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Influence of time constants on low energy buildings’ heating control

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Abstract

This paper estimates the range of time constant values for buildings with different insulation, thermal mass, and heat emitters for efficient temperature control by PI controllers, and comparing heat emission efficiency of the systems. Detailed models of the room, the heat emitter and the control system were used for dynamic simulations. For one case, the results were compared with measurements in a test building. Large variance in time constant values was found depending on the heat emitter, building parameters and the method used for the calculation. Time constant values were in the range of 1.9 to 94 hours. PI control with calculated parameters resulted in up to 8% heating energy difference between the low temperature water radiator and underfloor heating. The measurements showed lower time constant values than the simulations.

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Keywords: Low-energy building; heat emission efficiency; time constant; PI control parameters; low temperature heating; building automation

1. Introduction

The shift towards nearly zero energy buildings has resulted in the situation where heating systems operate most of time at very low power and need to be highly responsive to internal and solar heat gains. Moreover, often the systems are oversized in order to manage with night and weekend temperature setbacks [1]. This situation raises the question of heat emitter efficiencies under such conditions. Maivel et al. [2] have discussed the distribution losses and emission efficiency of low temperature radiators and underfloor heating under similar conditions in where they conclude that in

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spite of the operative temperature differences, the emitter efficiencies do not differ while controlled by proportional integral (PI) controller. However, these buildings, especially when including slow-responding emitters, e.g. underfloor heating (UFH), prove to be the most challenging to control by non-predictive methods. In this study, time constants for selected building and heating systems combinations are determined to enable further calculations of control parameter values, intermittent heating analyses, and emission efficiency analyses for heating systems.

2. Approach

2.1. Simulated building

Parametric analyses was carried out for a generic room model shown in Figure 1. The room was simulated for both light and heavy construction and the insulation was adjusted for modern (low-energy) and old (poorly insulated) buildings. The input parameters for the different insulation levels are defined in Table 1. Hydraulic underfloor heating (with supply/return temperatures 35/28°C) and low temperature water radiators (50/40) were compared. The UFH extends over the whole room and is located 58 mm under the floor surface; the parameters used for the radiators are shown in Table 2. Both emitters have been dimensioned for 115% of the heat losses in the default case. Over-dimensioning was designed to the extent of 80% for the light and 260% for the heavy modern building added to heat losses, emulating a design for weekend setback according to standard EN 12831-1 [1].

2.2. Calculations

For each of the defined building and heat emitter combination, a temperature step change simulation was carried out to maximal power from 30% heating power in the dimensioned and 10% heating power in the over-dimensioned case. Time constants of the building envelope were first calculated at 63.2% temperature rise of the total step bandwidth corresponding to the most widely applied time constant model definitions applicable for the heating up or cooling down as well as gain utilization factor predictions. These time constants of the simulated room were compared with standard ISO 13790 [3] values. Alternatively, for control purposes Ziegler-Nichols (Z-N) open loop step response method [4] was carried out and the whole system’s time constant was estimated. In this method, for the point where the rate of change is fastest, a tangent line is drawn and the time constant is read at the intersection of the tangent line and the final stable temperature line. The Z-N method was further followed by using the formulae defined in literature to calculate the PI parameter values from the time constants [4]. Control accuracy simulations were carried out from September to May using climate data for Munich, Germany [5] and the internal gains were defined as in [6]. Additionally to the compared emitters, cases with ideal heater were simulated for benchmark. For all simulations, a dynamic whole building model including heat emitter models with mass and climate processor were used in IDA-ICE energy simulation software [7].

Table 1. Input parameters of different building insulation levels

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Modern, low energy</th>
<th>Old, poorly insulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal envelope H, W/K</td>
<td>5.8</td>
<td>15.4</td>
</tr>
<tr>
<td>Window U-value, W/(m²·K)</td>
<td>0.75</td>
<td>1.40</td>
</tr>
<tr>
<td>Frame ratio, %</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Glazing solar heat gain coefficient, -</td>
<td>0.46</td>
<td>0.54</td>
</tr>
<tr>
<td>Infiltration, l/s</td>
<td>1.3</td>
<td>Included in air flow rate</td>
</tr>
<tr>
<td>Ventilation heat recovery temperature efficiency, %</td>
<td>80</td>
<td>0</td>
</tr>
<tr>
<td>Air flow rate, l/s</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Supply air temperature, °C</td>
<td>18 °C</td>
<td>Outdoor air</td>
</tr>
<tr>
<td>Heat losses at -22 °C, W; W/m²</td>
<td>380; 28.5</td>
<td>1440; 108.2</td>
</tr>
</tbody>
</table>
Table 2. Water radiator parameters in simulations

<table>
<thead>
<tr>
<th>Insulation level</th>
<th>Construction</th>
<th>Dimensioning</th>
<th>Max.power (W)</th>
<th>Radiator type</th>
<th>Height (m)</th>
<th>Width (m)</th>
<th>Exponent (-)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modern</td>
<td>Heavy/Light</td>
<td>+15% (dim)</td>
<td>437</td>
<td>11</td>
<td>0.4</td>
<td>1.6</td>
<td>1.3025</td>
<td>14.6</td>
</tr>
<tr>
<td>Old</td>
<td>Heavy/Light</td>
<td>+15% (dim)</td>
<td>1656</td>
<td>22</td>
<td>0.6</td>
<td>2.6</td>
<td>1.3358</td>
<td>86.8</td>
</tr>
<tr>
<td>Modern</td>
<td>Light</td>
<td>+80% (overdim)</td>
<td>684</td>
<td>11</td>
<td>0.6</td>
<td>1.8</td>
<td>1.3115</td>
<td>27.9</td>
</tr>
<tr>
<td>Modern</td>
<td>Heavy</td>
<td>+260% (overdim)</td>
<td>1367</td>
<td>22</td>
<td>0.4</td>
<td>3</td>
<td>1.3182</td>
<td>66.1</td>
</tr>
</tbody>
</table>

2.3. Measurements

For an initial comparison of the time constant values, a test case was measured in test rooms of the nearly zero-energy building (nZEB) technological test facility of Tallinn University of Technology. This nZEB test building is a light construction low energy building with small rooms, which are therefore similar to the modern building with light construction used in the simulation model. The building has been thoroughly described in [8]. During the tests, the floor heating was controlled by an on-off controller. The room temperature was first stabilized at 18 °C and then the setpoints were raised to 21°C. The time constant values were calculated from the steepest slope and from the 63.2% of the temperature rise.

3. Results and discussion

3.1. Time constants from the simulations

The simulated step change responses for all heating systems and modern building insulation cases are shown in Figure 2. The tangent lines for the times of steepest slope are depicted with dashed line and the region over which the slope was averaged is marked with vertical black lines. It can be seen that for radiator and ideal heater cases the air temperature starts to increase almost instantly after the power step occurring at time 0, whereas it is 1 to 5 hours later in the UFH cases.

All the time constant values calculated via different methods are depicted in Figure 3. The time constants calculated from the steepest rise are very short for all radiator cases and show significantly lower values for floor heating in heavy construction cases. The dissimilarity in the water radiator case illustrates the difference behind the definitions of the time constants. Namely, the ones calculated from the steepest rise characterize the dynamics of the heat emitter in the system whereas the 63.2% time constants characterize only the building envelope. The similarity of the time constants for UFH occurs because this system is only indirectly connected to the room air and has to heat up the structure first.

![Figure 2](image)

Figure 2. Temperature response curves to step change of the power signal in modern light (left) and modern heavy (right) normally dimensioned cases (dim, see Table 2). Displayed on relative temperature axis compared to the temperature at the time of power step.
For the calculation of the time constant values following the standard ISO 13790, different approaches could be taken. The values depicted in Figure 3 were calculated using tabular heat capacity values for light and heavy buildings. The resulting time constants for heavy modern buildings are 20 to 50 hours longer than in the simulated cases. However, it is not clear that the chosen tabular internal heat capacity values correspond exactly to the used building. What is more, the standard also allows using the approach of calculating the capacities from the used building structure with 0.1 meters of active thickness from the inside surface. This approach resulted in unrealistically high heat capacities and, therefore, correct values of active thicknesses should be determined for more accurate results.

The temperature performance results for the heating period simulation with PI control are shown in Figure 4. It can be seen that all the systems kept the setpoint temperature during the cold months; however, there were fluctuations up to 0.3 K for the UFH case. The temperature duration graphs show that the UFH did not manage to achieve exactly 21°C all of the time but stayed below it. However, the offset was mostly less than 0.1 K. For autumn and spring period, as shown in the example of April, temperatures increased over the setpoint for all heat emitter cases and occasionally no heating was needed. The overheating in the heavy building was significantly lower than for the light building. The fluctuations for floor heating had higher amplitudes also for the April case. This occurred due to the PI control characteristics not being able to predict the solar and internal gains, while the long time constant between 20 and 80 hours for the floor heating system does not enable fast changes in the system.

The resulting higher temperatures seen also in the temperature duration curves result in higher heating energy use. The resulting heating energy uses are depicted in Figure 5. It shows that the overheating occurring by UFH, requires about 8% more heating energy in light and 6% in heavy construction buildings compared to the ideal or the water radiator cases that lie within 1% range from each other in the modern buildings. Therefore, UFH is less efficient than the low-temperature water radiator in the compared cases. Measuring differences of the operative temperatures for similar systems, Maivel et al [2] concluded the opposite for the massive building where UFH was slightly more effective. The reasons for this difference has to be found in further research. The UFH is not compared in old building cases as the floor surface temperature and therefore also the UFH heating power are limited and the power needed for the old building cannot be installed. However, in the old building the heating energy use of the water radiator is 3% higher than in ideal case, caused by back-wall losses.

The differences between modern and old buildings are also showing in the calculated seasonal utilization factors when time constant values calculated from 63.2% temperature rise of water radiator or UFH cases is used. The maximum difference of 0.15 occurs when light well-dimensioned (dim) cases and water radiator utilization factors are compared. This is depicted in Figure 6, which also shows that the same factors calculated from ISO 13790 do not show any difference for modern and old buildings. A clear difference between light and heavy construction cases can be noted for all cases and used time constants, utilization factor ranging from 0.08 to 0.14. There is no clear rule when the ISO 13790 values over- or underestimate the utilization factors compared to the other used time constants, which shows the limitation of the method.
3.2. Time constants from measurements

The time constants calculated from the step change that was carried out in the test building, resulted in time constant values less than 10 hours (see Figure 7, right graph), whereas the similar simulation case showed time constant values 20 to 30 hours. This significant difference has to be investigated with the test building model as the simulated room was not identical with the test building. However, the difference between the various time constant calculation methods is less than one hour for the measured case and therefore, the reasons for the large difference in the simulated results have to be studied further.
4. Conclusions

This paper compares underfloor heating and low temperature radiator heating in different building insulation levels and constructions for the time constant values. Simulations as well as measurements have been used and time constants following step response method and standard methods were calculated. From the time constants, PI control parameters have been calculated and the control performance was estimated.

The time constant values show significant difference with respect to the concrete application. More importantly, the different methods in standard ISO 13790 result in significantly different time constants and the method should be therefore revised. The time constants for control are below 3 hours for radiator systems, which is significantly lower than for all other systems and methods. The different methods result in time constant values from less than 2 hours to as long as 80 hours for the water radiator, whereas less variance can be seen for UFH. For UFH the time constant values vary between 20 and 70 hours for different buildings. The seasonal utilization factor differs both between light and heavy construction and modern and old building cases, ranging from 0.74 to 0.97. The heating demand varies for different heat emitters within the same building insulation level up to 8% between the cases.

The time constant values calculated for similar cases in simulations and measurements differ by more than 10 hours. Further research has to be conducted to clarify the reasons. At the calculated PI control parameter values, UFH is less efficient than the radiator heating showing more fluctuating and higher temperatures than radiator heating. This indicates that model-predictive control could be beneficial to reducing the energy use of buildings with UFH.

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