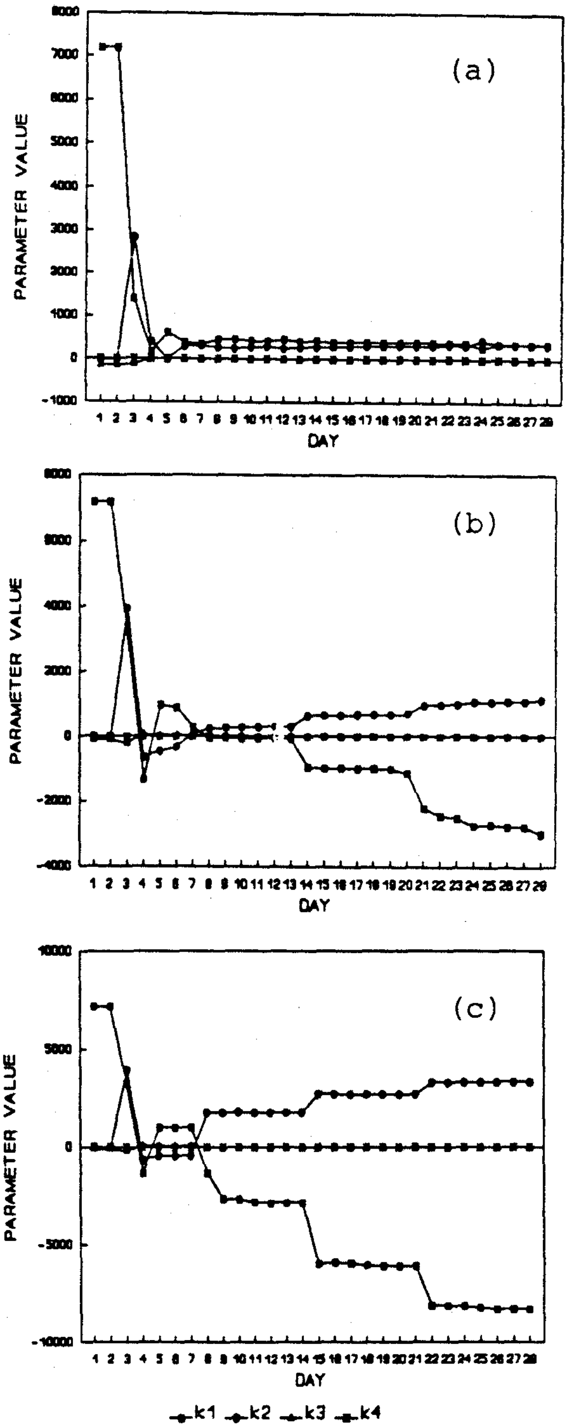

Figure 17: RLS, (a) 6 am-10 pm, (b) no occupation on weekends, (c) no occupation and no heating on weekends: parameter identification

CONCLUSIONS

The sensibility of optimal start/stop control on boiler and radiator sizing, supply temperature lift, and the building occupancy pattern is shown by computer simulation.

It is demonstrated that the size of the boiler has no influence and the size of radiators has only a small influence on the energy consumption of a hydronic heating system controlled by an optimal start controller. The substitution of weather compensated supply temperature control by constant maximum supply temperature control leads to better convergence of the optimal start algorithm and therefore better forecastings.

Two different optimal start algorithms are evaluated. The recursive least square method and also the 2 dimensional gradient method show a considerable inaccuracy. This is due to the linear nature of the preheat time approximation of the model in both algorithms. As the analytical preheat time is nonlinear it would be necessary to model it with two or three linear approximations each for a certain temperature range. The RLS-identification itself is very well suitable for DDC applications because it is easy programmable, provides relatively fast identification and does not have large memory requirenents.

The application of the gradient method requires a rather large memory. Within the gradient method the thermal inertia of the building should be considered in a better way. A possible solution is to equip the optimal start/stop system with an additional sensor which measures the structure temperature in a suitable location. Then the daily gradients can be stored in a 3 dimensional field $G_s = f(T_{s,i}, T_{s,o}, T_{structure})$. The disadvantage of this method is the long learning time of the controller, during which the empty sections of a 3-dimensional matrix are charged.

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