Test of New Control Strategies for Room Temperature Control Systems

Fully Controllable Surroundings for a Heating System with Radiators

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Abstract: About one third of Germany's energy demand is used for room heating thus offering a huge potential for energy savings. The development of intelligent home energy systems should optimize the energy consumption of buildings. In Germany the most common way to control the room temperature while heating is to use a thermostatic valve. This temperature-control system is self-sustaining but has no possibility to communicate to the heating system or other devices in the household. For the test and development of new control strategies and the appropriate components a Hardware-in-the-Loop test bench for hydraulic network applications is developed at the E.ON Energy Research Center. This test bench allows the test of a heating system of a flat in a controllable surrounding under dynamic boundary conditions. In this paper the new test bench concept will be described.

1 INTRODUCTION

The development of home energy systems forces more and more the investigation of new control systems for single room heating control. In Germany the most common way to control the temperature in a room while heating is to use a thermostatic valve. The user can define a set temperature and the thermostatic valve reduces or increases the volume flow in the radiator to adapt the heat output of the radiator. This temperature control system is self-sustaining but has no possibility to communicate to the heating system or other devices in the household. New electrical valves are designed to control the room temperature and to communicate with the home energy system. The use of these electrical actors is still in a developing state, and especially new investigations have to be tested in controllable surroundings.

This paper will show a test bench concept to develop and test new control strategies and components for single room heating. To combine the advantages of static experiments with fixed boundary conditions and the dynamic uncontrollable field studies we use a hardware-in-the-loop (HiL) system. The HiL testing is applied in many laboratories for the test and development of building automation control systems and heat supply units, as described in Barth, 2010 and Bianchi, 2005. The special feature of the described test bench is the reproduction of the room environment under dynamic and controllable surroundings.

2 CONCEPT OF THE TEST BENCH

With the test bench described in this paper it is possible to test room temperature control systems in dynamic and controllable surroundings realized with a HiL coupling, see Figure 1.

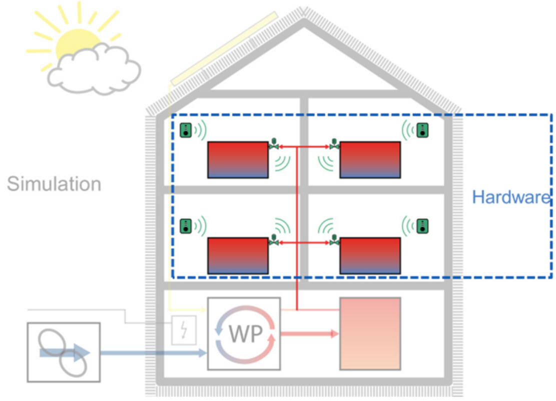

Figure 1: Scheme of the HiL test bench for single room heating control systems and components.

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The real hardware (radiator, thermostatic valve, hydraulic net and if applicable heat supply unit) will be examined under dynamic boundary conditions, which will be defined using a coupled simulation in Modelica.

The test bench consists of four rooms, which are heated with radiators. The hydraulic network is similar as in a small flat. These four rooms are coupled with a dynamic simulation in Modelica, so that each room can react dynamically as it exchanges the boundary conditions with the simulation. The type of building and the weather can be changed in the simulation setup. To test the direct communication with the heat supply system, the system has the possibility to provide the heat by an installed condensing boiler or water/water heat pump. But even other heat supply systems can be simulated and the supply conditions can be emulated at the test bench.

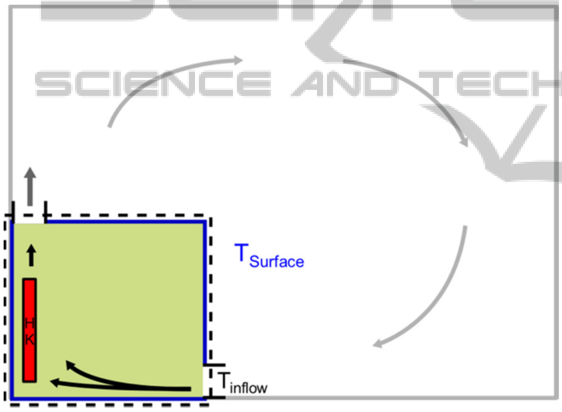

Figure 2: Reduced space requirements by downsizing the volume of each room.

To reduce the required space for the test bench we downsize the enclosing volume of the radiator to about 3 to 4 m³ as shown in Figure 2. More information about this concept can be found in Kopmann et al., 2011. The boundary conditions influencing the heat emission of a radiator are the surface temperatures of the enclosing walls and the room's air temperature. These boundary conditions are calculated in Modelica and relayed onto the test bench. We use the measured heat emission of the radiator and the pressure drop at the thermostatic valve as boundary condition for the simulation. The HiL concept is shown in Figure 3.

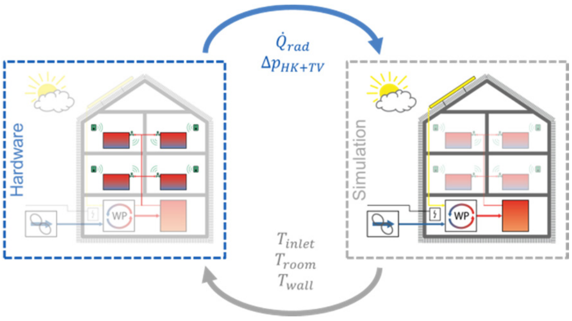

Figure 3: Data transfer using the HiL coupling.

2.1 Description of the Supply Structure

The four coupled rooms are installed in a rack construction which allows changing the components in each cabin individually, see Figure 4. Radiators of type 22 with a nominal heat output of 1570 W at 70/60/20 are installed in three rooms and the fourth room contains a radiator of type 11 with only 890 W nominal heat output. Each room is arranged with a standard valve body and the control component (thermostatic valve or electrical actuator) can be changed easily.

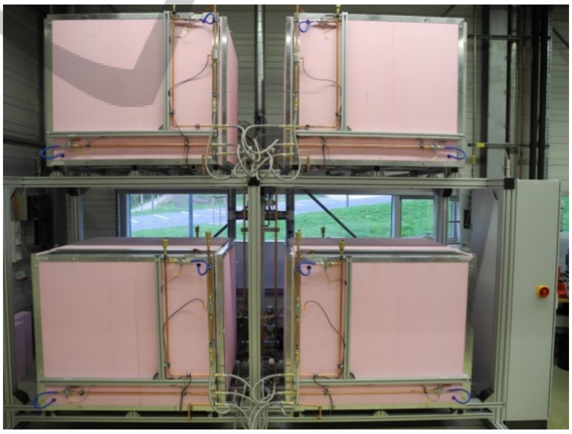

Figure 4: Installation of the four coupled rooms.

For the evaluation of the single room heating control the important parameters in each cabin are measured. The heat emission of each radiator is determined with the inlet and outlet temperature ($T_{R,IN}, T_{R,OUT}$) and the volume flow $\dot{V}_{R,rad}$. The working process of the installed control valve is measured by the pressure drop DP_R and the valve lift S. And the condition of each room can be described with the indoor air temperature T_{air} and the defined surface and inlet air temperatures ($T_{surface}, T_{inlet}$).

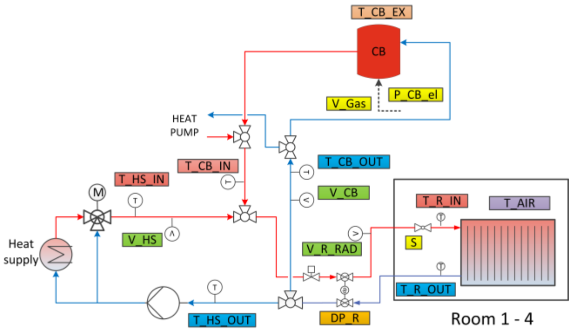

Figure 5: Installed supply structure of the test bench.

There are three possible supply units installed at the moment. On the one hand the central heat supply of the test hall provides the required supply temperature $T_{HS,IN}$ of a simulated heat source. The control of the supply temperature $T_{HS,IN}$ is realized with a three-way-valve in the form of a bypass control system, see Figure 5 on the left side. The inlet and outlet temperature $(T_{HS,IN}, T_{HS,OUT})$ and the volume flow $\dot{V}_{HS}$ of the supply system are measured to determine the total heat output of the system.

On the other hand an installed condensing boiler allows the test of a real hydraulic heating network of a small flat. For the analysis of the boiler efficiency the gas flow $V_{CB,Gas}$, the electric consumption $P_{CB,el}$ and the exhaust temperature $T_{CB,EX}$ can be measured, shown in the upper part of Figure 5. The evaluation of the heat output of the condensing boiler is possible by measuring the appropriate temperatures $(T_{CB,IN}, T_{CB,OUT})$ and the volume flow $\dot{V}_{CB}$.

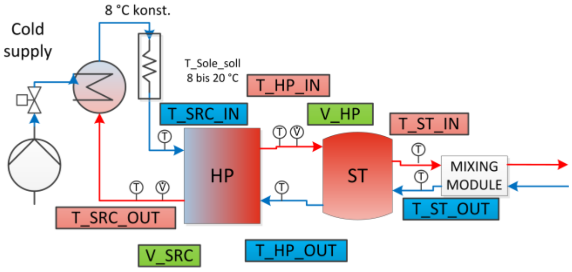

Figure 6: Supply structure for the water/water heat pump system.

For further research activities it is interesting to test the performance of the four coupled rooms in combination with a heat pump. Therefor the supply structure of the test bench provides the integration of a water/water heat pump, a storage tank and an appropriate mixing module. The included testing equipment, shown in Figure 6, measure the important state values of the heat pump source $(T_{SRC,IN}, T_{SRC,OUT}, \dot{V}_{SRC})$, the circuit between heat pump and storage tank $(T_{HP,IN}, T_{HP,OUT}, \dot{V}_{HP})$ and the temperatures after the storage tank $(T_{ST,IN}, T_{ST,OUT})$.

The heat pump needs a defined inlet temperature of 8 to 20 °C, which represents the heat source. The infrastructure of the test hall provides a constant supply temperature of 8 °C, and the higher temperatures are realized with a heating rod.

2.2 Definition of the Boundary Conditions

The ambient air temperature and the simulated room parameters (T_{room}, T_{wall}) influence the heat output and with it the air temperature T_{air} in the small scaled room. As mentioned above these simulated parameters need to be converted into the correct boundary conditions for the small-scaled ambient.

In this paper we will describe the idea of the small-scaled concept and first results regarding the control system and the behaviour of the setup will be shown. Further information about the conversion into the small-scaled boundary conditions will be published in an upcoming proceeding, as the received results are not verified yet.

The surface temperature $T_{surface}$ is a function of the simulated wall and room temperature, and also dependent of the according view factors of the scaled room parameters. These view factors are described in Glück, 1990. The inlet air temperature T_{inlet} and the volume flow are a function of the current room temperature, which correlation is shown in Kopmann et al., 2011. But also the ambient temperature influences the inlet air temperature as lower ambient temperatures results in a higher heat output and that means larger temperature gradient of the air in a real room.

$$\begin{aligned} T_{surface} &= f(T_{wall}, T_{room}, \varepsilon) \\ T_{inlet} &= f(T_{room}, T_{ambient}) \end{aligned}$$

In this paper we will present the characteristic of the test bench in terms of static boundary conditions without any room temperature control. The maximum heat output will be examined by using low temperature supply boundary conditions according the surface and the inlet air temperature $(T_{surface}, T_{air})$. Furthermore the stability and the repeatability of the static boundary conditions are examined and lately the control mode of the system is shown.

2.2.1 Heat Output of the Test Bench

The Table 1 shows the summarized heat amount of the four coupled rooms. The presented temperatures are the mean values of all four rooms in the time period considered. The influence of the supply temperature T_{in} is shown by using three different temperature levels 75 °C, 60 °C and 45 °C. The total volume flow of the heating water in all three states is constantly 6 l/min and the total air flow 440 m³/h.

Table 1: Heat output using static, low boundary conditions at three different supply temperatures.

T_{in}	$\sum\dot{Q}_i$ [W]	$\overline{T_{air}}$ [°C]	$\overline{T_{surface}}$ [°C]	$\overline{T_{inlet}}$ [°C]
75	6215	22.9 *SD=0.08K*	10.1 *SD=0.04K*	15.7 *SD=0.06K*
60	4353	19.9 *SD=0.05K*	10.0 *SD=0.03K*	15.4 *SD=0.02K*
45	2600	17.7 *SD=0.05K*	9.9 *SD=0.02K*	15.4 *SD=0.01K*

A high supply temperature ($T_{in} = 75\,°C$) and low boundary conditions ($T_{surface} = 10\,°C, T_{inlet} = 15{,}0\,°C$) result in the maximum heat output of 6.2 kW. In this case the air temperature T_{air} in the cabin is in a warm state with 23 °C.

Lower supply temperatures result in lower heat output and respectively lower air temperatures.

2.2.2 Stability of the Setup

To test different control strategies a stable and controllable surrounding is important. The measurements in Table 1 are obtained using a surface temperature of 10 °C and an air inlet temperature of 16 °C. The surface temperature in all three states is adjusted correctly. The air inlet temperature is about 0.4 to 0.7 K above the set-point due to an insufficient air cooling.

The mean standard derivation (SD) in all cases of the surface and the air inlet temperature is < 0.05 K which means a nearly constant control. The air temperature in the cabin has a standard derivation of < 0.08 K, which means that the boundary conditions are stable enough to test control algorithm in this setup.

2.2.3 Repeatability of the Setup

For the comparison of different control strategies and various components the repeatability of the setup is an important fact. Therefore two analysed data of each of the supply temperatures 75 °C and 45 °C are displayed in Table 2. These series of measurements were obtained using the same boundary conditions as mentioned above.

The measured results, for the supply temperature of 45 °C, show nearly identic results in all mentioned data. The difference of the heat output and the air temperature in the cabin in the two analysed series is less than 1 %.

Table 2: Repeatability of the measured data at two supply temperatures.

T_{in}	$\sum\dot{Q}_i$ [W]	$\Delta\dot{Q}$ [W]	$\overline{T_{air}}$ [°C]	ΔT [°C]	$\overline{T_{inlet}}$ [°C]	$\overline{T_{hall}}$ [°C]
75	6215	-134 *2%*	22,9	+0,7 *3%*	15,7	23,4
	6081		23,6		16,8	24,3
45	2600	-11 *0,4%*	17,7	+0,1 *0,6%*	15,4	23,1
	2589		17,8		15,5	23,2

The comparison of the heat output at a supply temperature of 75 °C is also satisfactory with a difference of 2 %. Especially when the increase of the temperature in the test hall T_{hall} of 1 K between the two analysed series is considered.

The installed air cooling unit provides a temperature level below the hall temperature for the air supply temperature (T_{inlet}). The maximum temperature difference between the hall temperature T_{hall} and the air inlet temperature T_{inlet} is about 8 K providing an air volume flow of 400 m³/h with the installed cooling capacity. That means that the higher ambient temperature in the second measurement series using a supply temperature of 75 °C results in a higher inlet temperature of the cooled air. Hence the air temperature in the cabin T_{air} rises by 1 K and as a consequence the heat output of the radiator decreases.

These results illustrate that the repeatability of the measurements is dependent of the correct control of the boundary conditions.

2.2.4 Control Mode

For the use of dynamic boundary conditions at the test bench, it is important that the temperature control units adapt satisfactory after the set-point is changed. To analyse the control mode of the setup, Figure 7 shows the profile of the surface temperature (blue lines) and the air inlet temperature (green lines) at a set-point change. The set-point of the air inlet is reduced from 20 °C to 16 °C and the set-point for the surface temperature is reduced from 14.5 °C to 11.5 °C.

In the diagram we have to distinguish between the surface temperature $T_{surface}$ and air inlet temperature T_{inlet} (dashed lines) and the controlled temperatures ($T_{KT,in}, T_{HT}$) of these control units (solid lines). The control temperatures are necessary due to the large dead times in the control loops, which forces an appropriate control value closer to the manipulated variable.

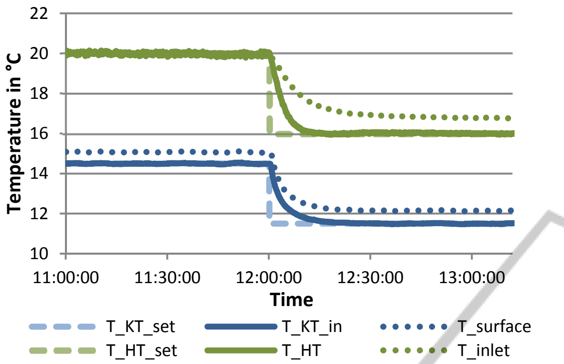

Figure 7: Control response of the surface temperature and the air inlet temperature.

The set-point of the air inlet is controlled using an electrical heater and the controlled temperature T_{HT} is measured directly behind this heating unit. The control needs only 15 minutes to adapt to the new set point and has a low control deviation ($\overline{T_{HT}} = 19.97\ ^{\circ}C$) and a stable control response ($SD = 0.06\ K$), see Table 3. Behind the control unit with the electrical heater the air flow passes a short air duct before being inducted in the cabin. Using an inlet air temperature of 20 °C, which is similar to the hall temperature T_{hall}, the controlled temperature T_{HT} corresponds with the air inlet temperature T_{inlet} at the cabins. Lower air inlet temperatures result in higher heat losses in the air ducts so that the temperature increases about 0.8 K before being inducted in the cabin. A cascade control will be implemented for further investigations to eliminate the control deviation.

Table 3: Mean temperatures and standard deviation to analyse the control mode of the air inlet temperature.

	$\boldsymbol{T_{HT,set}}$ [°C]	$\overline{\boldsymbol{T_{HT}}}$ [°C]	SD_{HT} [K]	$\overline{T_{inlet}}$ [°C]	SD_{inlet} [K]
air	20	19.97	0.06	19.87	0.03
	16	16.02	0.02	16.84	0.04

To control the surface temperature $T_{surface}$ the inlet temperature of the cooled walls $T_{KT,in}$ is used as the controlled value. The control is also satisfactory, as the set point is adapted after 20 minutes without control deviation and a negligible standard derivation of 0.02 K, see Figure 7 and Table 4. The actual surface temperature $T_{surface}$ is obtained from the arithmetic average of the inlet and the outlet temperature of the capillary tubes which are used to provide the surface temperatures. Compared to the controlled temperature this surface temperature has a constant deviation of 0.6 K, which hardly depend on the temperature level. This constant deviation should be observed for further investigations by using a constant set-point adjustment.

Table 4: Mean temperatures and standard deviation to analyse the control mode of the surface temperature.

	$\boldsymbol{T_{KT,set}}$ [°C]	$\overline{\boldsymbol{T_{KT,in}}}$ [°C]	$SD_{KT,in}$ [K]	$\overline{T_{surface}}$ [°C]	$SD_{surface}$ [K]
sur-face	14.5	14.50	0.02	15.07	0.02
	11.5	11.50	0.01	12.15	0.01

3 CONCLUSIONS

In this paper we describe the possibility to test and develop new control strategies and components for single room heating control under controllable and dynamic boundary conditions. First the concept of the new test bench is shown and the supply structure including the monitoring technique is described. The results of the considered measurement series give an overview of the behaviour of the test bench setup. The heat output of the radiators in the cabins, the stability and the repeatability of the measurements and the control mode of the setup were analysed. There were obtained some aspects to improve the control for further investigations. These aspects will be applied in the early future and shown in a following publication.

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