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Energy Performance of Water-based and Air-based Cooling Systems in Plus-energy Housing

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Abstract

Energy use in buildings accounts for a large part of the energy use globally and as a result of this, international building energy performance directives are becoming stricter. This trend has led to the development of zero-energy and plus-energy buildings. Some of these developments have led to certain issues regarding thermal indoor environments, such as overheating.

Thermal comfort of occupants should not be sacrificed for energy efficiency but rather, these should be achieved simultaneously. Although the priority should be to minimize the cooling demand during the design, this is not always achieved and cooling might be needed even in residential buildings.

This paper focuses on the cooling operation of a detached, single-family house, which was designed as a plus-energy house in Denmark. The simulation model of the house was created in IDA ICE and it was validated with measurement data in a previous study. The effects of the cooling demand (internal vs. external solar shading), the space cooling method (floor cooling vs. air-cooling with ventilation system), and the availability of a nearby natural heat sink (intake air for the ventilation system being outdoor air vs. air from the crawl-space, and air-to-water heat pump vs. ground heat exchanger as cooling source) on the system energy performance were investigated while achieving the same thermal indoor conditions.

The results show that the water-based floor cooling system performed better than the air-based cooling system in terms of energy performance and also regarding the energy use of auxiliary components such as pumps and fans. The total reduction in primary energy used was 31% compared to the air-based systems with intake air from outdoors.

The integration of natural heat sinks into the cooling system of the house results in significant energy use reductions. The coupling of radiant floor with the ground enables to obtain "free" cooling, although the brine pump power should be kept to a minimum to fully take advantage of this solution. By implementing a ground heat exchanger instead of the heat pump and use the crawl-space air as intake air an improvement of 37% was achieved.

The cooling demand should be minimized in the design phase as a priority and then the resulting cooling load should be addressed with the most energy efficient cooling strategy. The floor cooling coupled with a ground heat exchanger was shown to be an effective means to minimize the energy use for cooling purposes, and this can contribute to achieving zero-energy or plus-energy targets in future buildings.

1. Introduction

As the requirements for energy use in buildings are tightening, the focus on development of low-energy buildings, zero-energy buildings etc. is increasing. The thermal properties of the building envelopes have improved so much that it leads to undesired overheating in many buildings if no precautions are taken.

A method to avoid overheating is by installing mechanical cooling systems in buildings. Several systems have been developed and different studies have investigated the thermal indoor environment and energy use of these systems [1]–[3].

This study focuses on the investigation of the thermal indoor environment and energy use of different cooling systems by using dynamic building simulation models. The analyzed cooling systems are defined in detail in [4].The investigated house 'Fold' was constructed for an international competition, Solar Decathlon Europe 2012, by the Technical University of Denmark. The house is a single-family, one storey house with a floor area of 66 m^2 and an internal volume of 213 m^3. The house has two large glazing facades facing North (36.7 m^2) and South (21.8 m^2) with a 19° turn to the West.

Further details of the studied house can be found in [5], [6].

Figure 1 shows the exterior views of the house.

Figure 1 – South façade (left) and North façade (right) of Fold

2. Method

A dynamic building simulation model was created in IDA ICE with the purpose of validating the results from the dynamic simulation model with actual measurements from the house. Temperature measurements and measurements of energy use for different components of the house were used in the validation of the model [7]–[9].
The model was constructed with internal gains for two occupants (1.2 met), lighting (180 W), and equipment corresponding to normal housing equipment (380 W). The occupants, lighting, and equipment were controlled after a predefined occupancy schedule given in Table 1.

Table 1 – Schedule for internal gains

	Power output	Schedule [On]
Equipment 1 + PC	120 W + 80 W	Always
Equipment 2	180 W	Weekdays: 17-08, Weekends: 17-12
2 occupants	1.2 Met per occ.	Weekdays: 17-08, Weekends: 17-12
Lighting	180 W	06-08 and 17-23

The design idea for 'Fold' was to control the ventilation system by the CO_2 concentration and have the radiant heating and cooling systems installed in the floor control the thermal conditions in the house.

The HVAC system used a reversible air-to-brine heat pump for the radiant systems as a heat source and sink, and an air handling unit with active and passive heat recovery provided the necessary fresh air. The cooling systems was given a set point of 26°C and was controlled according to the operative temperature.

In order to get a validated model, a weather file was constructed from a combination of measurements taken at the site and supplemented with measurements from a nearby weather station [10]. The temperatures and energy use for certain system parts were then compared to actual measurements from the building to validate and improve the precision of the simulation model.

In this study, alterations were made to the validated IDA ICE model for the current investigations. The HVAC plant was replaced with a system consisting of two 100 L water tanks, one for hot water and one for cold water. The hot water tank was not used in this investigation but had to be included for the simulation model to function. The cold water tank was cooled by a reversible air-to-water heat pump. The cold water tank supplied the required cooling for the cooling coil in the air handling unit or for the floor cooling system depending on the case.

The investigated parameters were: two different types of shading (internal vs. external shading), variation of supply temperatures for air-cooling, air-cooling vs. floor cooling and the effect of implementation of nearby heat sinks; intake air from outdoors vs. intake air from the crawl-space beneath the house, and having the floor cooling system coupled to a ground heat exchanger.

The effect of shading factors was investigated by making simulations with internal shading and external shading respectively. The shading factor was set to 0.6 for the internal shading and to 0.1 for the external shading. The shading was controlled by the solar gain through the windows and the shading was activated when the solar gain exceeded a value of 50 W/m^2 window area.

Three different cases of supply temperatures for air-cooling were investigated with external shading implemented. The investigated supply temperatures were 14°C, 17°C and 20°C. The case with a supply temperature of 14°C was also investigated with the intake air taken from the crawl-space instead of outdoor air. Figure 2 shows the outdoor air temperatures and the air temperatures in the crawl-space.
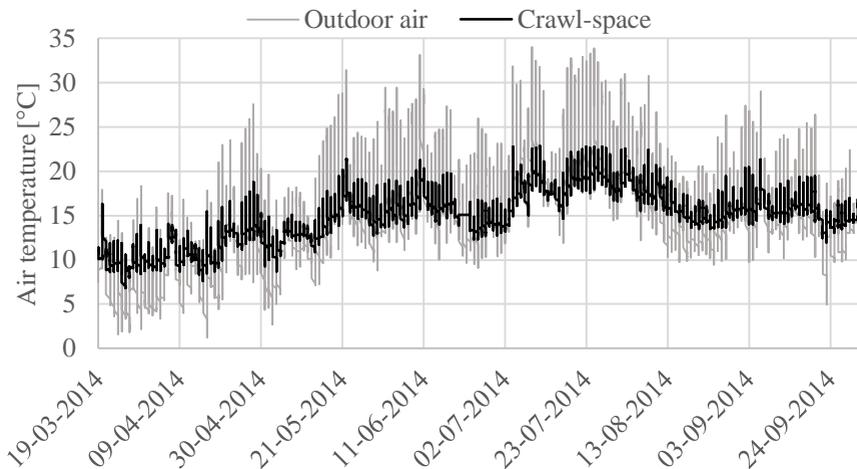
Figure 2 – Outdoor and crawl-space temperatures

The crawl-space acted as a buffer zone where the air temperature was lower compared to the outdoor air temperature in the cooling season and vice versa in the heating season.

Finally, three different cases of floor cooling were investigated. All floor systems had the same thermal properties as the one in the validated IDA ICE model. The first case used the outdoor air as intake air, the second case used the air from the crawl-space, and the third case also utilized the air from the crawl-space. Furthermore, in Case 8 the heat pump for the radiant system was replaced with a ground heat exchanger, thereby fully utilizing the available heat sinks.

Eight different cases were investigated in total. An overview of the differences is given in Table 2.

Table 2 – Case description [4]

Case	Shading	Cooling	Source	Intake air
1	Internal	AC	AWHP	OA
2	External	AC	AWHP	OA
3	External	AC	AWHP	OA
4	External	AC	AWHP	OA
5	External	AC	AWHP	CS
6	External	FC	AWHP	OA
7	External	FC	AWHP	CS
8	External	FC	GHEX	CS

AC – Air-cooling   GHEX – Ground heat exchanger
FC – Floor cooling   OA – Outdoor air
AWHP – Air-to-water heat pump CS – Crawl-space

For Cases 2, 3 and 4 different supply air temperatures were used: 14°C, 17°C and 20°C, respectively. In Case 1 and 5 a supply temperature of 14°C was used. The simulation period was from 1st of May to 30th of September.

The control of the HVAC system was regulated by the operative temperature. The control by operative temperature was chosen in order to keep the same indoor conditions for all cases to evaluate the energy performance of the different systems.

The cooling cases are described in full detail in [4].

3. Results

The duration curve of the operative temperatures is given in Figure 3. The figure shows how the temperatures were distributed in the investigated period from 1st of May to 30th of September.
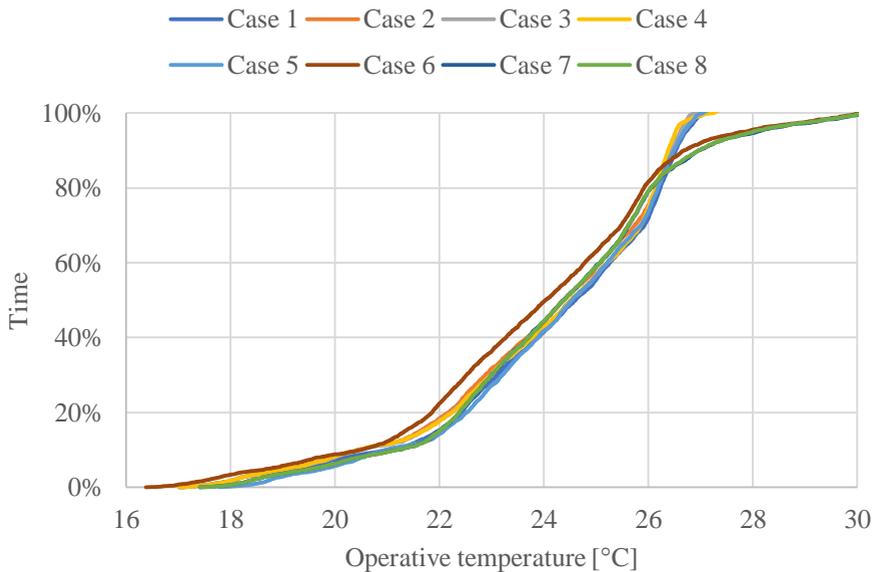

Figure 3 – Duration curves from simulations

Figure 3 shows that the temperatures for all simulations follow a similar pattern. However, there is a slight difference between the radiant and air-based cooling systems. The radiant cooling systems have warmer peak temperatures compared to the air-cooling

cases. The duration above 26°C was in contrary found to be lower for the radiant systems compared to the air-cooling cases.

The thermal indoor environment was assessed with the use of standard values for temperature ranges given in EN 15251 [11], Table 3. The distribution can be seen in Figure 4.

Table 3 - Temperature range for cooling [11]

Category	Temperature range for cooling (Clothing – 0.5 Clo)
I	23.5 – 25.5°C
II	23.0 – 26.0°C
III	22.0 – 27.0°C

■ I ■ II ■ III ■ Outside

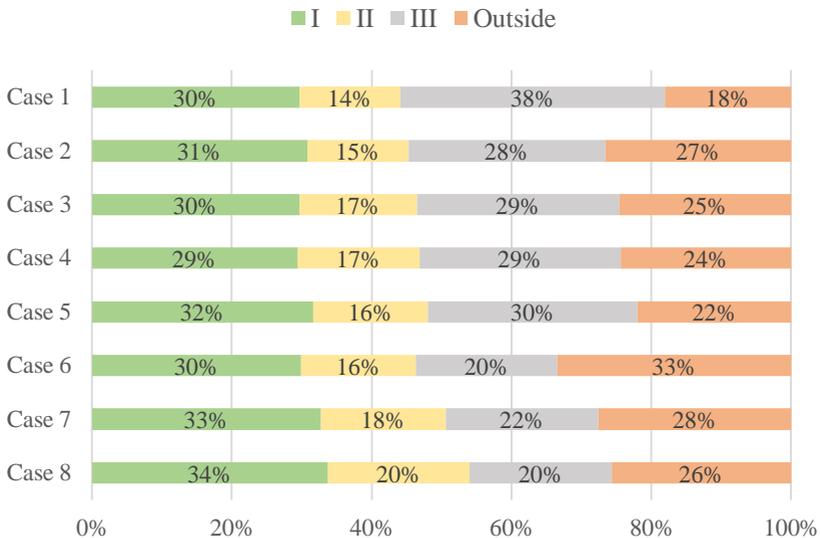| Case	I	II	III	Outside
Case 1	30%	14%	38%	18%
Case 2	31%	15%	28%	27%
Case 3	30%	17%	29%	25%
Case 4	29%	17%	29%	24%
Case 5	32%	16%	30%	22%
Case 6	30%	16%	20%	33%
Case 7	33%	18%	22%	28%
Case 8	34%	20%	20%	26%

Figure 4 – Distribution of time in indoor environment categories

Figure 4 shows a similar trend to Figure 3. In general, the air systems are able to change the indoor conditions more rapidly due to the supply of cold air directly into the indoors, whereas the floor systems require longer time to change the thermal indoor environment, although the radiant system itself reacts immediately to the changes in the indoor environment.

The primary energy used for all simulated cases are shown in Table 4. The electric cooling corresponds to the primary energy use of the reversible air-to-water heat pump

working in cooling mode and the brine pump in the ground loop for Case 8. The primary auxiliary energy use covers the air handling unit and pumps for the floor systems.

The primary energy factor was 2.5 according the Danish Building Code [12].

Table 4 – Primary energy use (1st of May to 30th of September)

	Electric cooling [kWh]	HVAC aux [kWh]	Total [kWh]
Case 1	765	524	1289
Case 4	472	671	1143
Case 2	591	442	1032
Case 3	515	516	1031
Case 5	475	445	920
Case 6	318	415	733
Case 7	277	416	693
Case 8	51	413	464

There is a clear distinction between the energy use of the radiant systems compared to air-based cooling systems with the solar gains. The radiant cooling system (Case 6) was found to have an average total energy use 31% lower than the air-based systems (Case 2-4) when outdoor air was used as the intake. With the crawl-space air as intake the radiant system (Case 7) had a reduced energy use of 25 % compared to the air-based system (Case 5).

4. Discussion

The results in Figure 3 and Figure 4, show that all systems performed comparably with regard to the thermal indoor environment. The radiant systems had higher peak temperatures as shown in Table 5.

Table 5 - Maximum temperatures for each case (1st of May to 30th of September)

Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
27.2°C	27.1°C	27.0°C	27.3°C	27.0°C	30.4°C	30.5°C	30.4°C

The main reason for the difference was that the radiant systems cannot affect the thermal indoor environment as fast as the air-based systems. The tendency is shown in Figure 5, where the operative temperature for Case 3 (air-based system) and Case 7 (water-based radiant system) are plotted together with the solar gain and outdoor temperature for a hot summer day.
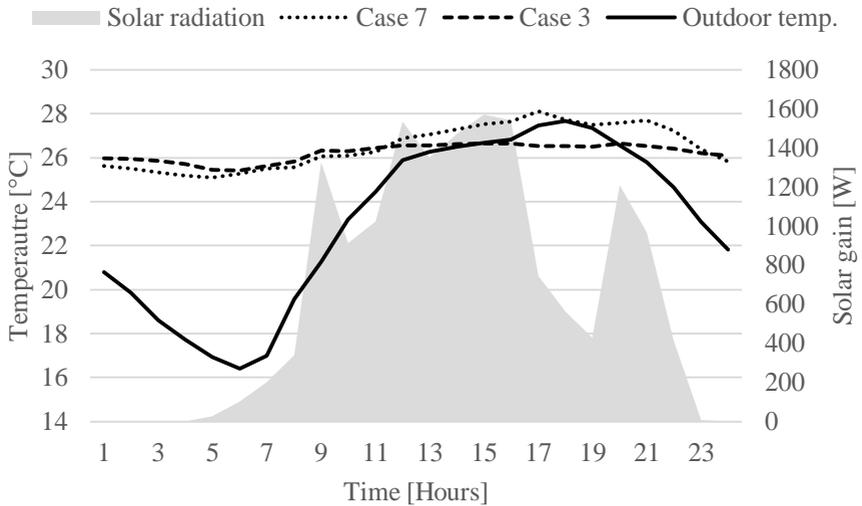
Figure 5 – Temperatures during a hot summer day

Figure 5 clearly illustrates that the air-based system is able to quickly adapt to the step changes by increasing the air change and keeping a constant operative temperature. The radiant system was slower to change the conditions resulting in higher peak temperatures. However, it should be noted that the radiant system reacts immediately to the changes in the indoor conditions due to its surface temperature. The performance of the radiant system in order to address this issue could be improved with a different control strategy.

It was a necessary condition that the thermal indoor environment was comparable in order to conduct a reasonable comparison of the energy use of the different setups.

The results show that there was a great difference in energy use for the radiant systems and air-based systems. The main difference occurred in the energy use for electric cooling. Furthermore, there was also associated a difference in auxiliary energy use. The reduction in total primary energy use from Case 2 to Case 6 was 299 kWh corresponding to 29%. The radiant systems were determined to be more energy efficient while still maintaining a similar indoor environment to the air-based systems.

The air-based systems had a large energy use for the fans in order to continuously sustain the set point especially at higher supply air temperatures. This point was underlined when comparing the two air-based cases, Case 2 and 4. Case 2 with the lower supply temperature had a total energy use that was 10% lower even though they had the same cooling demand. Case 2 used 119 kWh (20%) more primary energy for cooling of the air. However, this was offset with the energy use for auxiliary equipment which was 229 kWh (34%) less.

The results show that it was beneficial to use external solar shading compared to internal shading. By reducing the solar gains, the energy use was reduced by 20%.

The influence of natural heat sinks was also investigated. The investigation of the intake air for the AHU showed that there is a potential to lower the energy use for cooling. Case 2 and Case 5 have the same supply temperature but Case 5 utilizes the colder air temperatures in the crawl-space. Case 5 had an electric energy use of 116 kWh (20%) lower than Case 2. The main difference was the energy use for the cooling coil in the AHU as the auxiliary energy use was within 1% of each other.

The simulations showed that it was beneficial to have a floor cooling system coupled to a ground heat exchanger. Case 7 and Case 8 have the same supply water temperature but the only difference was that Case 8 utilizes a ground heat exchanger. Case 8 had 33% lower energy use compared to Case 7. When both of the investigated heat sinks were implemented (Case 8) the total energy use was lowered with 37% and the energy use for electric cooling with 84% compared to Case 6 with no heat sinks. There is, of course, associated with a large installation cost with the implementation of the borehole. However, it also provides a great possibility to lower the energy use in detached residential houses.

The simulation model has been validated with on-site measurements. However, the simulation models are not perfect and even though the original model was validated, assumptions were made in this study to simulate the different systems. For instance, two water tanks of 100 L each were implemented due to limitations in the software. The assumptions could have affected the outcome of the investigation.

5. Conclusion

The energy performances of different space cooling systems with similar thermal indoor environments were compared using dynamic building simulations, using a single-family house as a case study.

The investigation found that it was beneficial to lower the cooling demand by means of external solar shading compared to internal solar shading. It was concluded that the air-based systems have the ability to affect the conditions for the thermal indoor environment more rapidly compared to the radiant systems. In contrary, the water-based radiant systems were found to be the more energy efficient cooling systems as they have a lower energy use for electric cooling as well as auxiliary energy with a total energy saving of 31% with intake air from outdoors. Furthermore, the water-based systems achieved fewer hours of overheating compared to the air-based systems and provided more stable thermal conditions.

It was found that combining the radiant floor systems with a ground heat exchanger would be beneficial in terms of energy performance, especially if the energy used by the circulation pump was kept at a minimum. The simulation found that total energy use was reduced with 37% and the energy use for electric cooling with 84% when heat sinks was utilized.

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