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## **Effect of Set-point Variation on Thermal Comfort and Energy Use in a Plus-energy Dwelling**

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### **Abstract**

When designing buildings and space conditioning systems, the occupant thermal comfort, health, and productivity are the main criteria to satisfy. However, this should be achieved with the most energy-efficient space conditioning systems (heating, cooling, and ventilation).

Control strategy, set-points, and control dead-bands have a direct effect on the thermal environment in and the energy use of a building.

The thermal environment in and the energy use of a building are associated with the thermal mass of the building and the control strategy, including set-points and control dead-bands. With thermally active building systems (TABS), temperatures are allowed to drift within the comfort zone, while in spaces with air-conditioning, temperatures in a narrower interval typically are aimed at. This behavior of radiant systems provides certain advantages regarding energy use, since the temperatures are allowed to drift, and it also allows the occupants to benefit from adaptive opportunities.

This study presents the results of thermal environment measurements and energy use in a single-family dwelling during a one year period. A radiant floor heating and cooling system was used to condition the indoor space and the operative temperature set-points were varied during the heating and cooling seasons.

The results show that a lower temperature set-point will result in a decreased energy use but it might require the occupants to adapt to slightly lower temperatures in the heating season, and vice versa in the cooling season. The thermal mass of the building have significant effects on the applicability of lowered indoor temperature set-points.

**Keywords:** adaptive opportunity, temperature drift, thermal indoor environment, floor heating and cooling, energy use

### **1 Introduction**

Buildings are complex structures where different components and systems interact with each other. The main task of buildings and the installed mechanical systems (heating, cooling, and ventilation) is to provide a comfortable and healthy indoor environment to the building occupants.

While creating the necessary indoor conditions for human occupancy, other crucial aspects should also be considered: energy efficiency and environmental friendliness. These two principles apply to envelope design, material selection, and also to the choice and design of space conditioning systems.

Recently there have been research efforts regarding the development of low-energy houses, passive houses (The International Passive House Association, 2015) and active houses (The

Active House Alliance, 2015). In several cases, overheating has been reported from low-energy and passive houses (Janson, 2010), (Rohdin et al., 2014), (Holopainen et al., 2015), (Maivel et al., 2015), (Larsen and Jensen, 2011), and the main reasons for overheating have been identified as large glazing areas, poor or lack of solar shading, lack of ventilation (Larsen, 2011), lack of thermal mass, and lack of adequate modeling tools in the design phase (Phillips and Levin, 2015). Other problems such as varying room temperatures (Rohdin et al., 2014), (Holopainen et al., 2015), too low air temperatures in winter, stuffiness and poor air quality, and too low floor surface temperatures in winter (Rohdin et al., 2014) have also been reported in low-energy and passive houses. These results indicate that there is a need for improvement and a need for more data regarding the performance of houses that are designed for low energy use targets.

In order to evaluate the thermal indoor environment and energy performance of different heating and cooling systems, a detached, single-family house, which was designed for plus-energy targets (a house that produces more energy from renewable energy resources than it imports from external resources in a given year, according to the definition given by the European Commission (2009)), was operated for one year under different heating and cooling strategies. During the measurement period, thermal indoor environment and energy performance of the house were thoroughly monitored and recorded.

The main findings are presented considering the achieved thermal indoor environment according to national and international standards and resulting energy use with the different heating and cooling strategies. Improvement suggestions regarding the design and operation of the building and its heating and cooling systems are provided.

## **2. Details of the house**

### **2.1. Construction**

The test house was a single family, detached, one-story house with a floor area of 66.2 m<sup>2</sup> and a conditioned volume of 213 m<sup>3</sup>. The house was constructed from pre-fabricated wooden elements that were made from layers of laminated veneer lumber boards, which in combination with I beams in between formed the structural elements. The house was insulated with a combination of 200 mm mineral wool and 80 mm compressed stone wool fibers. The house was supported on 200-300 mm concrete blocks and the space between the ground and the house's floor structure was covered which created a crawl-space below the house.

Inside the house, there was a single space which combined kitchen, living room and bedroom areas. The technical room was completely insulated from the main indoor space, and had a separate entrance. The glazing façades were partly shaded by the roof overhangs. No solar shading was installed in the house except for the skylight window. All windows had a solar transmission of 0.3. The largest glazing façade was oriented to the North with a 19° turn towards the West. Figure 1 shows the exterior views of the house.



Figure 1. Exterior views of the house, seen from North-West (left) and South-West (right)

The surface areas and thermal properties of the envelope are given in Table 1.

Table 1. Thermal properties of the envelope

	North	South	East	West	Floor	Ceiling
<b>Walls, Area, [m<sup>2</sup>]</b>	-	-	37.2	19.3	66.2	53
<b>Walls, U-value, [W/m<sup>2</sup>K]</b>	-	-	0.09	0.09	0.09	0.09
<b>Windows, Area, [m<sup>2</sup>]</b>	36.7	21.8	-	-	-	0.74
<b>Windows, U-value, [W/m<sup>2</sup>K]</b>	1.04	1.04	-	-	-	1.04

## 2.2. Heating, cooling, and ventilation system

The house was mainly heated and cooled by the hydronic radiant system in the floor using the low temperature heating and high temperature cooling principle. The system was a dry radiant system, consisting of a piping grid installed in the wooden layer. The details of the floor system were: chipboard elements with aluminum heat conducting profiles (thickness 0.3 mm and length 0.17 m), PE-X pipe, 17x2.0 mm. Pipe spacing was 0.2 m. A wooden floor covering was used with a thickness of 14 mm and a thermal conductivity of 0.13 W/mK. The available floor area for the embedded pipe system installation was 45 m<sup>2</sup>. The design flow rates in the heating and cooling modes were 619 kg/h and 336 kg/h, respectively. The flow rates were calculated according to EN 15377-2 (European Committee for Standardization, 2008).

The floor heating and cooling system was coupled to a reversible air-to-brine heat pump. The minimum and maximum cooling capacities and the nominal power input in the cooling mode were 4.01, 7.1, and 2.95 kW, respectively. The minimum and maximum heating capacities and the nominal power input in the heating mode were 4.09, 7.75, and 2.83 kW, respectively.

A flat-plate heat exchanger was installed between the hydronic radiant system of the house and the air-to-brine heat pump. The pipes between the heat exchanger and the heat pump were filled with an anti-freeze mixture (40% ethylene glycol) to avoid frost damage during winter.

A mixing station which linked the radiant system with the heat source and sink, and a controller of the radiant system controlled the flow to each loop, and the supply temperature to the radiant system. The operation of the radiant system was based on the operative temperature set-point that was adjusted on a room thermostat (a matt gray half-

sphere) in 0.5°C intervals and on the relative humidity inside the house to avoid condensation during summer.

The house was ventilated mechanically by an air handling unit (AHU). The mechanical ventilation was only used to provide fresh air into the house since the main sensible heating and cooling terminal of the house was the radiant system. The design ventilation rate was 0.5 ach. The intake air was taken from the crawl-space.

Passive and active heat recovery options were available in the AHU. 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). By-pass was possible. The active heat recovery was achieved 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 of up to 320 m<sup>3</sup>/h at 100 Pa. The two air supply diffusers can be seen on the technical room wall in Figure 2.

Further details of the components and the system can be found in (Kazanci et al., 2014), (Skrupskelis and Kazanci, 2012), and (Kazanci and Olesen, 2014).

### **3. Methods**

During the measurements the house was located in Bjerringbro, Denmark. The thermal indoor environment and energy performance of the house were monitored from 26/9/2013 to 1/10/2014.

#### **3.1 Experimental settings**

The house was unoccupied during the measurement period and heated dummies were used to simulate the occupancy and equipment schedules (internal heat gains). The details of the dummies are given in (Skrupskelis and Kazanci, 2012).

The occupancy and equipment schedules were adjusted with timers. Two dummies were used to simulate occupants (the dummies had the same surface temperatures as a person would have) at 1.2 met (ON from 17 hours to 08 hours on weekdays and from 17 hours to 12 hours on weekends), one dummy (equipment #1, 120 W, 1.8 W/m<sup>2</sup>) was always ON to simulate the house appliances that are always in operation, the fourth dummy (equipment #2, 180 W, 2.7 W/m<sup>2</sup>) was used to simulate the house appliances that are in use only when the occupants are present and the fifth dummy was used to represent additional lights (180 W, 2.7 W/m<sup>2</sup>, ON from 06 hours to 08 hours and from 17 hours to 23 hours until 27<sup>th</sup> of May 2014, and after this date, ON from 20 hours to 23 hours, every day). The house had ceiling mounted lights ON from 21 hours to 23 hours, every day (140 W, 2.1 W/m<sup>2</sup>). Additionally, there was a data logger and a computer (80 W, 1.2 W/m<sup>2</sup>), and a fridge (30 W, 0.4 W/m<sup>2</sup>) which were always ON.

#### **3.2 Measurements and measuring equipment**

The air and globe temperatures were measured at 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 heights, at a central location in the occupied zone following EN 13779 (European Committee for Standardization, 2007).

The globe temperatures were measured with a gray globe sensor, 40 mm in diameter. This sensor has the same relative influence of air- and mean radiant temperature as on a person (Simone et al., 2007) and, thus, at 0.6 m and 1.1 m heights will represent the operative temperature of a sedentary or a standing person, respectively. The air temperature sensor was shielded by a metal cylinder to avoid heat exchange by radiation. Both the globe and air

temperature sensors have  $\pm 0.3^\circ\text{C}$  accuracy in the measurement range of 10-40°C (Simone et al., 2013). The output from the sensors was logged by a portable data logger.

Figure 2 shows a panoramic view of the interior of the house, the measurement location and the sensors used for the measurements.

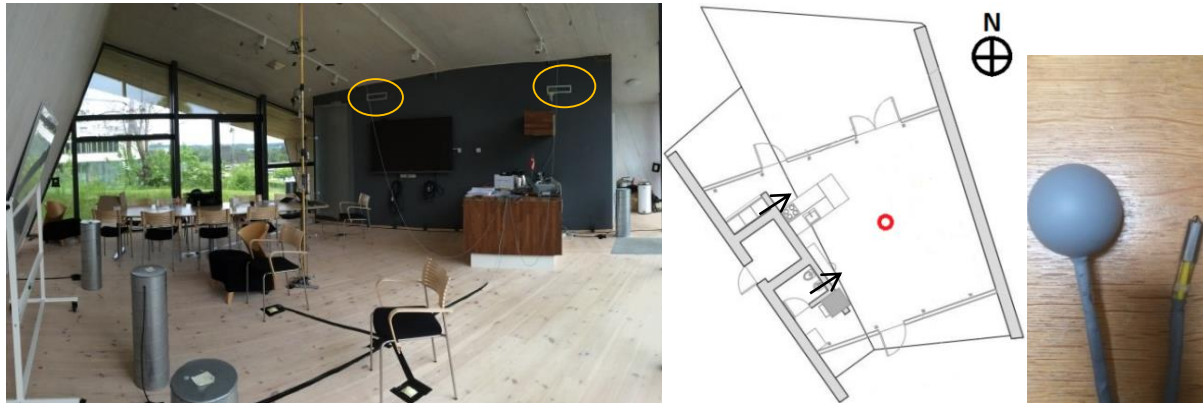


Figure 2. Panoramic view of the interior (left), the measurement location (middle) and the globe and air temperature sensors (right)

The energy consumptions of the air-to-brine heat pump, mixing station, and the controller of the radiant system were measured with wattmeters. The energy consumption of the AHU was measured through a branch circuit power meter (BCPM). The wattmeters that were used to measure the consumption of the mixing station and the controller of the radiant system had an accuracy of  $\pm 2\% \pm 2 \text{ W}$ . The wattmeter that was used to measure the consumption of the air-to-brine heat pump had an accuracy of 3%. The BCPM's accuracy was 3% of the reading.

A full specification of the parameters measured and the measuring equipment can be found in (Kazanci and Olesen, 2014).

#### 4. Experimental operation of the heating, cooling, and ventilation system

For the first part of the experiments in the heating season, floor heating was operated without any ventilation, with different operative temperature set-points. In the second part, floor heating was supplemented by warm air heating from the ventilation system, and during the last part of the heating season, floor heating was operated with passive heat recovery from the exhaust air. The design ventilation rate was 0.5 ach.

Table 2 shows the most important boundary conditions for these strategies in the heating season (FH: floor heating, HR: heat recovery, HRPH: heat recovery and pre-heating).

Table 2. Periods and experimental settings of the different cases, heating season

<i>Period</i>	<i>Average external air temperature [°C]</i>	<i>Floor heating set-point [°C]</i>	<i>Ventilation</i>	<i>Case abbreviation</i>
26 <sup>th</sup> of Sep to 21 <sup>st</sup> of Nov	8.2	22	Off	FH22
21 <sup>st</sup> of Nov to 18 <sup>th</sup> of Dec	4.0	20	Off	FH20
18 <sup>th</sup> of Dec to 16 <sup>th</sup> of Jan	4.6	21	Off	FH21
16 <sup>th</sup> of Jan to 10 <sup>th</sup> of Feb	0.0	21	On, heat recovery and pre-heating**	FH21-HRPH
10 <sup>th</sup> of Feb to 10 <sup>th</sup> of Mar	5.0	20	On, heat recovery and pre-heating**	FH20-HRPH

10 <sup>th</sup> of Mar to 3 <sup>rd</sup> of Apr	5.5	21	On, heat recovery	FH21-HR
3 <sup>rd</sup> of Apr to 1 <sup>st</sup> of May*	9.0	20	On, heat recovery	FH20-HR

\*: The dummies simulating the occupants and a dummy (equipment #2) were OFF during this experimental period.

\*\* : Heat recovery refers to the passive heat recovery and pre-heating refers to the active heat recovery in AHU. The supply air temperature was between 30 to 34°C, except for the periods with low outside air temperatures when it dropped to 27°C.

The operation of the HVAC system followed a similar approach during the cooling season. The house was cooled by floor cooling and was ventilated with the mechanical ventilation system with passive heat recovery from the exhaust airflow (by-pass was possible). Different operative temperature set-points and different ventilation rates were tested. Internal solar shading covering 20 m<sup>2</sup> (manually operated) was installed on the North façade on 30/07/2014 and it was used in the fully down position until the end of the experiments.

Table 3 shows the most important boundary conditions for the strategies used in the cooling season (FH: floor heating, CS: cooling season, FC: floor cooling, HV: higher ventilation rate, S: solar shading).

Table 3. Periods and experimental settings of the different cases, cooling season

<i>Period</i>	<i>Average external air temperature [°C]</i>	<i>Floor cooling set-point [°C]</i>	<i>Ventilation type and ventilation rate</i>	<i>Solar shading</i>	<i>Case abbreviation</i>
1 <sup>st</sup> of May to 27 <sup>th</sup> of May*	14.7	20**	Heat recovery, 0.5 ach	No	FH20-CS
27 <sup>th</sup> of May to 19 <sup>th</sup> of June	18.7	25	Heat recovery, 0.5 ach	No	FC25
19 <sup>th</sup> of June to 13 <sup>th</sup> of July	18.7	25	Heat recovery, 0.8 ach	No	FC25-HV
13 <sup>th</sup> of July to 30 <sup>th</sup> of July	22.7	24	Heat recovery, 0.8 ach	No	FC24-HV
30 <sup>th</sup> of July to 21 <sup>st</sup> of Aug	18.1	24	Heat recovery, 0.8 ach	Yes	FC24-HV-S
21 <sup>st</sup> of Aug to 1 <sup>st</sup> of Oct	16.0	24	Heat recovery, 0.5 ach	Yes	FC24-S

\*: The dummies simulating the occupants and a dummy (equipment #2) were OFF during this experimental period. \*\*: Floor system was in heating mode, transition period. \*\*\*: The house was not cooled from 20/06/2014 to 23/06/2014 to allow repairs to be made to the HVAC system.

## 5. Results and discussion

### 5.1 Heating season

The performance of different heating strategies was evaluated based on the indoor environment category achieved according to EN 15251 (European Committee for Standardization, 2007). The following categories are given according to EN 15251 (European Committee for Standardization, 2007) for sedentary activity (1.2 met) and clothing of 1.0 clo. Table 4 shows the indoor environment categories achieved for different heating strategies and during the entire heating season.

Table 4. The category of indoor environment based on operative temperature at 0.6 m height, heating season

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

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

Figure 3 shows the operative temperature at 0.6 m height and the external air temperature during the heating season.

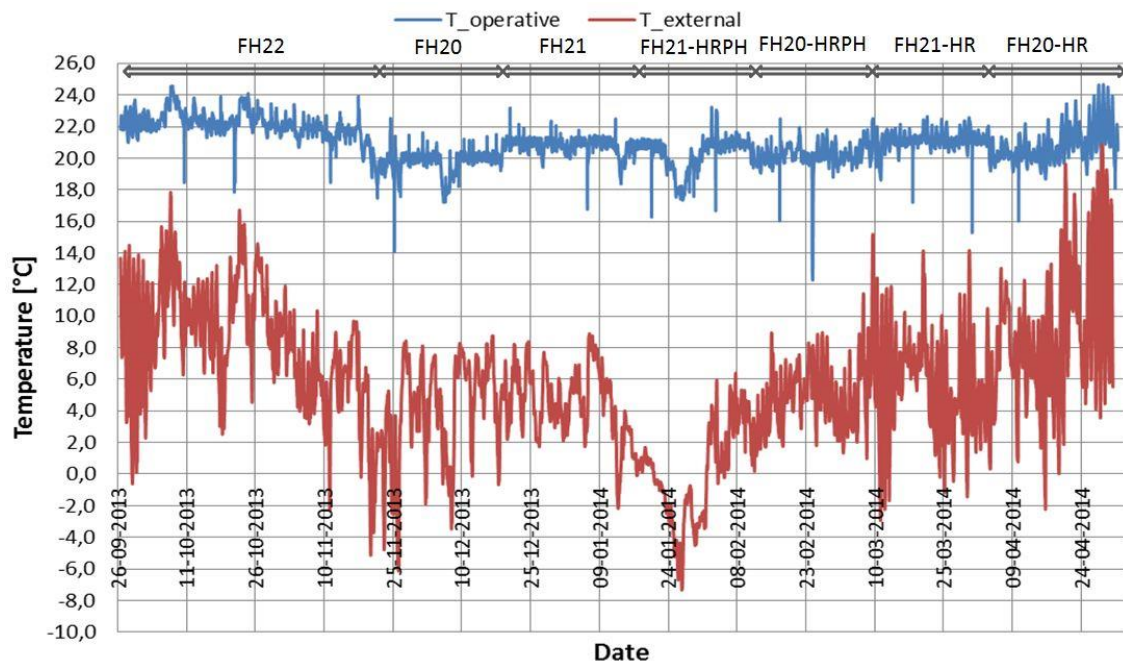


Figure 3. Operative temperature and external air temperature during the heating season

The results show 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 (European Committee for Standardization, 2007). It may also be seen that there were periods when the indoor environment was outside Category 3: for 2% of the time it was in Category 4.

It was possible to keep the indoor operative temperature close to the set-point, although the systems struggled to achieve this when the outside temperatures were below  $-5^{\circ}\text{C}$ . In addition to the increased heating demand, one possible explanation for this is that both the air-to-brine heat pump and the AHU were affected by the lower outside air temperatures.

The operative temperature set-point of  $20^{\circ}\text{C}$  proved to be too low. This is because even though the ventilation system would be heating the indoor space, the floor heating system did not start the water circulation in the loops until the operative temperature had dropped below  $20^{\circ}\text{C}$ . This resulted in several periods with room temperatures below  $20^{\circ}\text{C}$ .

## 5.2 Cooling season

The performance of different cooling strategies was evaluated based on the indoor environment categories given in EN 15251 (European Committee for Standardization, 2007) for sedentary activity (1.2 met) and clothing of 0.5 clo. In addition, the hours above  $26^{\circ}\text{C}$ ,  $27^{\circ}\text{C}$  and  $28^{\circ}\text{C}$  were calculated following DS 469 (Danish Standards, 2013) and following the most recent building code in Denmark, Bygningsreglement 2015 – BR15 (The Danish Ministry of Economic and Business Affairs, 2015).

According to DS 469 (Danish Standards, 2013),  $26^{\circ}\text{C}$  should not be exceeded for longer than 100 hours during the occupied period and  $27^{\circ}\text{C}$  should not be exceeded for longer than 25 hours. Even though these specifications are given for offices, meeting rooms, and shops, it is considered to be applicable also for residential buildings. It should be noted that according



to DS 469 (Danish Standards, 2013), mechanical cooling would normally not be installed in residential buildings in Denmark.

Denmark is one of the first countries to include the adaptive thermal comfort approach in its building code. In the most recent building code in Denmark, Bygningsreglement 2015 – BR15 (The Danish Ministry of Economic and Business Affairs, 2015), the temperatures given in DS 469 (Danish Standards, 2013) have been increased by 1°C, which now states that in residential buildings, 27°C should not be exceeded for longer than 100 hours during the occupied period and 28°C should not be exceeded for longer than 25 hours. The reasoning behind this is that it is possible to open windows and create air flow in residential buildings (The Danish Ministry of Economic and Business Affairs, 2015).

The indoor environment categories achieved, and the hours above 26°C, 27°C and 28°C as a function of the cooling strategy are given in Table 5, and the operative temperature and external air temperature during the cooling season are given in Figure 4.

Table 5. The category of indoor environment based on operative temperature at 0.6 m height, cooling season

<i>Indoor environment category/case</i>	<i>FH20-CS</i>	<i>FC25</i>	<i>FC25-HV</i>	<i>FC24-HV</i>	<i>FC24-HV-S</i>	<i>FC24-S</i>	<i>Total, average</i>
<b>Category 1 (23.5-25.5°C)</b>	52%	56%	36%	54%	39%	22%	41%
<b>Category 2 (23.0-26.0°C)</b>	73%	72%	49%	72%	58%	36%	57%
<b>Category 3 (22.0-27.0°C)</b>	87%	87%	75%	91%	84%	72%	81%
<b>Category 4</b>	13%	13%	25%	9%	16%	28%	19%
<b>Hours above 26°C</b>	48	129	79	87	7	0	350*
<b>Hours above 27°C</b>	19	71	38	34	0	0	162*
<b>Hours above 28°C</b>	6	35	19	13	0	0	73*

\*: Although the overheating hours cannot be directly added for the different cooling strategies, their total is given to indicate the duration of overheating during the cooling season.

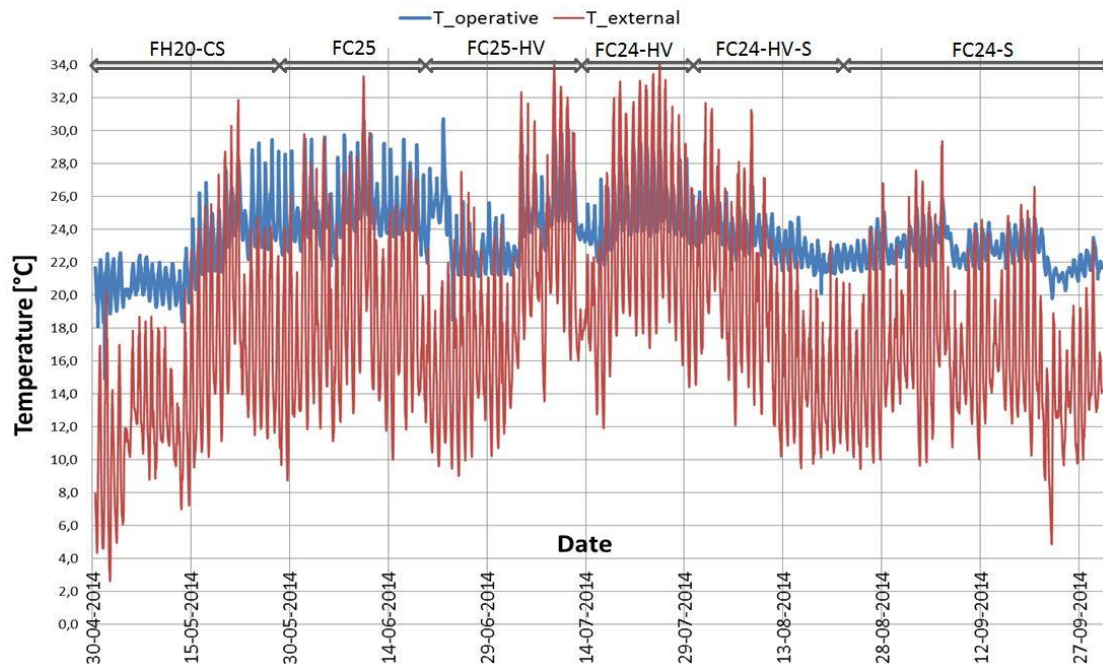


Figure 4. Operative temperature and external air temperature during the cooling season

The house performed worse in the cooling season than in the heating season; for 57% of the time the operative temperature was in Category 2 and for 19% of the time it was outside the recommended categories in EN 15251 (European Committee for Standardization, 2007). This occurred mainly in the transition periods (i.e. May and September) and due to overheating, which was a problem during the cooling season, except in August and September. The hours above 26°C and 27°C exceeded the values recommended in DS 469 (Danish Standards, 2013) and the hours above 27°C and 28°C exceeded the values recommended in BR15 (The Danish Ministry of Economic and Business Affairs, 2015).

Decreasing the operative temperature set-point and increasing the ventilation rate helped to address the increased cooling load, but with a higher energy consumption. This is mainly due to the longer operation of the floor cooling and to increased cooling of the supply air.

The results show that even though the floor system was in heating mode during most of May (transition period), floor cooling could have been activated in the second half of May, which would have reduced the overheating hours and improved the indoor environment.

Cooling demand of the house was high and the most significant problems were the large glazing façades including the lack of solar shading and the lack of thermal mass to buffer sudden thermal loads. In the current location of the house, direct solar radiation from the South façade was not a problem, because of the orientation and longer overhang on the South façade. Most of the overheating hours were in the late afternoon (i.e. from 18:00 hours until sunset), when there was direct solar gain through the North façade.

### 5.3 Energy performance

The HVAC system's energy use included the air-to-brine heat pump, mixing station, controller of the radiant system, and the AHU. The energy use of individual components can be found in (Kazanci and Olesen, 2016) and in (Kazanci and Olesen, 2014).

Heating degree days (HDD) and cooling degree days (CDD) were calculated for each case using a base temperature of 17°C and 23°C, respectively. Table 6 shows the average energy use per day and heating or cooling degree days per day, following the methodology described by (Quayle and Diaz, 1980), for each heating and cooling strategy.

Table 6. Energy use of the HVAC system

<i>Case</i>	<i>HDD</i>	<i>CDD</i>	<i>Total [kWh]</i>	<i>Total, average [kWh/day]</i>	<i>HDD/day or CDD/day</i>
<b>FH22</b>	496	-	539.7	9.5	8.7
<b>FH20</b>	350	-	453.4	16.8	13.0
<b>FH21</b>	361	-	480.6	16.6	12.5
<b>FH21-HRPH</b>	425	-	713.7	28.5	17.0
<b>FH20-HRPH</b>	337	-	531.4	18.9	12.0
<b>FH21-HR</b>	275	-	370.7	15.4	11.4
<b>FH20-HR</b>	220	-	358.0	12.8	7.9
<b>FH20-CS</b>	97	-	250.7	9.3	3.6
<b>FC25</b>	-	15	138.7	6.0	0.7
<b>FC25-HV</b>	-	20	189.8	9.0	1.0
<b>FC24-HV</b>	-	36	184.3	10.8	2.1
<b>FC24-HV-S</b>	-	12	189.3	8.6	0.5
<b>FC24-S</b>	-	6	212.4	5.3	0.1

The results show that the energy consumption increased markedly when the warm air heating (FH21-HRPH and FH20-HRPH) was in operation, and these strategies struggled to provide the intended thermal indoor environment despite the increased energy consumption. The energy consumption during the cases FH20 and FH21 were close to each other, but a more satisfactory thermal indoor environment was achieved with FH21. The last two cases in the heating season, FH21-HR and FH20-HR, have lower energy consumption and achieved a more satisfactory thermal indoor environment compared to the cases with the same set-points without ventilation (FH21 and FH20). The FH22 strategy had the lowest energy consumption (although it had the highest operative temperature set-point) and the best thermal indoor environment, although this was partly due to the relatively high external air temperatures during this period.

During the cooling season, the increased ventilation rate and lowered operative temperature set-point increased the energy consumption. This was expected, due to higher power input to the fans in the AHU and longer operation time of the pump in the floor cooling system. The increased energy consumption contributes to a more comfortable thermal indoor environment, but other strategies should be employed to reduce the cooling demand by means of energy efficient measures (e.g. lower ventilation rates when the house is unoccupied, natural ventilation when the outside conditions are suitable, decreased glazing area, solar shading, a better orientation of the house and so forth). The effects of different building and HVAC system improvements on the energy consumption and thermal indoor environment were parametrically studied and reported by (Andersen et al., 2014).

Throughout the 12-month operation of the house, the heating and cooling systems were active with respective set-points also during the transition periods (i.e. May and September) but it is not practical to provide constant heating or cooling during the transition periods, therefore the heating and cooling system operation and the switchover between these modes require careful consideration. Operation of the systems needs to be improved to avoid unnecessary heating and cooling in the transition periods.

Previous studies (Kazanci et al., 2014), (Skrupskelis and Kazanci, 2012), and (Andersen et al., 2014) showed that the large glazing façades (including the lack of solar shading) of the house resulted in a high heating and cooling demand and this drastically decreased the energy performance of the house. This was confirmed by the experiments; the currently installed heating and cooling systems of the house struggled to achieve a comfortable thermal indoor environment during the cold periods in winter and overheating was a significant problem during the cooling season.

The results show that the house would have benefited from a higher thermal mass to buffer the sudden thermal loads, especially during the periods in cooling season when there was direct solar gain and during the transition periods. This confirms a previous simulation study (Andersen et al., 2014) which showed that the house would benefit from increased thermal mass, in terms of energy performance and thermal indoor environment.

During the measurements, natural ventilation was not implemented. If occupants were living in the house, it is likely that they would have taken certain actions to make themselves comfortable during the overheating periods or during the periods with low indoor temperatures. Some of these examples could have been adjusting the clothing, opening windows, etc. The effects of natural ventilation on indoor thermal environment and energy use were simulated using commercially available simulation software, IDA ICE, in previous

studies (Andersen and Schøtt, 2014), (Andersen et al., 2014). The results of these studies showed that the implementation of natural ventilation with a set-point of 24°C, slightly improved the thermal comfort indoors (3% longer in Category 1 according to EN 15251 (European Committee for Standardization, 2007)) and considerably decreased the cooling energy use (51% compared to the no natural ventilation case).

## **6. Conclusion**

A detached, one-story, single family house designed for plus-energy performance was operated for one year. During this period different heating and cooling strategies were compared and the energy performance of the house and its thermal indoor environment were monitored. The main conclusions are as follows.

During the heating season, it was possible to provide the intended operative temperature inside the occupied zone except during periods when the external air temperatures were below -5°C.

The performance of the house in terms of maintaining a comfortable thermal indoor environment was worse in the cooling season than in the heating season. Overheating was a significant problem, and the main reasons for this were the large glazing façades, the orientation of the house, the lack of solar shading, and the lack of sufficient thermal mass to buffer the sudden thermal loads.

The house had a high heating and cooling demand that could easily have been reduced at the design phase. Although, it might be possible to address the excessive heating and cooling loads by adjusting set-points, water and air flow rates, these would result in increased energy use, as in the present study. It is crucial to minimize the demand before attempting to satisfy it in the most energy efficient way.

The operation of the heating and cooling system during the transition periods was problematic and this affected the thermal indoor environment and energy performance negatively. Further studies are required to optimize the thermal indoor environment and operation of the heating and cooling system during the transition periods.

The lower indoor temperatures in winter and higher temperatures in summer require the occupants to adapt and to use certain adaptive measures to make themselves comfortable. This also applies to the transition periods, where there might not be a dominant heating or cooling load on a daily or even hourly basis. In such situations, the adaptive actions of the occupants would play a crucial role in the thermal comfort and also in the operation of the heating and cooling systems, and, hence, on the annual energy performance of the building.

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