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Dynamic test bench for the analysis of the operating behaviour of radiators under controllable boundary conditions

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Abstract

The development in home energy systems forces more and more the investigation of new control systems for single room heating control. These new control systems and the appropriate components need to be tested in a controllable surrounding where the operating behavior of the radiator can be analyzed. In this test application the dynamic responses of the room and wall temperature have to be emulated to influence the heat emission of the radiator. At the E.ON ERC this is realized with a hardware-in-the-loop test bench which consists of the hydraulic network of a small flat with four heated rooms. These four rooms are coupled with a dynamic simulation in Modelica, where the geometry and the wall structure of the tested rooms are specified. The dynamic response of these simulated rooms is important to define the dynamic boundary conditions for the test bench rooms.

To reduce the required space of the test rooms (cabins) we reduce the enclosing volume around the radiator to about 3.5 m³. The boundary conditions influencing the heat emission of a radiator are the surface temperature of the enclosing walls and the room's air temperature. These parameters are calculated in Modelica and emulated at the test bench.

In this paper the dynamic behavior of the four cabins with the simulated boundary conditions is shown by controlling the test room temperature with a classical thermostatic valve.

Keywords – single room heating control, home energy systems, radiator test bench, hardware-in-the-loop test bench

1. Introduction

The most common way in Germany to control the temperature in a room while heating is a thermostatic valve. This control component is self-sustaining but cannot be set automatically nor communicate with other devices in the home energy system. This means that intelligent actors are necessary for the development of home energy systems including the heating system. For the test and development of these control components and new strategies the operating behavior of radiators need to be analyzed under controllable and dynamic boundary conditions. This paper presents a hardware-in-the-loop (hil) test bench which represents the dynamic response of a hydraulic network of a small flat with four heated rooms under fully controllable surroundings.

2. Design of the test bench and simulation model

The dynamic test bench at the E.ON ERC for the analysis of heat sinks consists of four rooms each heated with a standard radiator. The hydraulic network is similar to a small flat. The space requirement of each room is minimized by using a new approach for the investigation of the heat output of radiators in a room: the enclosing volume around the radiator is downsized to about 3.5 m³ as seen in Figure 1. The parameters influencing the heat output of the radiator have to be maintained for this volume. Therefore two enclosing walls of this cabin can be tempered to emulate the radiation (influenced by the wall temperature). The convection (mainly affected by the room air temperature and the heat output of the radiator) is provided with a forced air inlet at the bottom of the cabin.

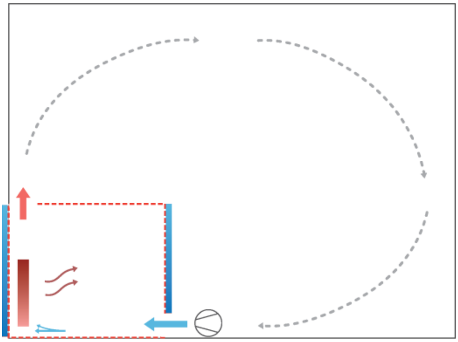

Figure 1: Reduced space requirements by downsizing the volume of the room whereas the heat transmission between radiator and room is maintained.

For the dynamic response of the room air temperature and the wall temperature the four rooms are coupled with a simulation model in Modelica, which calculates the dynamic boundary conditions. The simulation models are standard models published at the AixLib [3] by the E.ON ERC. Within the simulation model the following parameters can be changed:

- Ground plan / room geometry
- Insulation standard
- Weather model
- User profiles

For the simulation model of the flat used in this paper a floor space of 80 m² is used. The ground plan of the four rooms is shown in Figure 2. The insulation values are used with standard specification according to the German Heat Insulation Ordinance of 1984. Based on the norm DIN EN 12831 [1] the heat demand for each room with a set temperature of 20 °C can be specified. Taking into account the nominal heat output of the installed radiators, the oversizing of the simulated hydraulic network is shown in Table 1. This oversizing is used to demonstrate the control behavior of a standard thermostatic valve in this paper.

The ambient conditions can be simulated with typical diurnal variations for the outdoor temperature, the wind speed and the solar radiation. For the measurements in this paper, the outdoor temperature is constant at – 5 °C. The solar radiation and the wind speed are not taken into account.

Table 1: Design parameters of the heat demand for the implemented room structure and nominal heat output of the installed radiators.

Room	Floor space [m²]	Heat demand [W]	Radiator type	Nominal heat output [W]	Oversizing
1) Living room	30	1803	22	1649	- 10 %
2) Bedroom	20	1326	22	1649	+ 20 %
3) Kitchen	18	1238	22	1649	+ 25 %
4) Bathroom	12	838	11	893	+ 6 %

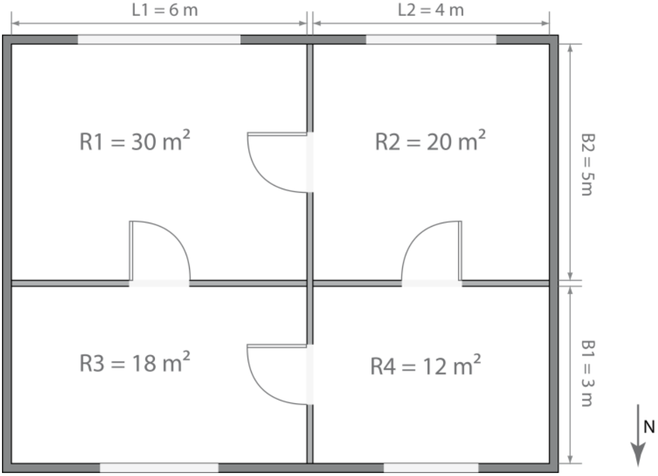

Figure 2: Ground plan of the simulated flat.

3. Concept of the thermal coupling between downsized rooms and the simulation model

For the downsizing of the room structure around the normal sized radiator it is important to convert the boundary conditions of a real sized room into the small sized structure, shown in Figure 3. The heat transport processes between a radiator and a real sized room are radiation, influenced by the wall temperature, and the convection, mainly affected by the air temperature and the heat output. The main parameters wall and air temperature have to be converted for the downsized volume and can be emulated at the cabins with tempered surfaces and a defined air flow. The basic concepts of the conversion terms are published in Kopmann et al., 2015 [2].

Figure 3: Setup of the test bench cabins: 1) radiator, 2) tempered walls, 3) supply air box, 4) slowed air inlet, 5) air outlet.

The data exchange for each room between simulation model and test cabin is shown in Figure 4. The measured volume flow and the inlet temperature of the heating medium at each radiator are the inlet parameters for the simulation model. The heat transfer inside the simulated room is calculated with these boundary conditions and it results in a variation of the calculated room and wall temperature. To complete the hil coupling these room parameters are converted into a surface and air inlet temperature using the following equations and those conditions are emulated at the test bench.

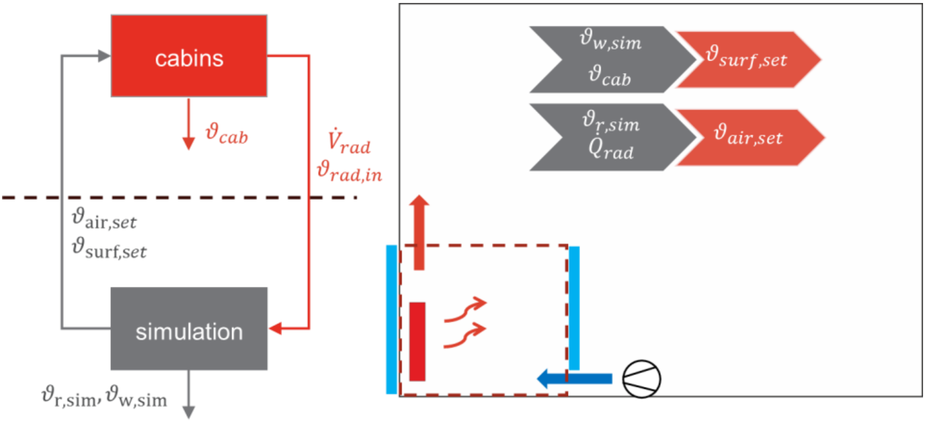

Figure 4: Data exchange for the thermal coupling between test bench and simulation.

The set temperature for the surface $\vartheta_{surf,set}$ is according to the simulated wall temperature $\vartheta_{w,sim}$ and the cabin air temperature ϑ_{cab} . The cabin temperature represents the surface temperatures of the non-tempered walls in the small sized cabin. This assumption was validated with experimental investigations.

$$\vartheta_{surf,set} = 0{,}756 - 0{,}744 \cdot \vartheta_{cab}[°C] + 1{,}748 \cdot \vartheta_{w,sim}[°C] \tag{1}$$

The set temperature for the air inlet $\vartheta_{air,set}$ depends on the simulated room air temperature ϑ_r and the heat output of the radiator $\dot{Q}_{rad}$:

$$\vartheta_{air,set} = \vartheta_r[°C] - 1{,}017 \cdot \dot{Q}_{rad}[kW] + 0{,}344 \tag{2}$$

4. Test setup

To demonstrate the dynamic behavior of the four coupled rooms heated with radiators the control mode of classical thermostatic valves (see Figure 5) is shown in this paper. A thermostatic valve is a self-regulating valve which controls the temperature of a room by adapting the flow of hot water to the heat demand of the room.

Figure 5: Thermostatic valve to control the room temperatur in the test rooms. Left: sensor inside the thermostat. Right: remote sensor.

The test bench is coupled with the simulation model of the small flat as described above. The cabin air temperature ϑ_{cab} is measured at the center of each cabin. The remote sensor of the thermostatic valve is placed at the same position, so that the actual temperature of the thermostatic valve is the same as the measured cabin temperature. The emulated surface temperatures are measured at the two tempered walls inside the cabins with surface temperature sensors. The emulated air inlet temperature is measured at the inlet of the cabin. The changes of the valve lift are measured with a way sensor which indicates steps of 0,001mm.

To demonstrate different operating conditions of a heat supply unit, the temperature set-point of the supply temperature $\vartheta_{rad,in}$ is varied in three steps, see Table 2. The set temperature of the thermostatic valve is 20 °C in all rooms.

Table 2: Profile of the inlet temperature of the radiator for the different operating conditions.

	Time [hour]	$\vartheta_{rad,in}$ [°C]
1)	1 – 5	75
2)	6 – 10	60
3)	11 - 15	45

5. Control of the dynamic boundary conditions

As the thermal coupling with a simulation model provides dynamic boundary conditions for the test rooms, the control of the surface and air inlet temperature have to adapt to that dynamic behavior to emulate the calculated boundary conditions.

Figure 6 shows the control mode of the air inlet temperature for a fluctuating set temperature. Excepting the first adaptation time of about 20 minutes, the measured air inlet temperature and the set temperature have no difference although the set point is varying with an amplitude of 0.8 K in about one hour.

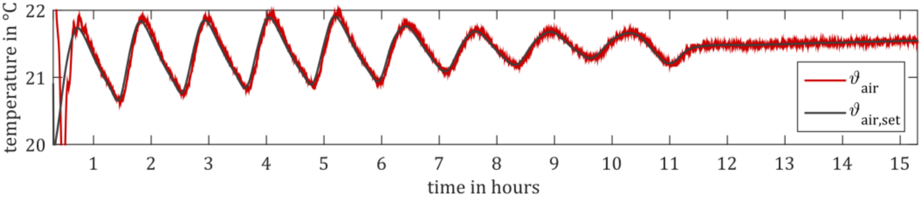

Figure 6: Dynamic control of the air inlet temperature at the test bench cabins.

The control mode of the surface temperature is shown in Figure 7. The fluctuation of the set temperature is less than 0.5 K, which means an amplitude of 0.2 K in one hour. The adaptation time for the surface temperature takes nearly one and a half hours. This is caused by the reaction time of the surface temperatures and by the heat output of the radiator which influences the surface temperatures inside the cabins. The temporal and absolute difference between the controlled and set temperature is negligible although the controlled surface temperature is oscillating faster than the set point.

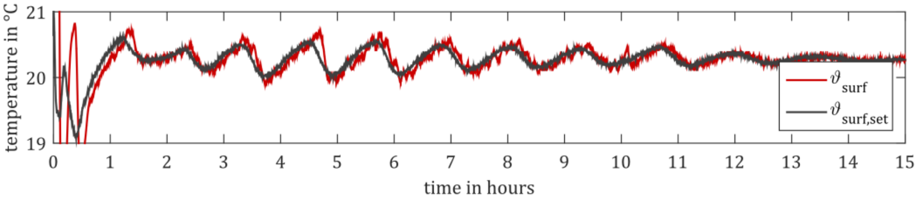

Figure 7: Dynamic control of the surface temperature at the test bench cabins.

6. Results of the thermal coupling

To demonstrate the time variant conditions of the radiators in the test bench controlled with classical thermostatic valves, the following parameters are shown in Figure 8: the simulated heat output of the radiators (the heat output between radiator and room/cabin cannot be measured), the radiator inlet temperature, the measured volume flow and the changes of the valve lift.

The heat demand of the largest room R1 (living room with 30 m²) is up to 1000 W. Because of the high heat demand the thermostatic valve is able to reach a steady state after two hours. The decrease of the supply temperature from 75 °C to 60 °C after five hours leads to a small change in the valve lift (only 0.02mm) and a threefold increase of the volume flow. The heat output remains at the same high level. The radiator inlet temperatures are constant during the measurement period in this cabin. With the inlet temperature of 45 °C the heat output decreases by half.

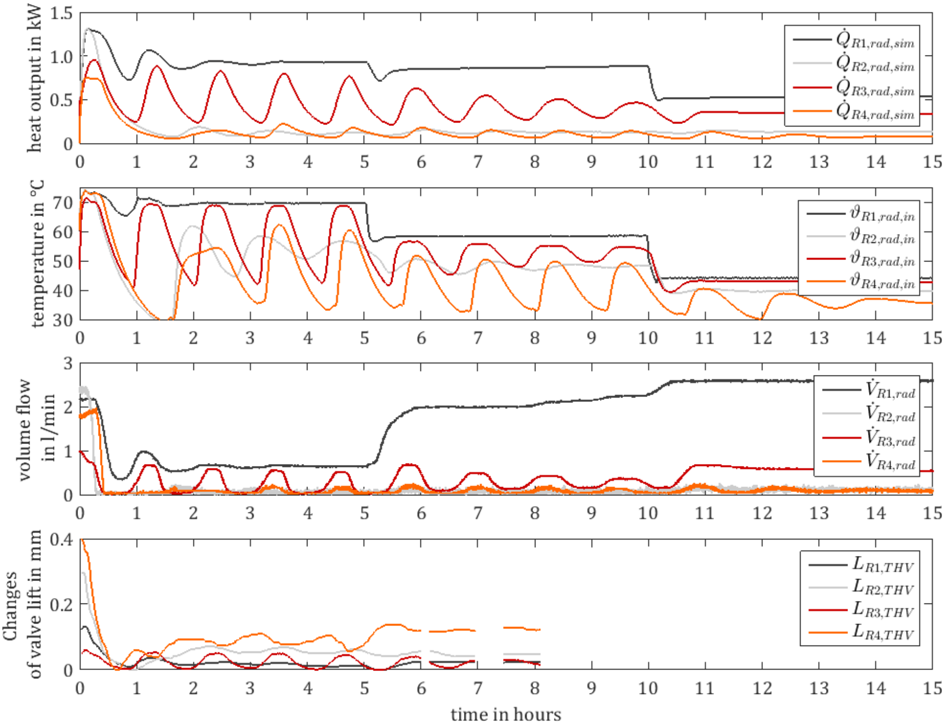

Figure 8: Dynamic behavior of the simulated heat output and the measured volume flow of the radiators and the valve lift.

The smaller rooms R2 (bedroom: 20 m²) and R4 (bathroom: 12 m²) have a very low heat demand (< 200 W) to provide the set temperature during the measurements. This is why the thermostatic valve is nearly closed during the measurement and the volume flow can hardly be detected (< 0.2 l/min). The radiator inlet temperature in rooms R2 and R4 is fluctuating with a medium temperature lower than in room R1. This is caused by the very low unsteady volume flow.

Due to its floor space, the third room R3 (kitchen: 18 m²) has a medium heat demand which leads into an oscillating control mode. The simulated heat output fluctuates with gradients of 500 W per hour.

The resulting air temperatures in the test bench cabins and the simulated room temperatures are shown in Figure 9 for all four rooms.

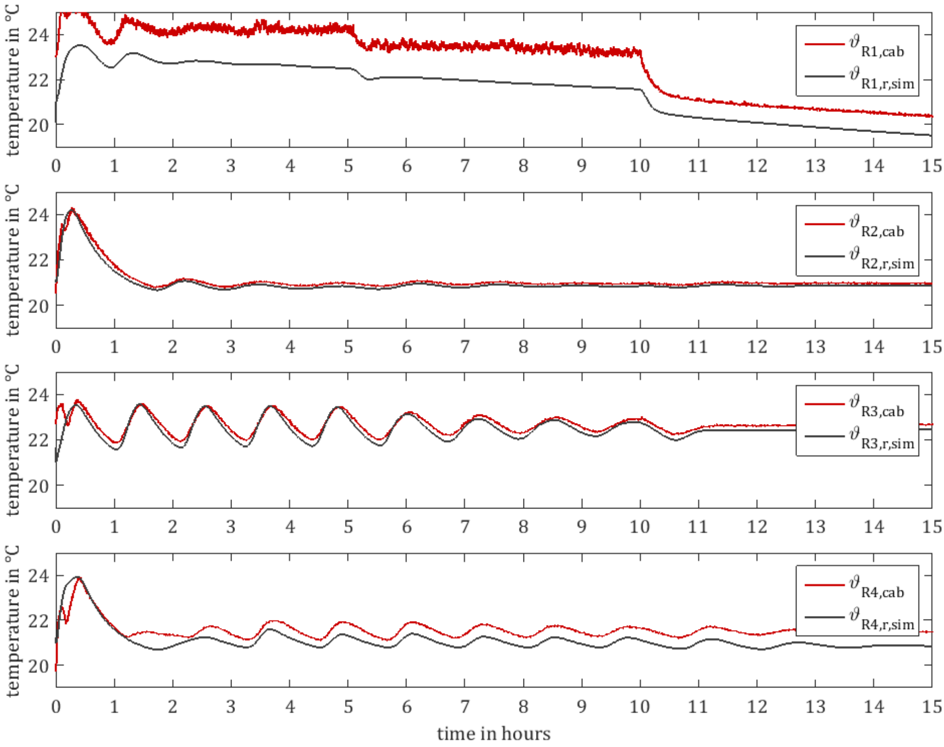

Figure 9: Dynamic response of the measured air temperature in the test cabins and the simulated room temperature while using a classical thermostatic valve as control component.

The high and stationary heat output in room R1 leads to a high and stable cabin and room temperature. Due to a gap between the simulated heat output and the measured heat output (calculation possible for steady state with the energy conservation law) the cabin temperature is about 1 K higher than the simulated room temperature. With the lower supply temperature of 45 °C the heat output in room R1 decreases from 1000 W to 500 W, and with it the gap between measured and simulated air temperature. For the control mode of the thermostatic valve a high deviation from the set-point of 4 K can be detected for high supply temperature and resultant high heat output. The deviation decreases with lower supply temperatures and resultant low heat output.

The control mode for the very low heat demand in room R2 is able to reach a steady state after two hours. The dynamic response of the simulated room at the beginning of the control period in the first hours can be seen in the cabin temperature as well. The deviation of the control mode in this case is about 1 K.

The strongly fluctuating heat output in room R3 leads to a room temperature oscillating by 2 K. Because of the calculated boundary conditions the dynamic behavior of this setting can also be seen in the test cabins. The amplitude of the fluctuation is decreasing with lower supply temperatures. In addition the control deviation in this case is between 2 and 3.5 K. This control mode can be seen as an example for a poor controlled system.

The results of the measured air temperature in room R4 are not taken into account. A mistake in the control mode for the inlet air temperature yields to wrong boundary conditions. The result is a gap between the simulated air temperature and the measured cabin temperature. For this reason the importance of providing correct boundary conditions is demonstrated.

7. Conclusions

The hydraulic test bench presented in this paper is able to represent the heat transfer between radiator and heated room. Therefore, the dynamic behavior of the heat transmission is emulated at the test cabins with the downsized volume using a coupled simulation model which calculates the real sized room conditions. With the well performing control of the boundary conditions the test cabins can follow the dynamic response of the simulated room.

The application of a classical control method for single room heating control shows the possibilities for further development and test studies of new control strategies and the appropriate components.

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