Energy Modelling of Night Storage Heater and Its Usage for Sector Coupling

Marc Gennat, Marc.Gennat@hs-niederrhein.de
Raschad Damati, Raschad.Damati@hs-niederrhein.de
Arne Graßmann, Arne.Grassmann@hs-niederrhein.de
Hochschule Niederrhein – University of Applied Science

Overview

Night storage heaters are used in many areas in Germany and facilitated in the past cheaper electrical energy during the night. In recent years no new installations were made due to higher costs of electrical energy compared to natural gas and oil, which are commonly used for heating. Moreover, electric heating uses more primary energy compared to e.g. natural gas, due to the losses resulting from the energy conversion of electric power plants. Nevertheless, night storage heaters are still in use in many flats and houses, which were built between the 1960s to 1980s. However, night storage heaters can facilitate and contribute some share of reducing greenhouse gas emissions by using electric power for heating in times of surplus renewable energy in the grid instead of using natural gas. Additionally, night storage heaters have the potential to allow demand-side-management of electrical energy. Hereby, explicit knowledge of room temperature profiles over time is mandatory.

In this contribution, an approach of modeling temperature profiles and simulating the temperature over time is shown, in order to compute the optimal electrical power switch-on time. The used data were derived from a laboratory test room. Several differential equations, which are based on thermodynamical principles, are used for modeling, and parameter estimation is used to compute unknown parameters of the differential equations. Finally, the model computes the room temperature based only on electric power energy supply and the outside ambient temperature. After parameter estimation, the maximum deviation of the test room temperature to the measured temperature computed to 0.96 Kelvin, and the average deviation is calculated to 0.20 Kelvin.

Climate test environment and measurement setup

The measurement setup, hereinafter called the test room, corresponds to a model of a conventionally living room. Built in dry construction method, the test room is divided into two accessible rooms by a sand-lime brick wall as a model of a common outer wall. One of these rooms corresponds to a test area and the other one, to a climate area for simulating different environmental conditions. Temperatures are measured by ten resistance sensors, which are distributed in the test area. In addition, the surface temperature of the sand-lime brick wall, as well as the surface and core temperature and the electrical power consumption of the night storage heater, are measured.

Methodology

To compute the room temperature, a thermodynamical approach is applied using the Fouriers´s heat conduction law

$$\frac{\partial T}{\partial t} = a \cdot \Delta T, \tag{1}$$

where T is the temperature in Kelvin, t is the time in seconds and a is the thermal diffusivity in square meters per second. The system to be solved consists of several layers of solid and fluid materials. This can be solved e. g. by a finite difference approach [1]. A solution for large time scales is numerical very difficult and time consuming, a relaxation of the given problem would increase the effort by factors. Additionally, the material properties of all layers must be known exactly to compute a in (1), which is usually difficult, as manufacturers of night storage heaters do not provide these data. This leads to the result, that classical thermodynamic approaches cannot be applied easily to our optimization problem. Thus, our approach is based on heat transfer equations [4] with

$$m\ c\ \frac{dT}{dt} = U_1 A_1 \cdot \Delta T_1 - U_2 A_2 \cdot \Delta T_2 \Leftrightarrow \frac{dT}{dt} = p_1 \cdot \Delta T_1 - p_2 \cdot \Delta T_2, \tag{2}$$

where m is the mass, c the specific heat capacity, U_i and A_i are heat transfer coefficients and areas. In the right part of (2), parameters p_1 and p_2 summarize all unknown material properties. Derived from (2), the test room temperatures can be modeled as a linear 8th order ordinary different equation (ODE), using the test room structure given in Fig. 1.

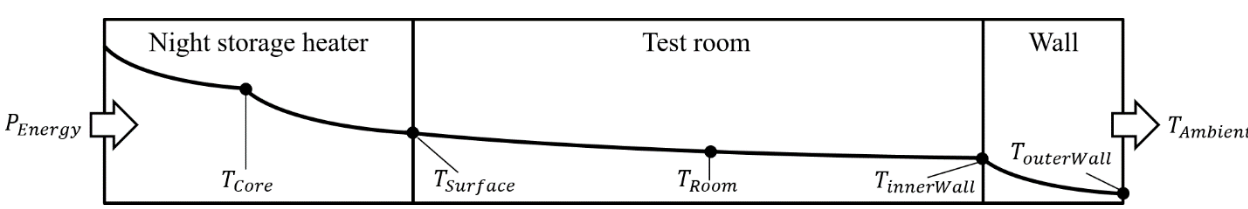

Fig. 1: Test room with the placement of temperature and heat transfer measuring points

With the states $x_1 = x_{Core}$, $x_3 = x_{Surface}$, $x_4 = x_{Room}$, $x_6 = x_{innerWall}$ and $x_8 = x_{outerWall}$, the heat transfer and its temperature coupling using (2) and Fig. 1, the ODE is derived by

$$\dot{x}_i = p_{2\mathrm{i}-1}\,(x_i - x_{\mathrm{i}-1}) - p_{2\mathrm{i}}(x_{i+1} - x_{\mathrm{i}}), i = 1, \cdots, 8;\; x_0 = P_{Enery}(\mathrm{t}) \text{ and } x_9 = T_{Ambient}(\mathrm{t}). \tag{3}$$

This ODE has two time variant parameters, namely energy supply $P_{Enery}(\mathrm{t})$ and outside temperature $T_{Ambient}(\mathrm{t})$, as an energy sink. Due to the time variance, the ODE system cannot be solved algebraically. A numerical approach is used for solving the ODE. A parameter estimation algorithm [2] computes a local optimal parameter set $p^* \in \mathbb{R}^{16}$ as

$$p^* = \underset{p}{\operatorname{argmin}} \sum_{i=1}^{5} \left(\sum_{k=1}^{k_{max}} \left(x_{Measure,i}(t_k) - x_{Model,i}(t_k) \right)^2 \right), \tag{4}$$

which represents the computation of the Gaussian L_2 norm summed up over all five measurement time series and over all temperature measuring points of time k_{max}. The optimal parameter set p^* is derived from a local optimization algorithm provided by Matlab's Optimization Toolbox [3].

Results

The computed results of a nine-day-simulation period are shown in Fig. 2, whereas the room temperatures maximum deviation is 0.96 Kelvin and the average deviation is 0.21 Kelvin. This represents an excellent result, considering the length of its underlying nine-day-simulation period.

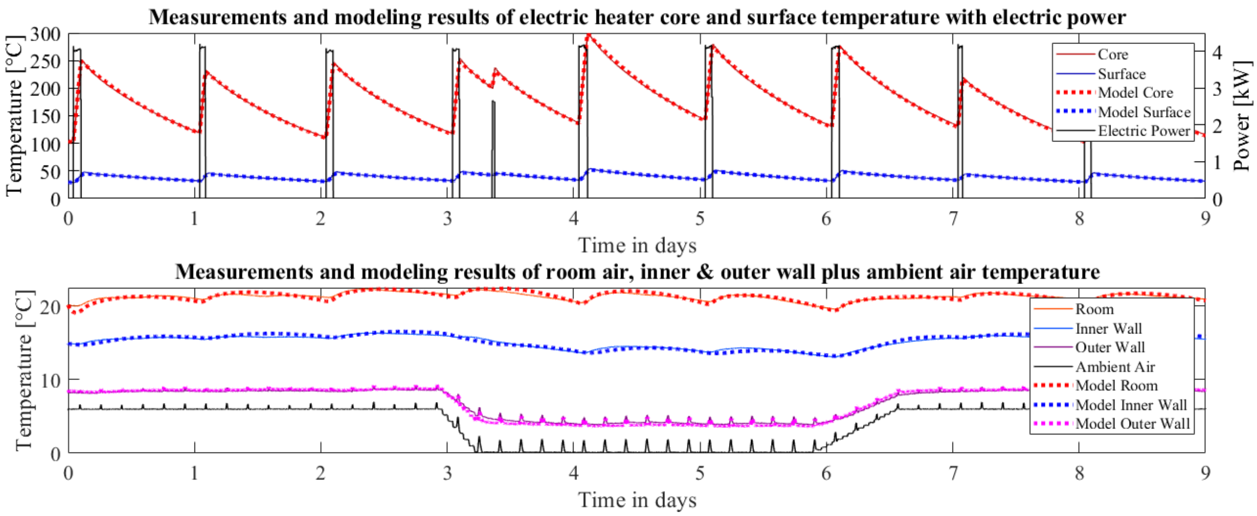

Fig. 2: Measurement and modelling results

Conclusions

In this contribution, a method is presented to simulate the temporal room temperature with ODEs. With parameter estimation based on real measurement data, it was shown, that the temporal room temperature can be approximated if both, the temporal electric power consumption and the outside ambient temperature, are known. This method enables the possibility to detect and define optimal charging times. It allows to operate night storage heaters more flexibly and even offers the opportunity to integrate them into the energy market. Following this, it is possible e. g. to charge the night storage heaters, if a surplus of renewable energy is available, or not to charge them if an overload in the power grid threatens. Finally, this method of temperature modeling can also be applied to other scheduled loading and unloading problems or energy storage challenges. Further research will apply the method in order to ensure the room temperature within a certain range by controlling the electrical power input.

References

[1] Graßmann, A, Peters; F., Experimental investigation of heat conduction in wet sand, Heat and Mass Transfer 35 (1999), 289-294, Springer

[2] Gennat, M. and Tibken, B. (2008). Computing guaranteed bounds for uncertain cooperative and monotone nonlinear systems. IFAC World Congress 2008, Seoul, Korea. IFAC Proceedings Volumes, 41(2), 4846-4851

[3] The MathWorks (2018). Matlab and optimization toolbox release 2018a. URL https://www.mathworks.com/products/matlab.html

[4] Embaye, M., Al-Dadah, R. K., & Mahmoud, S. (2016). Effect of flow pulsation on energy consumption of a radiator in a centrally heated building. International Journal of Low-Carbon Technologies, 11(1), 119-129.