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The effect of hydronic balancing on room temperature and heat pump efficiency of a building with underfloor heating

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Abstract

Underfloor heating is a common solution in single-family houses and a suitable solution for nearly zero-energy buildings as a low temperature heating system. According to general practice, the underfloor heating systems should be balanced to assure stable room temperatures and avoid under heating in rooms with higher heat losses. The purpose of the presented study was to analyze the effect of hydronic balancing on the room temperature fluctuations and heat pump performance. The tests were performed at full-scale nearly zero-energy building test facility with under floor heating and an air-to-water heat pump. We measured room and floor temperatures and monitored the heat pump electricity use and heat output. The heat balance of rooms was disturbed with internal gains introduced to several rooms in cycles. The results showed that room temperature fluctuations slightly increased of an unbalanced system, however during all tests, the average temperature fluctuations during night time were below 0.2 °C, so both systems performed well. We identified a negative effect of balancing on the heat pump performance as higher COP was measured in case of an unbalanced system. The results allow to conclude that in the case of studied system with one manifold and relatively small loop length differences the balancing had negligible effect on system performance. However, the topic should be studied further in more unfavorable conditions.

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Keywords: Underfloor heating; hydronic balancing; indoor climate; heat pumps.

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1. Introduction

Underfloor heating (UFH) is amongst the most commonly used heating system types in single-family houses. Being a low temperature heating system suitable for heat pumps, UFH is a good alternative for low and nearly zero-energy buildings. Generally, the floors have large thermal capacities and that may cause unnecessary over-heating as the floor still emits heat, when room temperature has exceeded the set point due to solar or internal heat gains. Also the heat output of the heating system is affected by the thermal resistance of upper layers of the floor and e.g. higher water temperatures are needed, when the floor is covered with wood.

Several studies have been conducted to analyze the performance of UFH. Seo et al. [1] measured thermal conductivity and transfer performance of 21 replicates of wood flooring materials and pointed out that laminated wood flooring exhibited the highest thermal conductivity. Wolisz et al. [2] analyzed the effect of furniture and floor covering on the dynamic temperature behavior of underfloor heating rooms and detected significant effect of furniture and floor covering on the simulation results. Zhou and He [3] studied the performance of UFH system with different heat storage materials and heating pipes and showed that capillary mats provided more uniform vertical temperature distribution compared to polyethylene pipes and phase change material increased the discharging time of the floor, which makes it suitable for using in combination with solar hot water systems. Gao et al. [4] investigated the indoor air temperatures of different under-floor heating pipe layouts and the best layout method was uniformly laid UFH pipes at 400 mm spacing. Maivel and Kurnitski [5] studied operative temperature corrections for EN 15316-2 and showed that the correction of 0.25 K should be used for radiators and no correction factor should be used with UFH. In [6] they also studied the effect of heating system return temperature on heat pump performance and pointed out that highest heat pump efficiency was achieved with direct connection of heat pump and heating system with lowest return temperature. They also showed that simple calculation of return temperature might lead to under-estimation over 10% of heat pump seasonal performance. So far little work, if any, has been done regarding the hydronic balancing of UFH systems.

General construction practice involves adequate dimensioning of water flows in the UFH loops and hydronic balancing, however the quality of heating and ventilation system design and construction may fluctuate significantly in case of single-family houses. The UFH loops may be unbalanced and it is assumed that it may cause problems achieving comfortable temperature levels in larger rooms with higher heat losses. However, during the process of this study we did not find any materials supporting these assumptions. We conducted UFH measurements at Tallinn University of Technology (TUT) nearly zero-energy building (nZEB) technological test facility with a balanced and an unbalanced system to determine the effect of hydronic balancing on the heating system. We measured room and floor temperatures in several rooms of the building and monitored the performance of the UFH system with air-to-water heat pump. The heat balance of some rooms was disturbed by internal gains introduced in cycles and also solar gains. As a result we calculated the temperature deviations in case of balanced and unbalanced systems and compared the heat pump coefficient of performance (COP) under different conditions.

2. Methods

Three tests were performed during February and April 2016 in the TUT nZEB test facility:

- Test #1: System with manual balancing (Feb 12-23)
- Test #2: System without manual balancing (Mar 11-21)
- Test #3: System with manual balancing (Mar 28-Apr 04)

The test facility was a building with heated area of 100 m² (Fig. 1), timber frame walls, concrete floor and roof. Internal walls were made of light-weight blocks or gypsum boards with light-weight insulation in between. UFH was used during the tests and the temperature set point was 21 °C in all rooms and on-off control was used. There was one UFH manifold located in the technical room in the middle of the building. Table 1 describes the heat losses of the building, UFH loops and the position of presetting valves during the different tests. All the valves were open during the unbalanced test except, the valve of room no. 6, which was left in the same position during the unbalanced test to represent a room with higher heat losses. Internal heat gains were introduced in cycles to disturb the UFH system to

rooms R05, R06 and R09. The maximum heat output was 15 W/m² and the internal gains daily profile is illustrated by Fig. 2. We measured the following during all tests with a 10-minute time step:

- Room temperatures in 6 rooms (Fig. 1)
- Floor temperatures in 3 rooms (4 points, Fig. 1)
- Heat pump electricity use
- Heat pump heat output
- Global solar irradiance on a horizontal surface
- Outdoor temperature

The average deviation of room temperatures was used to assess the performance of the UFH during different tests and it was calculated with the following formula:

$$D_{avg} = \frac{\sum_{i=1}^n |t_i - \bar{t}|}{n} \tag{1}$$

Where, D_{avg} – average temperature deviation, °C; t_i – measured room temperature at time step i , °C, \bar{t} – average measured temperature, °C; n – number of time steps during the analysed period, -.

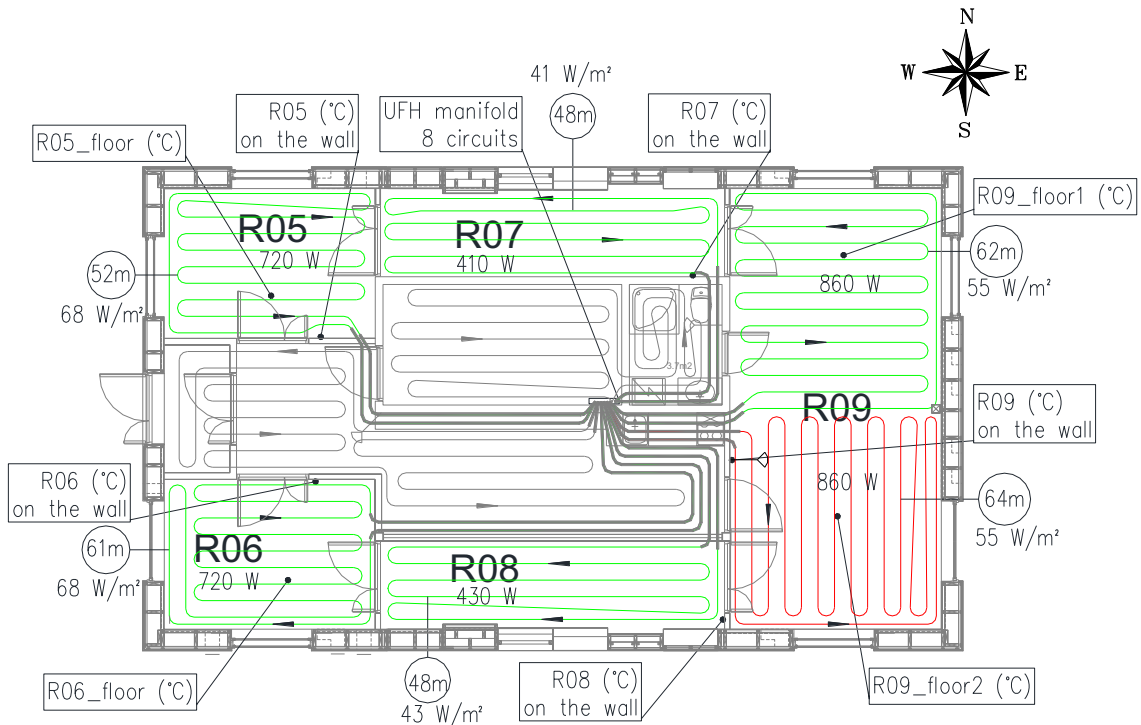


Fig. 1 The plan of the building, underfloor heating loops and location of temperature sensors.

Table 1. UFH design parameters.

Room no	Room area, m ²	Heating load		Loop length, m	Flow rate, l/min	Loop pressure drop, kPa	Valve pressure drop, kPa	Valve presetting, -	
		W	W/m ²					Tests #1,3	Test #2
2	22.6	640	28.3	60	1.83	1.50	3.99	4.3	Open
3;4	13.2	270	20.5	51	0.77	0.26	5.23	3.1	Open
5	10.4	720	69.2	52	2.06	1.56	3.93	5.0	Open
6	10.4	720	69.2	61	2.06	1.83	3.66	4.5	4.5
7	10.0	410	41.0	48	1.18	0.53	4.96	3.5	Open
8	10.0	430	43.0	48	1.23	0.58	4.91	3.3	Open
9	30.7	860	56.0	62	2.46	2.60	2.88	5.5	Open
9		860	56.0	64	2.46	2.69	2.80	5.5	Open

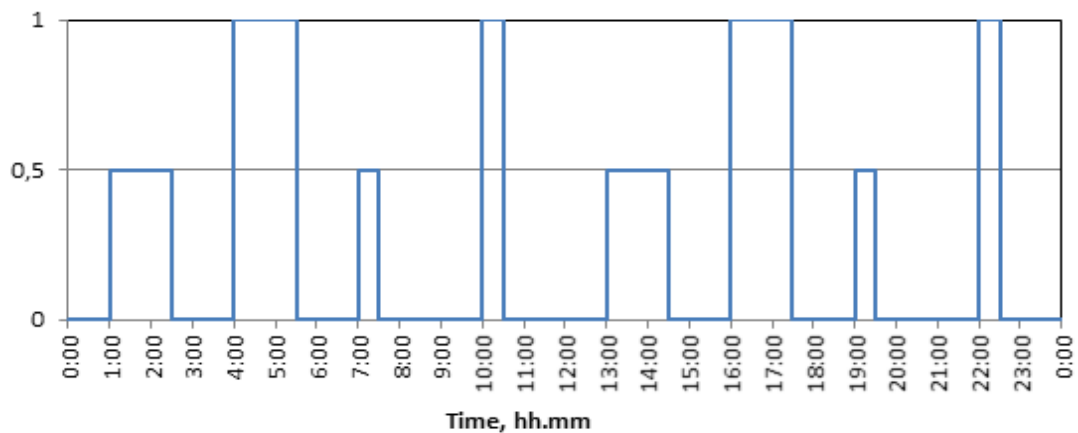


Fig. 2 Internal gains profile for 24 hours: maximum generated heat gains for small test rooms (R05 and R06) was 150W and for large test room (R09) 450W.

We used the following measuring equipment: Onset Hobo U12-013 for air temperature measurements and U12-013 combined with TMC20-HD for floor temperature measurements; Sensus Pollustat E for flow and energy consumption measurements; Flex-Core M2V-25-1DC clamps with U12-013 data logger for internal gains generators electricity consumption measurements and Janitza ECS3-80 for heat pump electricity consumption measurements. The specifications of the instruments are shown in Table 2. The weather data was acquired with LSI Lastem weather station with E-Log environmental data logger located on the rooftop of the test building. The specifications of the instruments are given in Table 3.

Table 2. Specifications of measuring equipment.


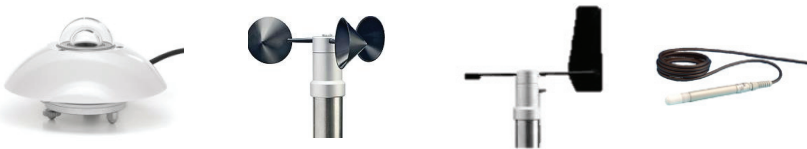
Device/ Sensor	Onset Hobo U12-013	Onset TMC20-HD	Sensus Pollustat E	Flex-Core M2V-25-1DC	Janitza ECS3-80
Description	Temperature/RH logger	Temperature sensor	Flow/ thermal energy meter	AC current sensor	Electric energy meter
					
Measuring range	-20...+70°C 5%...95% RH 0...5 VDC	-40°C... +100°C	$q_p = 0.6...60\text{m}^3/\text{h}$	0.5...25Aac	190...480VAC 0.015...80A 48...68Hz
Resolution	Temp: 0.03°C at 25°C RH: 0.03% RH	0.03°C at 20°C	pulse value for energy 1kWh pulse value for flow 1dm ³	0.03% of full scale (w/ 0-5 Vdc cable)	0.01kWh
Accuracy	±0,35°C ±2,5% RH ±2 mV	±0.25°C (from 0° to 50°C)	<±(2+0.02q _p /q)%	±4 mV ±2.7% of reading (w/ 0-5 Vdc cable)	acc.to EN 50470-3

Table 3. Specifications of the weather station equipment.

Device/ Sensor	LSI Lastem DPA053	LSI Lastem DNA202	LSI Lastem DNA212	LSI Lastem DMA672.1
Description	Pyranometer	3-cup anemometer	Wind vane	Temp and RH probe
				
Measuring range	0÷2000 W/m ²	0÷75 m/s	0÷360°	-30÷70°C 0÷100% RH
Resolution	Logger dependent	0.5 m/s	Logger dependent	0.04°C
Accuracy	<±10 W/m ²	±2.5%	5°	±0.2°C ±1,5% RH

3. Results

3.1. Outdoor conditions

Fig. 3 illustrates the outdoor temperatures and solar radiation of each day during the tests. The daily average outdoor temperature ranged between -5 °C and 7 °C and the daily global solar radiation of a horizontal surface reached approximately 5000 Wh/m². The outdoor condition varied remarkably throughout the study and therefore we chose characteristic days from each test period to illustrate the room and floor temperature behavior during different tests.

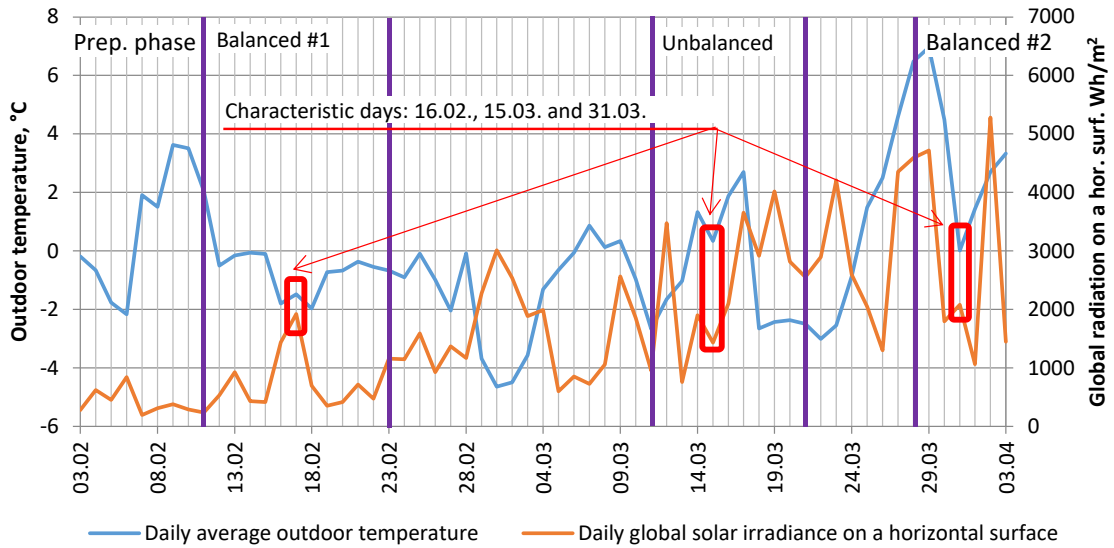


Fig. 3 Daily average outdoor temperatures and global solar radiation on a horizontal surface during the test period.

3.2. Room temperatures

The daily room temperature fluctuations were largest in test room 6, followed by rooms 5 and 9. The rooms 7 and 8 had no internal gains and only small windows, which is why temperature fluctuations there were the smallest. In order not to over-load figures with information, the detailed results of only rooms R06, R07 and R09 are given in the subsequent figures.

Figures 5-7 present the temperature measurements in rooms 6, 7 and 9 during the characteristic days of each test. In all cases the room temperature correlation with internal and solar gains can be seen in rooms R06 and R09 and room temperatures in room R07 were stable during all tests. Room temperatures peaked in the afternoons, when

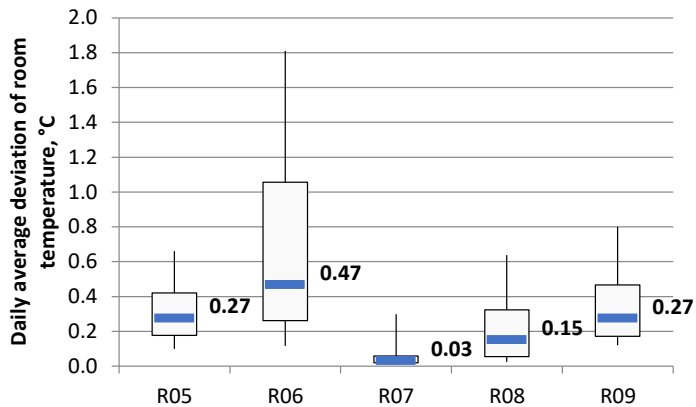


Fig. 4 Daily room temperature fluctuations in different rooms described by average deviations, which were calculated for each day. The figure presents minimum, maximum values, 25th and 75th percentiles and the median values are described with the blue markers. The legend gives test room numbers.

room temperature became equal or even exceeded the floor temperature. Based on the information on these figures, no significant distinctions between the performances of a balanced and unbalanced UFH systems could be detected.

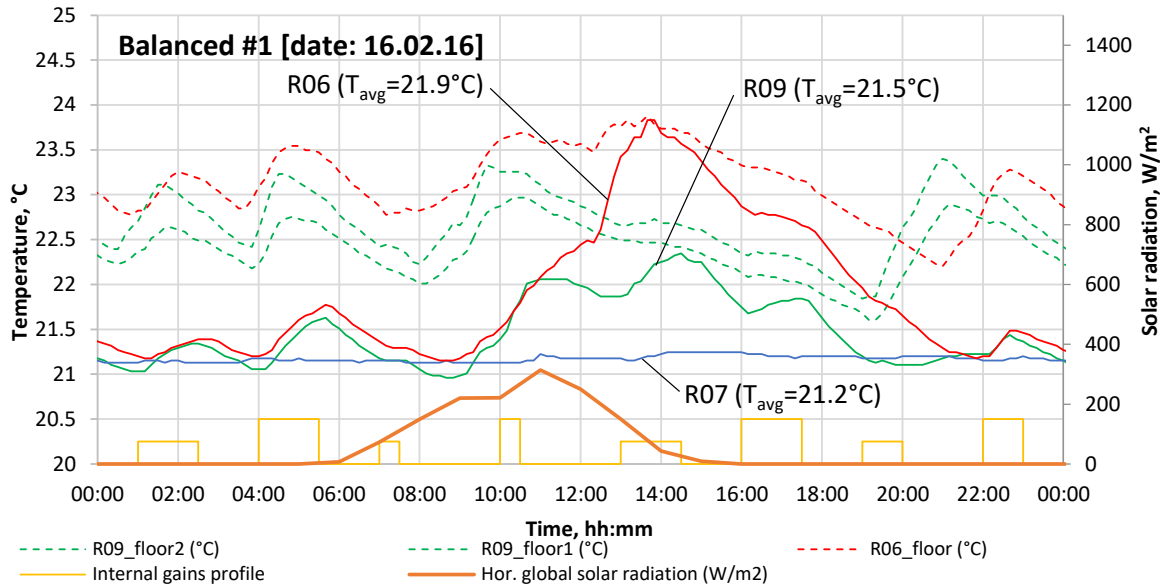


Fig. 5 Measured room and floor temperatures, internal gains profile and horizontal global solar radiation in rooms R06, R07 and R09 during the first test with balanced UFH system on 16.02.2016.

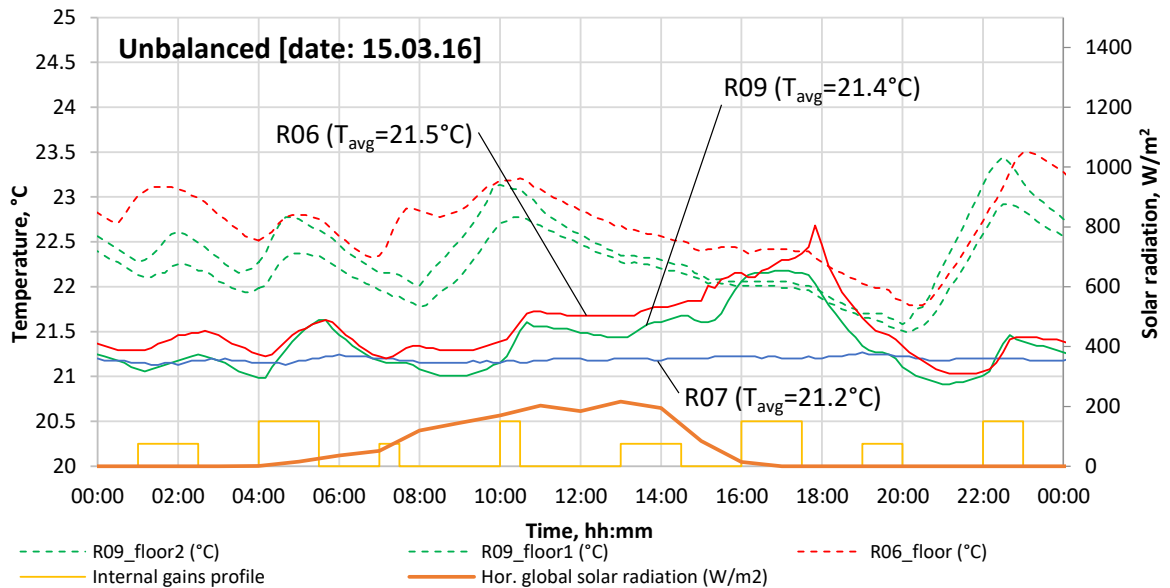


Fig. 6 Measured room and floor temperatures, internal gains profile and horizontal global solar radiation in rooms R06, R07 and R09 during the test with unbalanced UFH system on 15.03.2016.

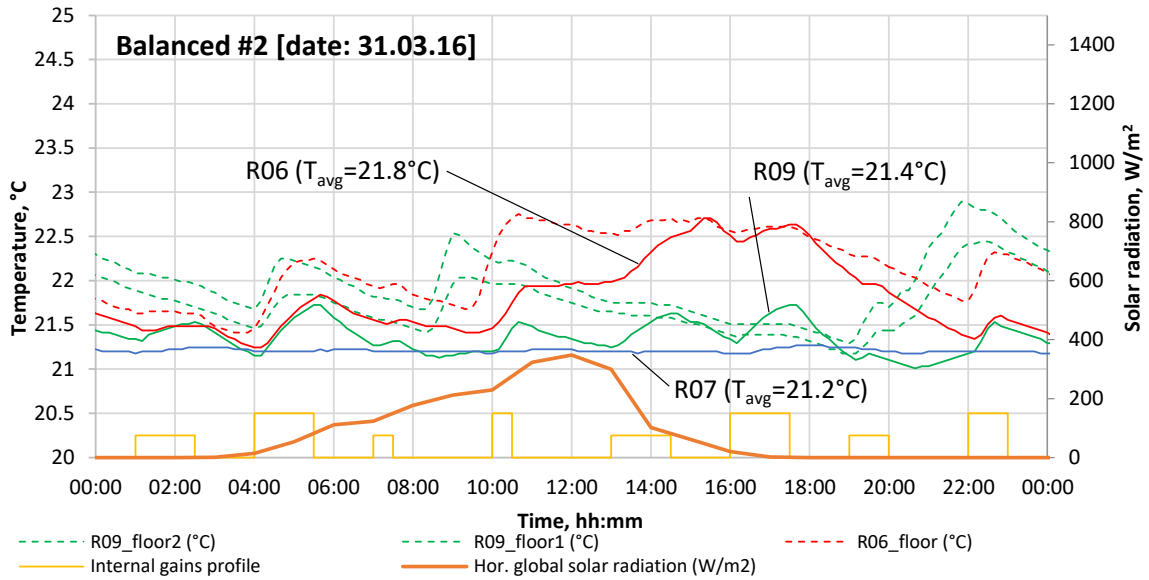


Fig. 7 Measured room and floor temperatures, internal gains profile and horizontal global solar radiation in rooms R06, R07 and R09 during the second test with balanced UFH system on 31.03.2016.

Solar gains significantly influenced the room temperatures and therefore the night-time room temperatures are presented in the following figures. Three nights were chosen from all tests, so that the room temperatures had dropped close to heating setpoint by 22:00 and no significant outdoor temperature fluctuations appeared). The studied periods were from 22:00 in the evening to 06:00 in the morning during:

- Balanced, #1 – 18.02. 22:00 – 21.02. 06:00
- Unbalanced – 13.03. 22:00 – 16.03. 06:00
- Balanced, #2 – 29.03. 22:00 – 02.04. 06:00

The measurement results for three characteristic rooms (room 6 – south/west oriented with internal gains, room 7 – north oriented without internal gains and room 9 – south/east oriented with internal gains) are presented in Fig. 8. The amplitude of room temperatures at night time were generally within 0.5 °C in rooms R06 and R09 where internal gains were present. In room R09 without internal gains, the temperature fluctuations were small.

Average deviations of room temperature for the periods in all rooms during the chosen periods of tests are shown in Fig. 9, which shows that generally the room temperature deviations were below 0.2 °C. Slightly higher temperature deviations were measured in case of an unbalanced UFH system. The average deviation of all rooms was 0.08-0.09 °C in case of a balanced system and 0.10 °C in case on an unbalanced one.

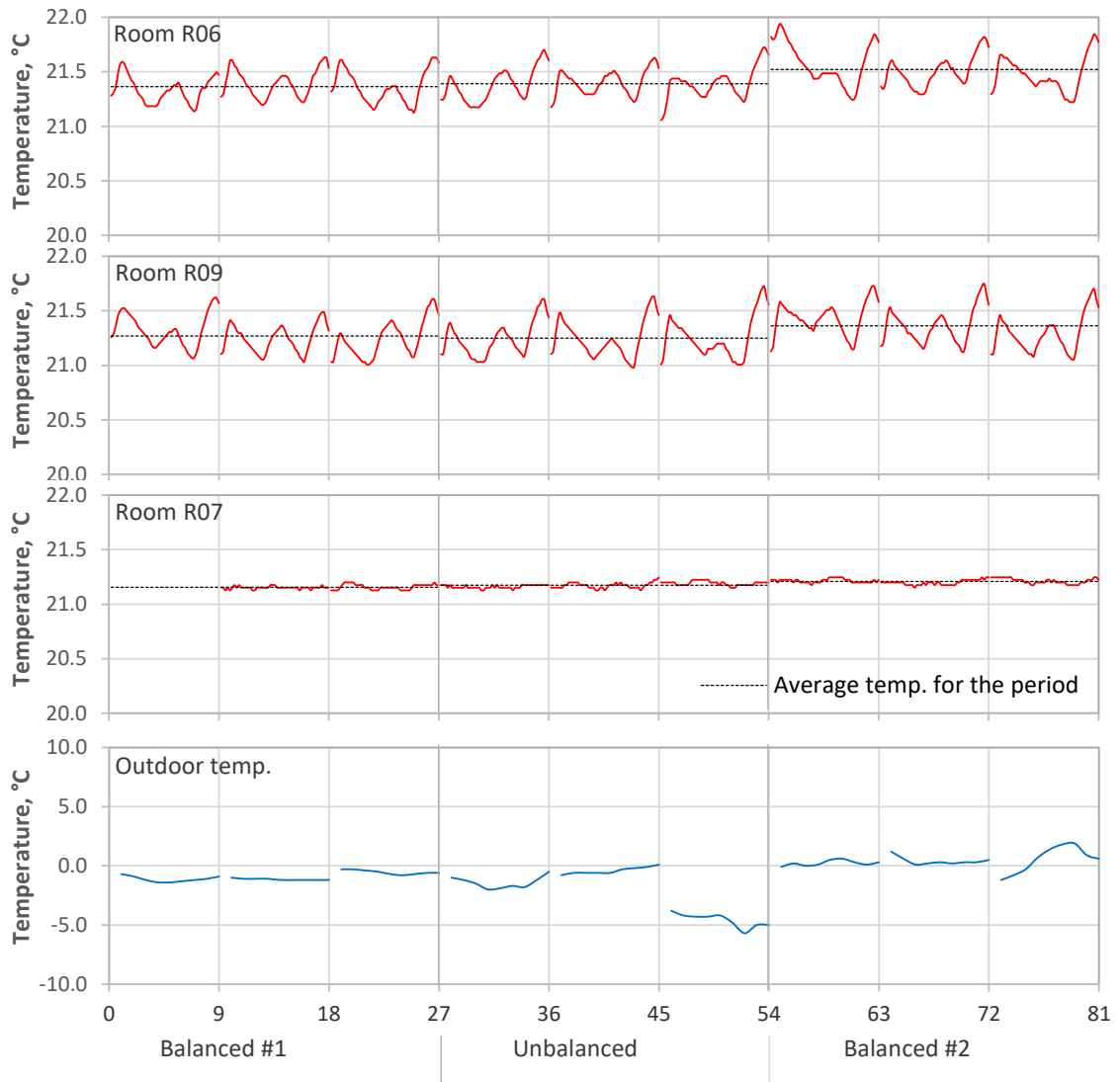


Fig. 8 Room temperature measurement results from the selected 3 night cycles from every test for the characteristic rooms R06, R07 and R09.

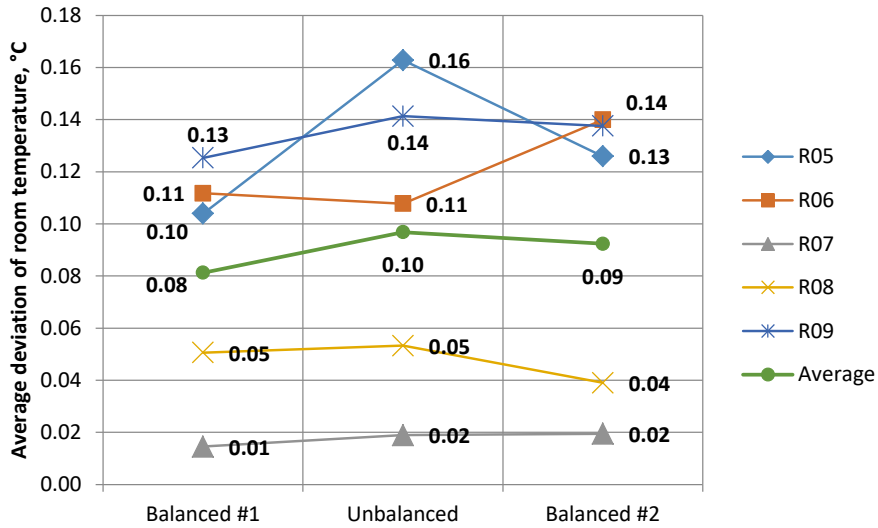


Fig. 9 The average deviation of room temperature during the night in different rooms during the chosen periods of tests.

3.3. Heat pump efficiency

Fig. 10 presents the heat pump electricity consumption and heat output during the characteristic days of the tests.

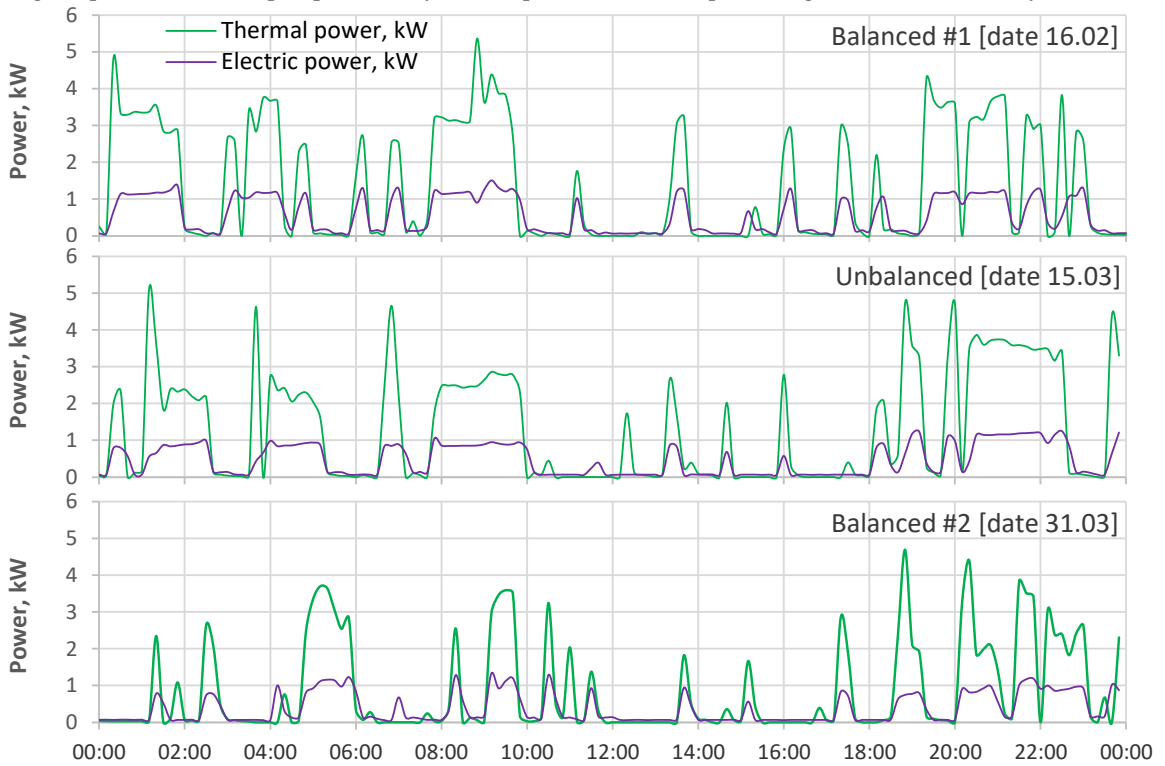


Fig. 10 Heat pump electric and thermal power during the characteristic days.

The heat pump work was slightly more stable in case of an unbalanced UFH system compared to the tests with balanced system. This might suggest that the number of working cycles is smaller with an unbalanced system, however the time step for measurements was 10 minutes and that did not allow to count the work cycles. The heat pump coefficients of performance (COP) presented in Table 4, show that the conditions were more favorable for the heat pump during the unbalanced test. The COP of the entire unbalanced test period was 2.60, which was slightly higher than COP-s 2.52 and 2.55 measured during the balanced tests. Larger differences between the tests were identified during the chosen night period, when the COP-s were 2.72 and 2.39 or 2.37 respectively.

Table 4. Average heat pump COP-s during the tests

Test	Entire test periods			Chosen night periods	
	Outdoor temperature, °C	Average daily solar irradiance, Wh/m ²	COP, -	Outdoor temperature, °C	COP, -
On-off, balanced #1	-0.8	760	2.52	-0.9	2.39
On-off, unbalanced	-0.4	2560	2.60	0.4	2.72
On-off, balanced #2	3.1	2730	2.55	0.0	2.37

4. Discussion and conclusion

The purpose of this study was to compare the effect of hydronic balancing on the performance of a UFH system with an air-to-water heat pump. We measured room and floor temperatures in TUT nZEB test facility and monitored the performance of the heat pump during the tests with a balanced and unbalance heating systems. The results showed that room temperature fluctuations slightly increased of an unbalanced system, however during all tests, the average temperature fluctuations during night time were below 0.2 °C, which is small. The temperature fluctuations were small if no internal gains were introduced in the rooms and therefore some internal gains should be used, when testing the heating systems ability to maintain stable room temperatures. We identified a negative effect of balancing on the heat pump performance as higher COP was measured in case of an unbalanced system.

The used test facility had only one UFH manifold and the loop lengths were similar ranging between 48 and 64 meters. This set-up represents a good design practice of UHF and allows to conclude that under such reasonably favorable conditions balancing has no practical meaning. However, the results may not be generalized for systems with high differences between loop lengths and multiple manifolds. Further studies are needed to quantify balancing effects for different systems typology.

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