CONTROL STRATEGIES FOR HEATING SYSTEMS

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ABSTRACT

A controller for heating systems is normally equipped with many facilities to make it flexible and the heating system more cost-efficient. This results in a number of input parameters to be given by the user. It is not obvious how to choose appropriate values for these parameters unless the user has a large experience in this field. The aim of this paper is to reduce the number of parameters, with thermal comfort and energy consumption intact.

This paper will show the benefits with a feedback from the room temperature. First it will be shown that a room temperature feedback will lower the energy consumption and improve the thermal comfort compared to other strategies with night-time set back. Once the indoor temperature sensor is used, the measurement can be used to calculate a model of the system, together with outdoor temperature and supply water temperature by using system identification. The model is then used to reduce the number of input parameters.

Both measurements and simulations are used in this paper. This allows various aspects to be compared for different solutions under the same conditions.

INTRODUCTION

A heating system consists of a heat producing unit e.g. a boiler or district heating heat-exchanger, which supplies hot water to the radiators inside a room. Normally a heating controller measures and controls the supply water temperature to the radiators. The reference signal to the controller is calculated from the outdoor temperature by using a calibration curve, which describes the relation between the outdoor temperature and the set point for radiator supply water temperature. This control principle is called feed forward compensation. The curve is based on experience, and has to be described in the controller by some input parameters. There is often no feedback from the room temperature.

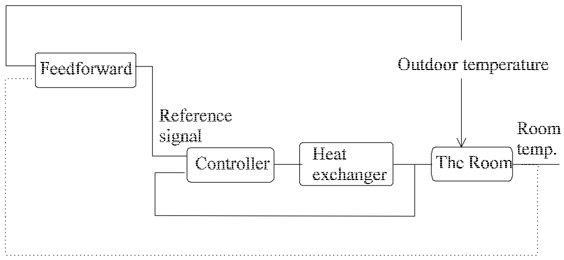

Figure 1 Block diagram for control of a heating system.

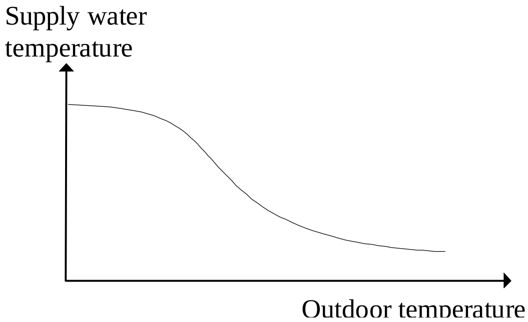

Figure 2 The relation between outdoor temperature and the set point for the radiator supply water temperature.

At night-time, the reference signal can be decreased a few degrees to save energy, and then be reset to the normal level in the morning. To shorten the time of heating in the morning the reference signal may be increased during the heating period. This is called boost.

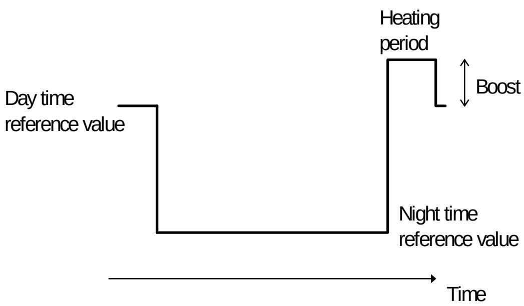

Figure 3 Night time set back of the reference value for supply water temperature.

The required time to reset the room temperature in the morning (the heating period) depends on the thermal inertia of the building and the size of the boost. Both values have to be given as input parameters to the controller.

Apart from ordinary control parameters, such as gain and integration time, a common controller for heating systems typically has the following parameters to be chosen by the user:

- Parameters for the feed forward curve.
- Thermal inertia for the building (or equivalent).
- Size of the night time setback.
- Boost size and duration

It is not obvious how to choose appropriate values for these parameters above unless the user has a large experience in this field.

The aim of this paper is to reduce and/or simplify the parameter selection. One way to do this is to use system identification methods to derive a mathematical model of the system, based on measurement of the indoor temperature, the outdoor temperature and the supply water temperature. The parameters for the feed forward curve and the thermal inertia of the building can then be calculated from the model.

Concerning the night-time setback, different strategies are compared in order to give guidelines for a suitable choice of strategy.

SIMULATION

It is difficult to practically evaluate different control strategies in real buildings. Load disturbances change from one day to another. The variations in climate make it very difficult to compare two different methods under the same conditions, while simulations do not have these pitfalls.

A powerful simulation tool should contain a library with components, which can be linked together into a complete model. The program used here is IDA [Sahlin 1996]. The primary application area of IDA is building and energy systems simulation, but the technology is general enough to be applicable in many other fields.

The IDA-models are described by differential-algebraic systems of equations, i.e., a free mixture of first order differential and algebraic equations. The model is composed of physical components like walls, windows, valves and controllers (see figure 4).

The simulation results are validated with measured values from a reference building. Two of the measured values, the outdoor temperature and the supply water temperature from the district heater producer, are saved in an input file to the simulation program.

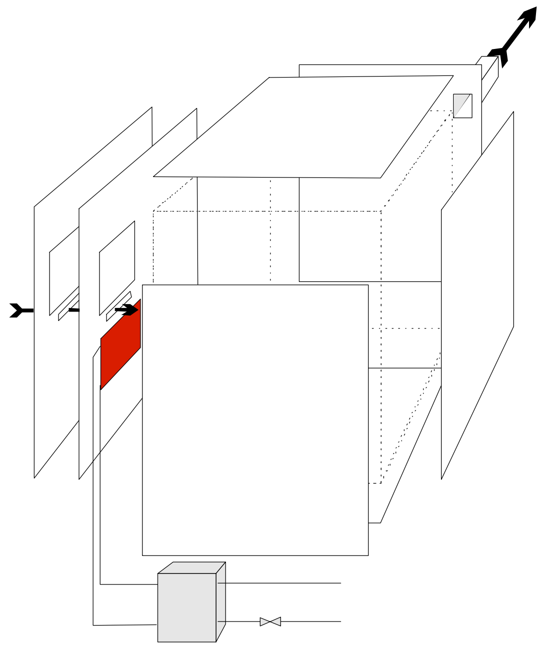

Figure 4 The components in the model. A naturally ventilated room with one external wall, a window, a radiator and a heat exchanger.

The most important value is the room temperature. As can be seen in figure 5 the simulation result is satisfying. The temperature differences are small and the dynamic behavior is matching.

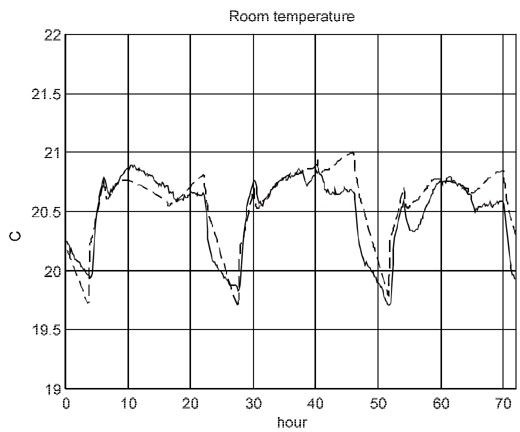

Figure 5. The room temperature during the period 8-10 March 1996. The dashed line is the simulated value and the solid is the measured.

ANALYSIS

The aim is to find an optimal solution for increasing the water supply temperature to achieve the desired room temperature in the morning after a night-time setback; optimal in the sense of energy-saving and thermal comfort. Initially, the supply temperature may be increased above the normal day temperature until the desired room temperature is reached. This strategy is known as ”morning boost”.

Four different solutions have been simulated and evaluated.

1. No night-time setback.
2. Night-time setback without boost.
3. Night-time setback with boost.
4. A separate controller for the room temperature.

Day-time is defined as 06.00-22.00. To justify a comparison between different solutions, the mean room temperature during day-time is kept the same for all cases. This done by adding an offset to the set point for radiator supply water temperature.

Four criteria for comparing the different solutions are used:

- Energy consumption.
- Room temperature in the morning (6.00).
- Standard deviation of the room temperature during day-time.
- Room temperature over-shoot, if any.

The figures below shows the simulation results from the four different strategies. The results are summarized in Table 1. A separate controller for the room temperature gives the lowest energy consumption and the best comfort, but the combination of night-time setback and morning boost is also reasonably good.

Table 1 Comparison of the four cases.

	Case 1	Case 2	Case 3	Case 4
Energy consumption [%]	100,0	95,7	95,4	95,2
Standard deviation [C]	0,047	0,202	0,096	0,059
Morning temperature [C]	20,75	20,32	20,69	20,63
Over-shoot [%]	0	0	0	12

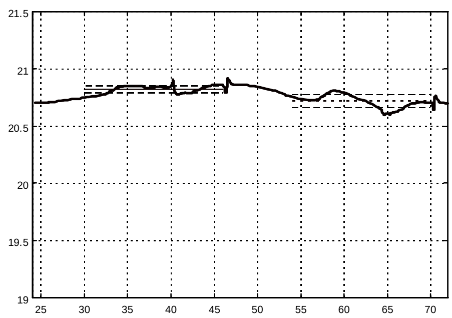

Figure 6 No night-time setback. The room temperature (solid line), day-time mean temperature (dotted line) and standard deviation (dashed line) over two days.

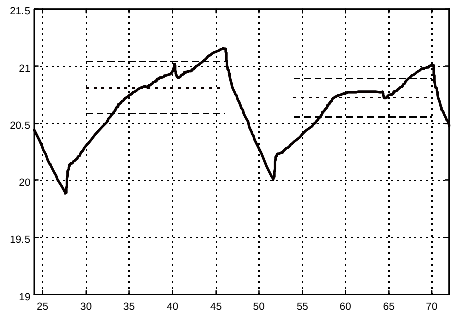

Figure 7 Night-time setback without boost. The room temperature (solid line), day-time mean temperature (dotted line) and standard deviation (dashed line) over two days.

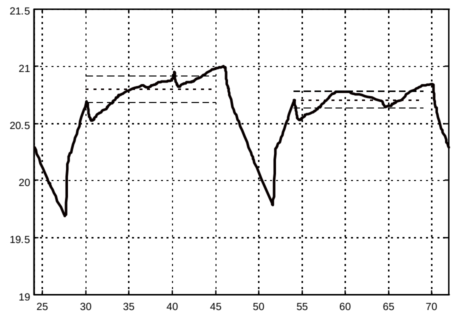

Figure 8 Night-time setback with boost. The room temperature (solid line), day-time mean temperature (dotted line) and standard deviation (dashed line) over two days.

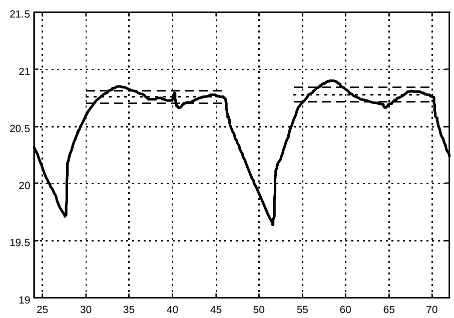

Figure 9. A separate controller for the room temperature. The room temperature (solid line), day-time mean temperature (dotted line) and standard deviation (dashed line) over two days.

Earlier studies [see e.g. Jensen 1983] have focused on the energy saving potential, and shows similar results. This paper also considers the aspects of indoor thermal comfort, start-up and commissioning. Besides that all aspects are compared under the same circumstances. An indoor temperature sensor opens up new possibilities to automatically select appropriate values for some of the parameters the user normally have to select. This will shorten the start-up and commissioning time. A controller can be tuned to give a smooth control signal to minimize the wear of the valve.

One relevant question to ask is: When do we have to start heating to reset the room temperature to the desired level in the morning? The heating period depends on the thermal inertia and the size of the boost. If one can find a mathematical model of the system, the effect of the thermal inertia will be included in the model. Such a model may be found by system identification.

We have found that a simple model structure describes the system satisfactorily:

$$y(t) = ay(t-1) + b_1 u_1(t-1) + b_2 u_2(t-k) + e(t) \quad (1)$$

where

y(t) is the room temperature.
$u_1(t)$ is the supply water temperature.
$u_2(t)$ is the outdoor temperature.

The sampling period is 10 minutes. The sampling period and the delay time from the outdoor temperature is tuned for this particular case.

The parameter *a* depends on the thermal inertia.

$$a = e^{-\tau h} \quad (2)$$

where

τ is the time constant for the building.
h is the sampling period.

The identification is performed from data during one week. The model output is then compared to the measured room temperature from the beginning of the following week. Small temperature differences appear, but the important dynamic behavior is matching.

The model can be used to predict future room temperatures for given outdoor and supply water temperatures. Assume that the boost size is given. Then we can calculate backwards the required time to reset the room temperature in the morning. Equation 1 describes the dynamic behavior of the heating system The effect of a raise of supply water temperature will give the following result on the indoor temperature *m* time steps ahead assuming the outdoor temperature remains constant during the time.

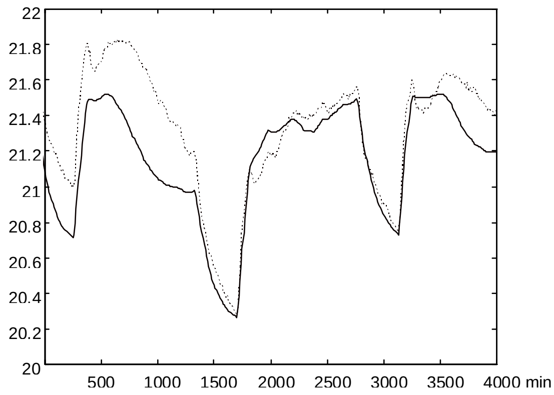

Figure 10. The measured room temperature (dotted line) and the model output (solid line) during the beginning of week two.

$$\Delta\hat{y}(t+m|t) = \sum_{j=0}^{m-2} b_1 a^j \Delta u_1 \quad (3)$$

where

$\Delta\hat{y}(t+m|t)$ is the predicted increase of room temperature.

Δu_1 is the increase of the supply water temperature.

The necessary raise of the indoor temperature is measurable and the boost was given. From equation 3 the required time *m* can be calculated as follows.

$$\Delta\hat{y}(t+m|t) = b_1 \Delta u_1 \frac{1-a^{m-1}}{1-a} \quad (4)$$

$$m = 1 + \frac{\ln\left[1 - \Delta\hat{y}(t+m|t)\left(\frac{1-a}{b_1 \Delta u_1}\right)\right]}{\ln(a)} \quad (5)$$

The required time has been calculated for two different cases: boost size of 6ºC and 3ºC, respectively. The first case is the same as the measured case in the test apartment. The method suggests 2.4 hours heating period which corresponds well with the measured case, as can be seen in both figure 5 and figure 8. This is elucidated in figure 11.

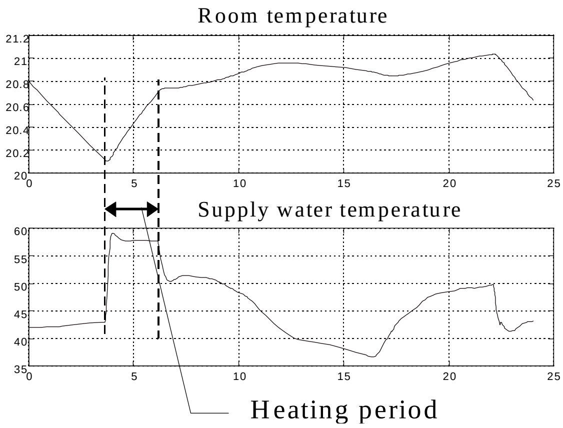

Figure 11 The room temperature and the supply water temperature. The heating period is 2.4 hours and the boost size is 6 ºC.

In the second case the suggestion is four hours. It has been simulated and is presented in figure 12. The result is satisfying.

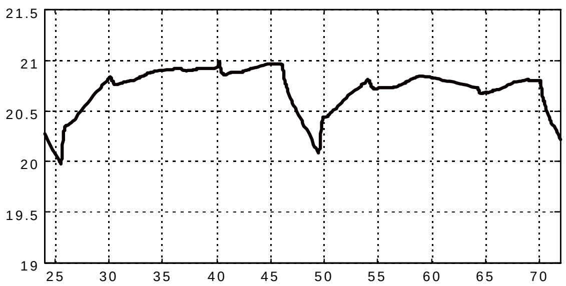

Figure 12 The simulated room temperature for the case with 3ºC boost size and four hour heating period.

Different solutions to decide when the heating period should start already exist. The benefits with this method is that the mathematical model can be used for additional tasks. One such task is to select the ordinary control parameters, e.g. gain and integration time, by using the step response method. [see e.g. Åström Wittenmark 1997]. The model can also be used in an adaptive feed forward compensation.

The feed forward compensation curve has to be given by the user, normally based on experience. Measured room and outdoor temperature from the reference building is shown in figure 13. It can be seen that the system is overcompensated, because in the afternoons the indoor temperature is decreasing despite the fact that the outdoor temperature is increasing.

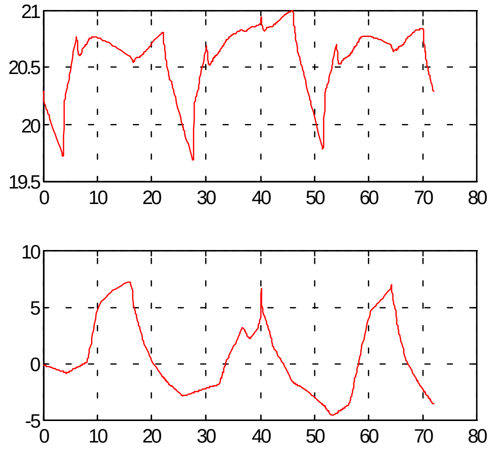

Figure 13 The room temperature (upper curve) and the outdoor temperature (lower curve) without model based feed forward compensation.

The parameters from the model are used to optimize the feed forward compensation in order to eliminate the effect from the outdoor temperature. In this paper a very simple method has been used. Other algorithms for adaptive feed forward are going to be evaluated later on. The constant b_2 in equation 1 states the effect from the outdoor temperature. If the compensation is perfect b_2 should be zero. The feed forward compensation is adjusted to minimize the b_2 coefficient.

The room temperature has been simulated with the new compensation curve, and is presented in the figure below. The outdoor temperature has no longer any effect on the room temperature. It increases exponentially towards an equilibrium temperature level, which is the temperature the room would have had if no night-time setback was used.

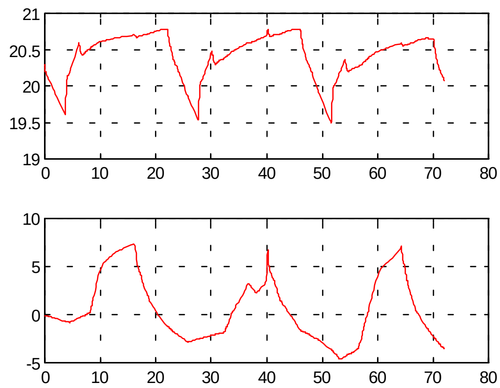

Figure 14 The room temperature (upper) and the outdoor temperature (lower) with model based feed forward compensation.

EXPERIMENT

The simulation results are compared to measured values from a reference building. The main purposes for the measurements are:

- Validation of the simulation model.
- Input data to the simulation.
- Input data for system identification

The reference building is located in the center of Gävle, Sweden, and contains 24 apartments.

One of the apartments is our reference. This apartment is on the second floor, and has one external wall with a window facing the north. The apartment is naturally ventilated. Below the window and above the radiator is an adjustable opening for fresh air. The building heating system is district heating.

We have chosen to use three different rooms for measuring the room temperature. The reason is to minimize the effects of disturbances. While the apartments are in use, the number of possible disturbances are quite a few. Two of the easiest measurable disturbances, solar radiation and outdoor temperature, are logged by the computer.

16 measurement signals are measured and logged every 30 seconds.

- The room temperatures in three different rooms with different location, two facing the north and one facing the south.
- The outdoor temperature
- The solar radiation
- The supply water temperature from the district heating producer
- The return water temperature to the district heating producer
- The supply water temperature to the heaters
- The return water temperature from the heaters
- The district heating water flow rate
- The water flow rate to the heater
- The control signal from the controller
- The energy consumption (district heating)
- The control signal from the domestic hot water controller
- The domestic hot water temperature

CONCLUSIONS

Simulations show that a controller for a heating system with feedback from the room temperature improves the indoor thermal climate, and lowers the energy cost. The indoor temperature sensor can also be used to reduce the number of input parameters, to be chosen by the user.

The indoor temperature can be used to calculate a model of the system, together with outdoor temperature and supply water temperature. The model is then used to calculate parameters for the controller, the feed forward compensation and the length of the heating period.

The remaining parameters are selected by the user, such as different room temperature set points over the day and night and the boost size, which can be pre-set to a default value. This will give a better tuned controller, less wear of the valves, shorter commissioning time and lower total cost.

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