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Published in:
Proceedings of ROOMVENT 2014, 13th SCANVAC International Conference on Air Distribution in Rooms

Publication date:
2014

Citation (APA):
Kazanci, O. B., & Olesen, B. W. (2014). Air and operative temperature measurements in a plus-energy house under different heating strategies. In Proceedings of ROOMVENT 2014, 13th SCANVAC International Conference on Air Distribution in Rooms (pp. 312-319)

AIR AND OPERATIVE TEMPERATURE MEASUREMENTS IN A PLUS-ENERGY HOUSE UNDER DIFFERENT HEATING STRATEGIES

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Abstract

The studied house was a detached, one-story, single family, plus-energy house located in Denmark. The house was being used as a full-scale experimental facility without actual occupants living in the house.

The house was operated a whole heating season (October to April, both months included) and different heating strategies were tested during this period. These strategies were floor heating without ventilation (with different indoor operative temperature set-points), floor heating supported with warm air heating (ventilation system), and floor heating with heat recovery on ventilation. A total of seven different experimental conditions were studied.

Among the various measurements taken from the house, the present study focuses on air temperatures, globe temperatures, and operative temperatures, measured at different heights, and at one of the representative locations in the house. The performance of different heating strategies regarding the indoor operative temperature, and thermal stratification were compared. It was found that the optimal combination is a floor heating system with heat recovery on ventilation based on the provided indoor environment and thermal stratification.

Keywords: full-scale measurement, plus-energy house, floor heating, temperature measurements, thermal stratification

1 Introduction

People spend most of their time indoors, Olesen and Seelen (1993), therefore the buildings are built for people to live in and to have a comfortable, healthy and productive indoor environment and not to save energy, i.e. with fewer buildings there would be higher energy savings.

The goal of providing a pleasant indoor environment for occupants should be achieved with the lowest energy consumption because buildings are very energy intensive structures. The buildings are responsible for 40% of the energy consumption in the member states of the European Union, European Commission (2010).

One possible way to classify buildings is to divide them into residential and non-residential buildings. These two groups differ in occupancy period, size, expectations of the occupants to the building, user activities and so forth. Nevertheless, similar energy efficiency and energy saving measures could be applied to both types of buildings. Examples of these measures could be innovative building components, efficient heating, cooling and ventilation strategies and others.

The present study focuses on a one-story, detached, single family, plus-energy house, located in Denmark, Kazanci et al. (2013), Kazanci et al. (2014). The house was being used as a full-scale experimental facility and different heating strategies were tested during the period from 26 September 2013 to 01 May 2014. The tested strategies were floor heating (with different indoor operative temperature set-points), floor heating supported with warm air heating by the ventilation system, and floor heating with heat recovery on the ventilation. In its current location, the house is occasionally being used as a meeting room and as a showcase. The data presented in this study include the data collected during meetings, various visits and when the experimenter has been inside the house.

Among the various physical parameters measured in the house, the focus of this study is on the air, globe and operative temperatures (measured at 0.6 m and 1.1 m heights). These temperatures were measured at different heights, at representative locations inside the house (one of the expected locations of an occupant).

The performance of the different heating strategies were compared based on the achieved indoor climate category according to EN 15251 (2007), and temperature stratification at the given measurement location. The temperature stratification was also used as an indicator of differences in heat loss, hence the energy efficiency.

2 Details of the house and its HVAC system

The house considered in this study was a single family, detached, single-story, plus-energy house with a floor area of 66 m^2 and a conditioned volume of 213 m^3. Inside the house, there was a single space combining kitchen, living room and bedroom areas. Shower and toilet areas were partly separated by partitions. The technical room was completely isolated from the main indoor space, having a separate entrance. The wall between the technical room and the indoor space was insulated with the same level of insulation as the outside walls.

The house was constructed from wooden elements. Walls, roof and floor structures were formed by installing prefabricated elements in a sequential order and sealing the joints. The North and South glazed façades were inserted later and the joints between the glazing frame and the house structure were sealed. The largest glazing façade was oriented to the North with a 19° turn towards the West. The glazing façades were partly shaded by the overhangs. The outside and inside views of the house may be seen in Figure 1:

Figure 1. *Outside (left) and inside (right) views of the house*

The surface areas and the corresponding thermal properties are shown in Table 1:

Table 1: *Thermal properties of the walls*

External walls	*South*	*North*	*East*	*West*	*Floor*	*Ceiling*
Area [m^2]	-	-	37.2	19.3	66.2	53
U-value [W/m^{2}K]	-	-	0.09	0.09	0.09	0.09
Windows	*South*	*North*	*East*	*West*	*Floor*	*Ceiling*
Area [m^2]	21.8	36.7	-	-	-	0.74
U-value [W/m^{2}K]	1.04	1.04	-	-	-	1.04
Solar transmission	0.3	0.3	-	-	-	0.3

The main sensible heating and cooling strategy of the house relied on the low temperature heating and high temperature cooling principle via the hydronic radiant system. The floor heating system was a dry radiant system, consisting of a piping grid installed in the wooden layer, with aluminum profiles on the pipes for better thermal conductance. The details of the floor system were:

chipboard system, with aluminum heat conducting profiles (thickness was 0.3 mm and length was 0.17 m), PE-X pipe, 17x2.0 mm. Pipe spacing was 0.2 m. In total there were four loops in the floor. The available floor area for the embedded pipe system installation was 45 m^2. The area was limited by the structural boundaries. A mixing station was installed in the system to control the flow to the individual loops, flow rate, and the supply temperature to the embedded pipes.

The main heat source of the house for the space heating purposes was a reversible air-to-brine heat pump. There was a flat plate heat exchanger between the hydronic loops of the floor and the heat pump to avoid frost damage during winter.

An air handling unit, AHU, which was coupled with the domestic hot water tank via a reversible air-to-water (or water-to-air, depending on the operation mode) heat pump was used to provide fresh air into the house. Passive and active heat recovery options were available. The passive heat recovery was obtained by means of a cross-flow heat exchanger and this passive heat recovery system had an efficiency of 85% (sensible heat). The active heat recovery was obtained by means of a reversible air-to-water heat pump that was coupled to the domestic hot water tank. The AHU could supply fresh air at a flow rate up to 320 m^3/h at 100 Pa. The design ventilation rate was determined to be 0.5 ach. Humidification of the supply air was not possible due to the limitations of the AHU. The two air supply diffusers can be seen on the technical room wall in Figure 1.

3 Measurements and measuring equipment

During the experimental period, various physical measurements were taken from the house. The temperature (air and globe) measurements were taken at the heights of 0.1 m, 0.6 m, 1.1 m, 1.7 m, 2.2 m, 2.7 m, 3.2 m, and 3.7 m. The reason to measure the heights above the occupied zone was to evaluate the effects of thermal stratification based on the different heating strategy. The stratification is particularly important for the house that was considered in this study because of its high and tilted ceiling. It is aimed in this study to use thermal stratification as an indicator for the performance of the heating strategy regarding heat loss from the heated space.

The globe temperatures were measured by a gray globe sensor, 4 cm in diameter. This sensor has the same relative influence of air- and mean radiant temperature as on a person, Simone et al. (2008), and will thus at 0.6 m and 1.1 m heights represent the operative temperature of a sedentary or a standing person, respectively. The air temperature sensor was shielded to avoid heat exchange by radiation, Simone et al. (2013). These sensors provided a voltage output and the voltage output was logged via a portable data-logger. The measurement location, the sensors and a close-up of the sensors are shown in Figure 2:

Figure 2. *The location of the measurements (left) and the measurement equipment (middle and right)*

The internal heat gains inside the house were simulated with five "dummies". A dummy is a circular aluminum duct, with a diameter of 220 mm and with a height of 1 m. It had closed ends and an electrical heating element (wire) was installed on the internal surfaces of the duct. Dummies had an adjustable heat output up to 180 W, Skrupskelis and Kazanci (2012). Their locations were based on where the occupants and the equipment were expected to be in the house.

The schedules were adjusted with timers. Two dummies were used to simulate occupants at 1.2 met (ON from 17 to 08 on weekdays and from 17 to 12 on weekends), one dummy (equipment #1, 120 W) was ON all the time to represent the house appliances that are always in operation, the fourth dummy (equipment #2, 180 W) was used to simulate the house appliances which are in use only when the occupants are present and the fifth dummy was used to simulate the lights (180 W, ON from 06 to 08 and from 17 to 23 every day). The house also had ceiling mounted lights ON from 21 to 23 every day (140 W). Additionally, there was a datalogger and a computer (80 W), and a fridge (30 W) which were always ON, inside the house.

The outdoor temperatures used in this study are obtained from a weather station 30 km away from the house's location, Jessen (2014), to compensate for some of the duration where the outside temperature sensor of the house had a problem. An initial investigation of the difference between the temperatures measured at the house's location and the data from the weather station did not show significant differences.

4 Case studies

Different heating strategies were tested during the heating season. For the first part of the experiments, the floor heating system was operated with different operative temperature set-points (at 1.1 m height), following a previous study by Kazanci and Olesen (2013). In the second part, floor heating was supported by warm air heating by the ventilation system, and during the last part of the heating season, floor heating was operated with heat recovery of the ventilation system. The building code in Denmark requires that each habitable room and the dwelling as a whole must have a fresh air supply and individual room temperature control, The Danish Ministry of Economic and Business Affairs (2010).

The data presented in the present study consist of measurements from 26 September 2013 to 01 May 2014. The most important information regarding different case studies is given in Table 2:

Table 2: *Periods and experimental settings of the case studies*

Period	*Average external air temperature*	*Floor heating set-point*	*Ventilation*	*Case study abbreviation*
26th of Sep to 21st of Nov	8.2°C	22°C	Off	FH22
21st of Nov to 18th of Dec	4.0°C	20°C	Off	FH20
18th of Dec to 16th of Jan	4.6°C	21°C	Off	FH21
16th of Jan to 10th of Feb	0.0°C	21°C	On, heat recovery and pre-heating**	FH21-HRPH
10th of Feb to 10th of Mar	5.0°C	20°C	On, heat recovery and pre-heating**	FH20-HRPH
10th of Mar to 3rd of Apr	5.5°C	21°C	On, heat recovery	FH21-HR
*3rd of Apr to 1st of May**	9.0°C	20°C	On, heat recovery	FH20-HR

*: The dummies simulating the occupants and the dummy, equipment #2, were OFF during this experimental period.

**: Heat recovery refers to the passive heat recovery in the AHU and pre-heating refers to the active heat recovery in the AHU.

5 Results and discussion

The results regarding the air and operative temperatures were analyzed. The indoor environment category was analyzed for the different heating strategies and for the entire heating season. Categories are given according to EN 15251 (2007) for sedentary activity (1.2 met) and clothing of 1.0 clo. The results are shown in Table 3:

Table 3: *The category of indoor environment based on operative temperature (at 0.6 m height)*

Indoor environment category/case	*FH22*	*FH20*	*FH21*	*FH21-HRPH*	*FH20-HRPH*	*FH21-HR*	*FH20-HR*	*Total, average*
Category 1 (21.0-25.0°C)	92%	2%	37%	22%	11%	67%	35%	45%
Category 2 (20.0-25.0°C)	97%	44%	92%	72%	61%	98%	77%	80%
Category 3 (18.0-25.0°C)	100%	95%	100%	93%	99%	100%	100%	98%
*Category 4**	0%	5%	0%	7%	1%	0%	0%	2%

*: Category 4 represents the values outside Categories 1, 2, and 3.

The operative temperature (at 0.6 m height) and the external air temperature during the experimental period are shown in Figure 3:

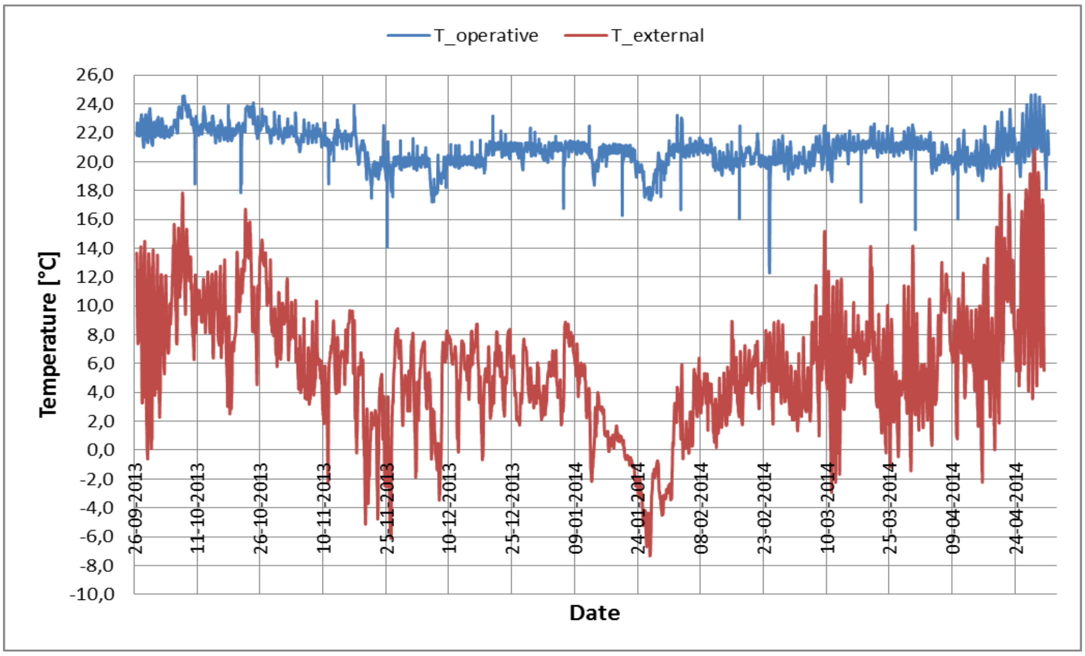

Figure 3. *Operative temperature and external air temperature during the heating season*

It may be seen from Table 3 and Figure 3 that even though different heating strategies were tested, the overall performance regarding the indoor environment was satisfactory, i.e. 80% of the time in category 2 according to EN 15251. It may also be seen that there are durations where the indoor environment is out of category 3, during 2% of the time in category 4. This is an undesirable situation however these instances might correspond to the previously mentioned disturbances.

The results showed that it was possible to keep the indoor operative temperature close to the set-point however the systems struggled to achieve this when the outside temperatures got relatively low. In addition to the increased heating demand, one possible explanation to this behavior is that both the air-to-brine heat pump and the AHU are affected by the lowered outside air temperatures.

The operative temperature set-point of 20°C is too low. This is because even though the ventilation system would be heating, the floor heating system (which is the main sensible heating terminal) would start the hot water circulation in the loops when the operative temperature drops below 20°C. This resulted in several periods with room temperatures below 20°C.

Vertical air temperature difference between head and ankle levels (1.1 m and 0.1 m above the floor, respectively) at the measurement location was evaluated according to EN ISO 7730 (2005) as an indicator of local thermal discomfort. The average temperature differences with respect to the heating strategy are shown in Table 4 and the temperature difference during the entire heating season may be seen in Figure 4:

Table 4: *Time-averaged vertical air temperature difference between head and ankles*

Case	*FH22*	*FH20*	*FH21*	*FH21-HRPH*	*FH20-HRPH*	*FH21-HR*	*FH20-HR*	*Total, average*
Temperature difference [°C]	0.4	0.4	0.3	0.7	0.9	0.3	0.3	0.5

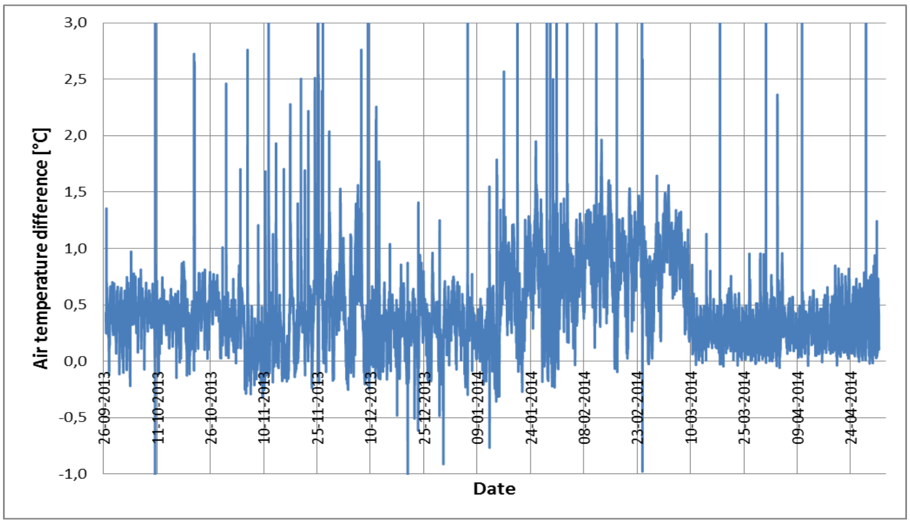

Figure 4. *Vertical air temperature difference between head and ankles during entire heating season*

It may be seen from Table 4 and Figure 4 that the vertical air temperature difference was the highest for the cases where the floor heating was supported with warm air heating by the ventilation system. For each heating strategy and for the overall heating season the average temperature difference is less than 2 K indicating that Category A is met according to EN ISO 7730 (2005) at the measurement location.

The thermal stratification is an inevitable physical phenomenon and it can be used to analyze the indoor environment created by different heating strategies. The thermal stratification is important for occupant thermal comfort (due to local thermal discomfort) and for heat loss from the building (hence energy efficiency). In Table 5, average air temperatures at selected heights are presented based on the heating strategy:

Table 5: *Time-averaged air temperature at the selected heights and the difference between highest and lowest measurement points*

Height/case	*FH22*	*FH20*	*FH21*	*FH21-HRPH*	*FH20-HRPH*	*FH21-HR*	*FH20-HR*	*Total, average*
0.1 m [°C]	21.7	19.2	20.3	19.5	19.5	20.8	20.4	20.4
*1.7 m [°C]**	22.3	19.7	20.7	20.7	20.7	21.2	20.9	21.1
2.2 m [°C]	22.3	19.6	20.6	20.9	21.0	21.1	20.8	21.1
3.7 m [°C]	22.6	20.0	21.0	22.3	22.3	21.5	21.2	21.7
Temperature difference between 3.7 m and 0.1 m [°C]	0.9	0.8	0.8	2.8	2.8	0.7	0.8	1.3

*: For this height, globe temperature was used instead of the air temperature due to a problem with the air temperature sensor.

In Figure 5, air temperature differences (globe temperature is used for 1.7 m) between the selected heights are presented for the entire heating season:

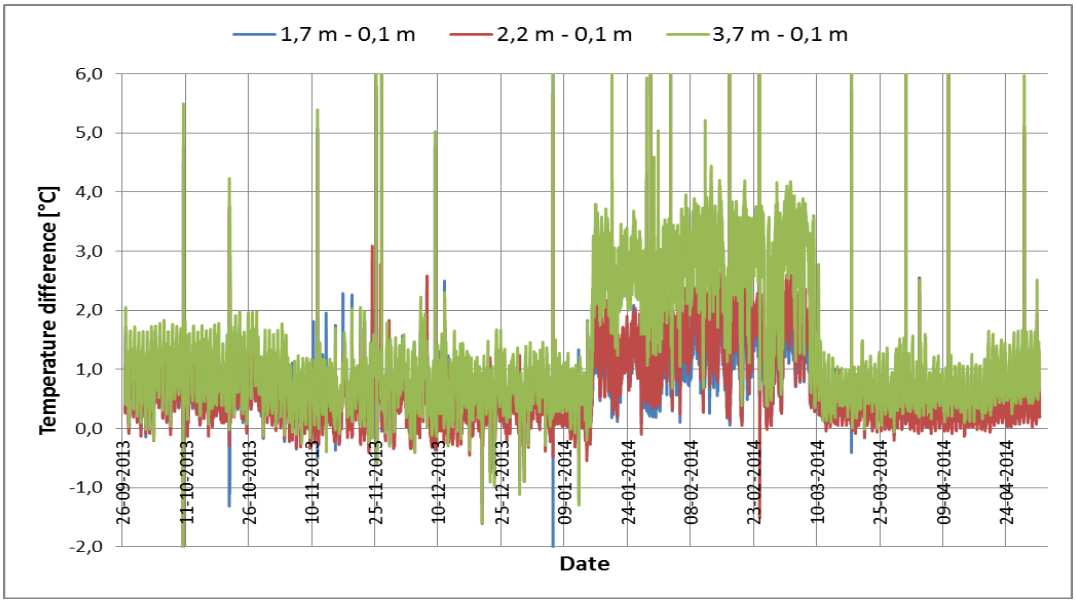

Figure 5. *Air temperature difference between the selected heights*

The results presented in Table 5 and Figure 5 indicate that the thermal stratification inside the house is greatest when the floor heating is supported by warm air heating by the ventilation system. Because of the lower density of the supplied warm air compared to the room air, the supply air tends to flow along the ceiling and not to mix with the room air. Due to this phenomenon and the thermal stratification, in the cases where the floor heating is supported by warm air heating with ventilation, the space above the occupied space is being heated. This increases the heat loss from the indoor space and especially where there are glass façades with lower U-values. Increased thermal stratification is a crucial phenomenon to avoid, especially in a house with a high and tilted ceiling as the present one.

The results presented in this study include the irregularities and disturbances that took place during the experimental duration such as meetings, visitors, door openings, the experimenter going in and out of the house and so forth (for example on 24-02-2014 the doors of the house were opened and closed several times due to door repairs which explains the temperature drop at that date).

In the present paper, operative temperature was used as an indicator of the thermal indoor environment, and vertical air temperature difference between head and ankles was used as an indicator for local thermal discomfort but human thermal comfort depends also on other factors such as humidity, draught and so forth. All of these factors should be considered for a definitive conclusion on the occupant thermal comfort.

6 Conclusion

In the present study, different heating strategies were tested in a one-story, single family, plus-energy house. It was observed that the heating system was able to provide the given set-point inside the occupied space. It was also observed that the heating system struggled to provide the given set-point at relatively low outside temperatures (increased heating demand) and this is because the main heat source of the house was an air-to-brine heat pump with a limited capacity.

No significant difference concerning the temperature difference between the head and ankles were found. Category A of EN ISO 7730 was met for all the heating strategies.

It was aimed in this study to use thermal stratification as an indicator for the performance of the heating strategy regarding the thermal indoor environment and the energy consumption. The greatest thermal stratification (the air temperature difference between 3.7 m and 0.1 m) was obtained when the floor heating was supported with warm air heating by the ventilation system. This meant that the unused space (above the occupied zone) was being conditioned with the supplied warm air. This increases the heat losses and decreases the energy efficiency of the house. Hence in this case a radiant heating system is preferable.

Among the investigated cases, the floor heating with heat recovery on the ventilation is the optimal heating strategy concerning occupant thermal comfort, and thermal stratification (heat loss).

7 Acknowledgements

This study was supported by Elforsk, project number 344-060, titled “Sustainable plus-energy houses”.

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