PERFORMANCE ASSESSMENT OF HEAT DISTRIBUTION SYSTEMS FOR SENSIBLE HEAT STORAGE IN BUILDING THERMAL MASS

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ABSTRACT

With the growing share of renewable non-dispatchable energy generation the challenge of matching electricity production and consumption arises. To facilitate balancing excess renewable electricity generation (i.e. at times of strong wind) the potential for thermal energy storage in buildings is analyzed within our project. As of today, pricing schemes for electricity in Germany and most other countries are either not time dependent at all or a lower price for electricity is only provided at night. Considering the rising share of renewable electricity generation, it is expected that dynamic electricity prices, driven by the actual availability and demand, will be introduced in the future creating demand for more storage capacities.

The focus of this analysis is the evaluation of energy storage in buildings’ thermal mass, comparing conventional radiator heating with concrete core activation (CCA) as heat distribution system. Therefore, within an accurately monitored room at our research center a field study was performed and the results were compared to simulation outcomes of a thermal model for the same room. Since the behavior of the simulation model proves to be close to the thermal behavior of the real room, the model is then used to simulate a scenario for activation of the building’s thermal mass according to a signal describing the availability of renewables.

For both systems a three-hour overheating phase allowed to postpone further heating demand in winter by more than eight hours. The radiator based system lead to a room temperature increase of 3.1 K compared to only 0.2 K for the CCA. Thus, due to the potential thermal discomfort the radiator based system would require either the limitation of permitted indoor temperature or a more complex control with occupancy monitoring / prediction. Furthermore, it is shown for the CCA system that integration of an exemplary signal indicating high availability of renewable energies (RE) would have doubled the consumption of the RE during our field test time without compromising thermal comfort.

Keywords: demand side management, dynamic simulation, thermal storage, heating systems

INTRODUCTION

With the growing share of renewable non-dispatchable energy generation the challenge of matching electricity production and consumption arises. Thereby, residential and commercial buildings, accounting for up to 30% of Germany’s end energy consumption, could potentially provide flexibility to balance fluctuating electricity supply. Therefore, within the Dual Demand Side Management (2DSM) approach a concept is developed to manage the total energy demand (i.e. electrical and thermal) on city district level in a holistic way.

To facilitate balancing excess renewable electricity generation (i.e. at times of strong wind or high photovoltaic (PV) generation), the potential for thermal energy storage in buildings is analyzed within 2DSM. Thus, intending to use renewably generated electricity for heating purposes (i.e. through heat pumps (HP)) whenever it is abundantly available. Instead of prevalent hot water tank storage technologies, this analysis focuses on the inherent thermal storage capacity of a building attributable to thermal capacity of the used construction materials.
As of today, pricing schemes for electricity in Germany and most other countries are either not time dependent at all or a lower price for electricity is only provided at night [1], when lower room temperatures are preferred by residents anyway [2]. Fossil fuel powered heating systems have the same cost of operation at any time, therefore the effects of time-dependent room heating were not subject to close analysis in the past. Nevertheless, the lower electricity prices at night were already used in the past to pre-cool non-residential buildings, thus lowering the electrical load throughout the day [3, 4]. Considering the rising share of renewable electricity generation, it is expected that dynamic electricity prices, driven by the actual availability and demand, will be introduced in the future creating demand for more storage capacities.

However, the commonly used radiator-based heat distribution systems seem not to be the optimal heat delivery method for thermal storage purposes. This can be accounted to the partially air based heat transfer between the radiator and the thermal mass as well as to infiltration and ventilation processes cooling the air down before it can reach the thermal mass. Hence, due to the direct heat transfer within the thermal mass e.g. floor heating or concrete core activation seem to be favorable heat distribution systems.

The focus of this analysis is the evaluation of energy storage in buildings’ thermal mass, comparing a conventional radiator heating with concrete core activation (CCA) as heat distribution system. Therefore, within an accurately monitored room at our research center a field study was performed and the results were compared to simulation outcomes for a thermal model of the same room. Furthermore, the impact of thermal storage based demand side management (DSM) upon the integration of RE is shown through the integration of a binary “availability of renewables” signal into the simulation. In the next section, the method is presented in detail explaining the properties of the observed room, the implementation of the field study as well as the modeling and simulation approach. Afterwards, the obtained field test and simulation results are presented, compared and discussed.

**METHOD**

**Measurement setup**

The measurements are performed in an office within the E.ON Energy Research Center of RWTH Aachen University in Germany over one winter week in 2013. The building conforms to the requirements of the German energy directive 2009 [5]. The room is a corner office with a floor area of 41 m², two external walls (north-east and south-west orientation) and with a total window area of 24 m². In order to reduce the influence of solar radiation the external blinds were drawn throughout the experiment. The room was unoccupied.

The office room is conditioned using HP-supplied concrete core activation (CCA) within the ceiling. As the considered office is a reference room in the building, it is equipped with additional monitoring equipment measuring the supply and return temperatures as well as the volume flow in the CCA. Additionally, six tripods with air temperature sensors at four different heights were set up in the room according to the ISO 7726 standard [6]. The temperature of the ceiling surface was measured at three positions as well. An electrical radiator with a maximum power of 2.0 kW was used to represent a conventional radiator-based heating system for comparison with the CCA. The total electrical consumption of the test set-up, which consists of radiator and measuring equipment, was constantly measured. Weather data (outdoor air temperature, wind speed, global and diffuse solar radiation) is available from our own weather station situated on the roof of the nearby experimental hall.

At winter conditions (ambient temperature ~ 3 °C) the test room was repeatedly overheated for approx. 3 hours with the maximum power of either the CCA or the radiator system. Afterwards, the cool-down period was monitored until the indoor temperature reached 0.5 K below the start value, with particular focus on the resulting postponement in heating demand.
Simulation setup

Two simulation setups are created: one for comparing the simulation with measurement data and a second for simulating a scenario with intelligent activation of the thermal mass according to an “availability of renewables” signal.

The simulation model is built using the modelling language Modelica and the simulation environment Dymola by using components from our Modelica libraries [7]. Each wall, window and door is individually modelled and an additional thermal mass representing furniture is integrated. The air volume is modelled as one node. For the CCA a physical model is used with the pipes inserted between the concrete layers. The electrical radiator is an ideal heat source with both convective and radiative heat transfer.

In order to compare the simulation with the measurement data, the relevant measurements (weather data, supply temperature and volume flow of the concrete core activation) were used as an input for the simulation and the response of the simulated system was compared against the real system, focusing mainly on the measured free-flowing air temperature in the room.

Implication for the integration of renewable energies through DSM

Based on real energy generation data for the winter of 2012 collected from the European Energy Exchange AG (EEX) [8] an exemplary binary reference signal for availability of renewable energies (RE) is generated for a period equal to our field test (ten days). The electricity generation from renewables for the considered period was analyzed and for all generation values among the top 20% (approx. > 9.5 GW) the signal is set to one, while for all other values the signal remains zero. This results in a total of six intervals where the signal has a value of one with a cumulated duration of 35 h over ten days. Thus, the availability of renewables is indicated for approx. 15% of total field test time. This signal is then integrated into the performed simulation, where each time the signal turns to one, a three-hour overheating phase begins. The resulting DSM impact upon integration of RE is then analyzed.

RESULTS

Measurement

The gathered temperature values from all sensors are aggregated to an average temperature value for the room temperature. Also, based on three sensors, an average surface temperature of the ceiling is calculated to monitor the status of heat stored into the concrete.

Out of several heating and cooling sequences performed with the CCA as well as with the electric radiator, two measurement series were chosen due to their strong similarity of boundary conditions. For a clearer comparison, average values for the indoor and ambient temperatures are calculated over the time frame of overheating and cooling down to the initial room temperature. Table 1 shows main characteristics of the analyzed measurement series.

<table>
<thead>
<tr>
<th>Measurement series (compare with figure 1)</th>
<th>CCA</th>
<th>Radiator</th>
</tr>
</thead>
<tbody>
<tr>
<td>start temperatures room / ceiling</td>
<td>22.1 °C / 24.1 °C</td>
<td>22.2 °C / 23.9 °C</td>
</tr>
<tr>
<td>overheating time / energy input</td>
<td>3 h / 6.5 kWh</td>
<td>3⅔ h / 6.2 kWh</td>
</tr>
<tr>
<td>overheating temperatures indoor / ambient</td>
<td>22.2 °C / 2.5 °C</td>
<td>23.7 °C / 3.6 °C</td>
</tr>
<tr>
<td>→ resulting ΔT between indoor and ambient</td>
<td>19.7 K</td>
<td>20.1 K</td>
</tr>
<tr>
<td>maximum room temperatures reached</td>
<td>22.3 °C</td>
<td>25.3 °C</td>
</tr>
<tr>
<td>→ ΔT between start and maximum temperature</td>
<td>0.2 K</td>
<td>3.1 K</td>
</tr>
<tr>
<td>time until room temperatures return to start value</td>
<td>6 h</td>
<td>7.5 h</td>
</tr>
<tr>
<td>time until room reaches 0.5 K below start value</td>
<td>12 h</td>
<td>11.5 h</td>
</tr>
</tbody>
</table>

Table 1: Main characteristics of two series within the thermal storage field study
To allow for a comparison of these overheating processes the average heating demand of the observed room is calculated. Based on the actual heat delivery of the existing supply system a normalized heating demand is calculated for an indoor / ambient ΔT of 20 K. Thus, for the CCA approx. 910 W and for the electric radiator 650 W are needed. The difference between these values is explained by the fact that the CCA also delivers energy to the room above. Table 2 summarizes the heating demand for the two measurement series compared above.

<table>
<thead>
<tr>
<th></th>
<th>CCA</th>
<th>Radiator</th>
</tr>
</thead>
<tbody>
<tr>
<td>normalized heating demand</td>
<td>910 W</td>
<td>650 W</td>
</tr>
<tr>
<td>actual heating power during overheating</td>
<td>2190 W</td>
<td>1930 W</td>
</tr>
<tr>
<td>energy demand regular operation/with overheating</td>
<td>5.5 kWh / 6.5 kWh</td>
<td>4.9 kWh / 6.2 kWh</td>
</tr>
<tr>
<td>consumption overhead due to overheating</td>
<td>18 %</td>
<td>27 %</td>
</tr>
</tbody>
</table>

Table 2: Heating demand and energy balances for the analyzed supply systems

Simulation

The first simulation is used for comparison with the measurement data in order to assess the suitability of using the simulation to produce realistic results when testing other scenarios.

Figure 1 shows the comparison between the simulation and measurement results for the room air temperature during a five day phase of the field study. The increase in the air temperature on the first day is due to overheating with the CCA. The following four peaks are results of overheating with the radiator. At a first glance we recognize that the simulation follows a similar trend to the measurements and there is an overall similar temperature level.

![Figure 1: Comparison between simulation and measurement for the room air temperature](image)

The simulation of the field test phase was repeated integrating the signal on availability of renewables. In the regular operating mode the CCA delivered 13 % of the total heating energy demand when the signal was true. However, in the signal-controlled operation, the CCA was able to incorporate 27 % of the total heating demand into the renewable phases, thus approx. doubling the consumption of electricity available from renewable generation. In both cases the room temperature was kept between 21 °C and 22 °C.
DISCUSSION

The measurement shows that through energy storage in the thermal mass a considerable shift in energy demand is possible for both tested heating systems. However, the temperature profiles and the storage behavior vary distinctly between the CCA and the radiator-based heating.

While the overheating phase causes a room temperature increase of only 0.2 K for the CCA system, the radiator setup induces a 3.1 K temperature increase, thus heating the room to possibly inconvenient 25.3° C. However, this increase of the room temperature enables thermal storage in all wall surfaces and other thermal masses (e.g. furniture), while the CCA mainly uses the capacity of the activated wall. Therefore, the radiator system yields many thermal masses which are just loaded in their surface layers, resulting in an exponential temperature decrease within the cool-down phase. For the CCA, however, the single thermal mass which is loaded up to the deeper layers leads to an almost linear temperature decrease.

![Figure 2: Comparison of the measured overheating and cool-down phases](image)

It can be seen that both storage approaches allow more than eight hours without heating demand, if temperatures of 0.5 K below the start value are allowed. However, since the radiator system can interfere with thermal comfort expectations it would be preferable to schedule overheating phases at times without occupancy. Both systems have an increased energy demand due to overheating. However, the CCA system mainly loses energy to rooms adjacent to the activated ceiling while the radiator system loses heat to the ambient due to an increased temperature difference to the ambient air. This results in 18 % higher energy demand for the CCA and 27 % higher energy demand for the radiator setup due to the overheating (table 2).

The comparison between the measurements and the performed simulations shows a coefficient of determination of 0.94 with an absolute mean difference of 0.18 K and a standard deviation of 0.03 K. Since our goal is to test the similarity in the room reaction between simulation and measurements and not to exactly reproduce a set of measurements, we consider the model adequate.

The exemplary signal for availability of renewables was integrated into our field test scenario. During regular operation the energy consumption from renewables corresponded to their relative availability (15 % of total time). When using the signal, the CCA system was able to double the consumption of the available RE. Considering that this increase in integration of the RE is reached without violating strict comfort constraints, the theoretical potential is even larger.
CONCLUSION

For a state of the art thermally well-isolated office within a building according to the German energy directive 2009, the potential for demand side management through heat storage within the building’s thermal mass was successfully shown. The thermal storage activation was performed with a CCA as well as with a radiator-based supply system within a field test in winter time. For both systems a three hour overheating phase allowed to postpone further heating demand in winter by more than eight hours. The radiator system lead to a room temperature increase of 3.1 K compared to only 0.2 K for the CCA. Thus, due to potential thermal discomfort the radiator-based system would require either the limitation of indoor temperature or a more complex control with occupancy monitoring / prediction. Furthermore, the radiator system had indeed a significant increase in the heating demand due to higher losses to the ambient. The CCA system, however, has a very low impact upon indoor temperature. Therefore, heat loses to the ambient do not increase and even today’s electricity pricing schemes could potentially be exploited, since overheating phases at night-time are acceptable.

Thus, for thermal storage in the building’s wall mass CCA or other heat delivery systems within the building structures seem favorable, especially since they are also suitable for cooling and pre-cooling of the thermal mass. Nevertheless, radiator heating which is by far more common and will still be the typical heating system for many years to come is also suitable for thermal storage. Still, the usage of radiator systems must be thoroughly planned to take higher energy demand into account and ensure comfortable indoor climate. Furthermore, it is shown that integration of an exemplary signal indicating high availability of RE would have doubled the consumption of RE during our field test phase, without compromising thermal comfort.

This analysis indicates considerable potential for thermal energy storage in building mass as well as the suitability of our simulative approach to investigate this process. Building on these results, analysis will be extended for further building structures and DSM algorithms based on thermal storage in building mass will be developed for different supply systems.

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REFERENCES