Free cooling of low energy buildings with ground source heat pump system and bidirectional ventilation

Ola Gustafsson*, Caroline Haglund Stignor, Huijuan Chen, Svein Ruud and Jon Persson

RISE Research Institutes of Sweden
Box 857 SE-50115, Borås, Sweden
**Corresponding author: ola.gustafsson@ri.se*

ABSTRACT

Earlier field measurements in Low Energy Buildings have shown that excess temperatures can easily occur during summertime in well-insulated houses, also in northern part of Europe. If a ground source heat pump is used for heating and there is a bidirectional ventilation system, the borehole can be used for free cooling in summertime and the chilled air can be distributed by the ventilation system. In this study, a simulation of a single family nZEB located in the Swedish city Gothenburg was conducted. Several different cases investigating the effect of window opening, ventilation air flow rate and installation of a free cooling system was simulated. As expected, the simulation showed that an increase of the ventilation flow and opening of windows can be efficient means to increase the thermal comfort by lowering the number of hours with temperature exceeding 24°C. However, the results show that the free cooling system reduces the number of hours with high temperatures even more, especially for cases when the windows are not opened. To validate the simulation results, a prototype free cooling system was installed in a real nZEB, with the same properties as the nZEB in the simulation study. The measurements confirmed that it is possible to lower the indoor temperature considerably by free cooling by use of the borehole and supply the air system, even though the cooling capacity is limited due to restrictions on ventilation rates and supply air temperature. Another conclusion of the measurements was that the control of the free cooling system is crucial to achieve the full cooling potential and for high system energy performance.

KEYWORDS

Free cooling, borehole, heat pump, bidirectional ventilation, nZEB

1 INTRODUCTION

1.1 Background

Field measurements in Low Energy Buildings, for example in the so-called "Hamnhuset" in Gothenburg in Sweden, show that excess temperatures can easily occur during summertime in well-insulated houses, also in northern part of Europe (Gervind *et al, 2011)*. In many cases, it is possible to lower the temperature by opening of windows, but this is not always desirable. The reason can be either noise or insecurity, or a desire from residents not to get too much pollen or air pollution for allergy or health reasons.

In a heating system with a ground source heat pump it is well known that the borehole can be used for free cooling in summertime (*Shou, Z. et al, 2016, Yuan, T. et al. 2017, Khilström, P. 2016).* And if the house has a bidirectional ventilation system, the chilled air can easily be distributed throughout the building, which can be efficient from both an energy and cost point of view. However, such a solution requires that the heat pump and the ventilation system is linked and controlled together, which is rarely done today. The aim of this project was therefore to investigate the potential and to increase the knowledge of how a heat pump system can be integrated with a bidirectional ventilation system with heat recovery to enable free cooling.

1.2 Scope

The scope of this study was to investigate the potential and to increase the knowledge of how a ground source heat pump system can be integrated with a bidirectional ventilation system with heat recovery to enable free cooling in a single family nearly Zero Energy Building (nZEB). This was done by simulation of the building and the building services engineering systems in IDA-ICE and by follow-up field measurements in a research villa.

1.3 Delimitations

Measurements were only performed during a part of one cooling season. It would have been beneficial to perform measurements during several full cooling seasons to be able to compare the different settings in a better way. In addition, the full range of the ventilation air flow rate used in the simulations, could not be validated due to restrictions of fan capacity.

In this study, it has not been possible to predict the "cost" for the free cooling, in form of additional pumping and fan power. However, this should be taken into account when evaluating the "efficiency" of the free cooling. Even though less energy is most probably used compared to compressor driven cooling, there will still be a certain energy cost for the "free cooling".

2 METODOLOGY

2.1 Simulation/measurement objects

In this study a reference house is used for the model. The house, situated at RISE's premises in Borås (Fig 1), Sweden, is a low energy single family house (average heat transfer coefficient, $U_{average} = 0.16$ W/m^2 K) with a total floor area of 166 m^2 and two floor levels. See table 1 for more technical information of the building.

Table 1. Technical information about the nZEB and the heating and ventilations systems evaluated in this study.

Place	Borås
Size	166 m^2, 22 kWh/m^2/yr (projected space heating and DHW demand)
Ventilation	Balanced (bidirectional) ventilation system with heat recovery, design supply flow rate 60l/s. Manufacturer efficiency data 82%
Heating source	Ground source heat pump (4.5 kW, on/off controlled) Storage tank 150l. Borehole 90 m (81m active) Dimensioning temperature: 0°C
Heating system	Floor heating on upper and 1st floors Dimension temperature: 36°C at dimensioning outdoor winter temperature
Solar	PV-panels 3000 kWh/yr
Habitants	Simulated family

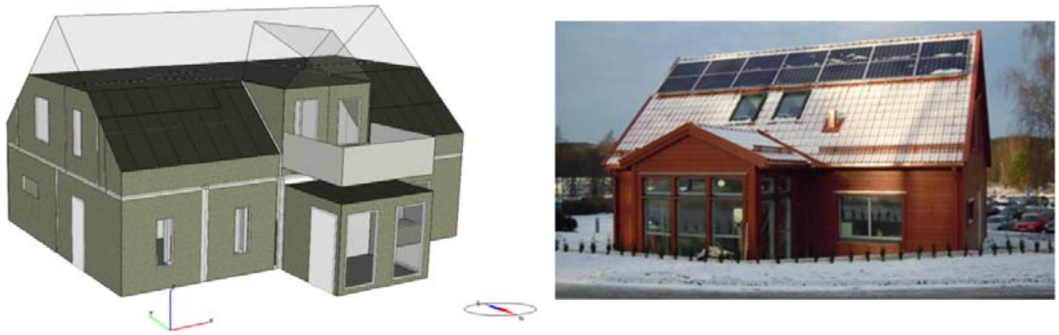

Fig. 1. The IDA model (left) and the reference house (right).

2.2 Simulations

A model of the single-family house is created in IDA Indoor Climate and Energy (ICE) 4.6, and the construction and the configuration correspond to the reference house situated in Borås (see Fig. 1). Result from the model for the heating demand is compared with measurements from the reference house and show good agreement (Ylmén, P. & Persson, J., 2017).

The program of IDA ICE is used to investigate the cooling demand and thermal conditions with different ventilation airflow rate, effects of window opening and a free cooling system. IDA is a dynamic simulation tool for studying indoor climate in the zones as well as energy use in the zones and the entire building for general-purpose. It models buildings, systems and its controls, and it provides user interface to define, build up and simulate different cases which makes it possible to simulate a wide range of system designs and configurations (Equa Simulation Technology, 1999).

The climate data used in the model is for Gothenburg-Landvetter (45 km from Borås), which is fairly representative for Swedish conditions with a yearly average temperature of 8°C. The weather data files are available in the IDA program and they are derived from integrated surface hourly weather data originally archived at the national climate data centre. Regarding the internal heat load, i.e., heat emission from lighting, equipment and appliance, 30 kWh/m^2 is used, suggested by SVEBY (Sveby, 2009) as a standard value for residential building energy simulation. The internal heat load is distributed to the rooms with specific schedules and unevenly distributed over the year i.e., higher household electricity use in the winter and lower in the summer. Occupancy schedules are considered with a specific distribution. IDA simulations were performed for the cooling season, i.e., May to August.

To investigate the effect of different means of reducing the hours of overheating different cases were modelled. These cases included different ventilation flow rates, schedule for window opening and installation of a cooling coil (connected to borehole and placed after the air handing unit); see Table 2 for short descriptions of case studies. For each of these cases the number of hours that the temperature in three different rooms in the nZEB exceeded 24°C was investigated.

Table 2: Descriptions of modelled cases

Case	Ventilation flow rate (l/s)	Schedule for window opening	Connected to cooling coil
1	60	No	No

2	100	No	No
3	60	Yes	No
4	60	No	Yes *
5	100	No	Yes *
6	60	Yes	Yes *

* The cooling coil starts to work when the room air and supply air temperature is above 21°C and 16°C, respectively.

The designed ventilation flow rate for the modelled house was 60 l/s (corresponding to 0.35 l/s/m^2), and the maximum flow rate was assumed to be 100 l/s. The schedule for window opening was made based on literature study together with assumptions of opening window behavior (when and how often people is likely to open window). A cooling coil was added to cool down the supply air temperature to 16°C in warm days, i.e., case 4-6.

Further, additional cases are modelled to obtain the required cooling capacity for maintaining the maximum room temperature below 24°C at all times. This was done by adding fan coils in the living spaces, i.e., living room and kitchen and sleeping rooms for case 1, 2 and 3.

In addition, the maximum cooling capacity from free cooling system was investigated by estimation of the potential on the air side.

2.3 Measurements

2.3.1 System setup

The system setup is depicted in Figure 2 below, and consists of the following main components;

- A ground-source heat pump with a 2.3 kW electric compressor, operated in on/off mode. The heating power, excluding auxiliary resistive elements (blocked), is about 4.5 kW. The heat-pump is supplying both DWH and hot water for floor-heating.
- An air-handling unit with a rotating disk heat recovery. The electric power of the fans are about 170 W and delivers a max flow of about the 90 m^3/h in the given installation (without additional cooling-coil).
- A cooling-battery dimensioned to give about 1 kW cooling power at the anticipated operation conditions.
- A separate frequency-controlled circulation pump on the brine circuit of the cooling battery.

The cooling battery was installed on the supply air duct, directly after the air-handling unit. A by-pass, operated by manual valves, allows for the cooling battery to be disabled when not needed. The liquid circuit of the cooling battery was connected in parallel with the return pipe from the borehole to the heat pump. The additional circulation pump, along with a non-return valve, allow for brine to be circulated through the cooling battery, the heat-pump and the borehole (all in series) independently of the heat-pump operation.

2.3.2 Measurement system setup

The monitoring included PT100 and PT500 sensors for temperature readings for both the air- and brine side of the system. The flow-rate on the brine side was given by a volumetric flow sensor. Both brine temperature and flow rate were measured by a Kamstrup energy meter. The air flow was measured by differential pressure sensors. In addition, the electric power used by the equipment was logged with integrating energy meters. Data for evaluation the thermal system performance was recorded as 15 minutes averages. Some, but not all, measuring points are indicated in the system diagram in Figure 2.

2.3.3 Control system

The cooling power was controlled to reach a given set-point temperature on the supply-air to the living space. The control was achieved by regulating the speed of the circulation pump on the brine side of the cooling battery. A PID regulation was implemented to provide a feed-back from the supply air temperature to the operation circulation pump. The cooling was activated when the outdoor temperature exceeded 16.3 °C, and it turned off again when the outdoor temperature went below 15.0 °C (taking the temperature rise of the air due to the fan power into account).

2.3.4 Operation settings

Three separate operation settings are presented here, which each has different effects on the final indoor air temperature of the house.

Operation setting 1 – Full ventilation, no cooling, HP in operation. The cooling battery was not activated, and the air went via the by-pass. The fans of the air-handling unit were running at maximum speed to give a supply air-flow of about 70 l/s. In this case a ventilation air flow of 100 l/s, was aimed for, but due to restrictions in fan capacity only 70 l/s was reached. The heat pump was running as normally, in an eco-mode setting. The measurement period for this operation mode was from 2017-06-19 to 2017-06-28.

Operation setting 2 – Full ventilation, 16°C cooling, HP in operation. The cooling battery was activated with a supply air temperature set-point of 16 °C. With an additional pressure drop over the cooling battery, the air-flow was reduced to about 60 l/s. The heat pump was running as normally, in an eco-mode setting. The measurement period for this operation mode was from 2017-08-22 to 2017-08-31.

Operation setting 3 – Full ventilation, 16°C cooling, HP turned off. The cooling battery was activated with a supply air temperature set-point of 16 °C. The air-flow was about 60 l/s. The heat pump was turned off. The measurement period for this operation mode was from 2017-08-11 to 2017-08-22.

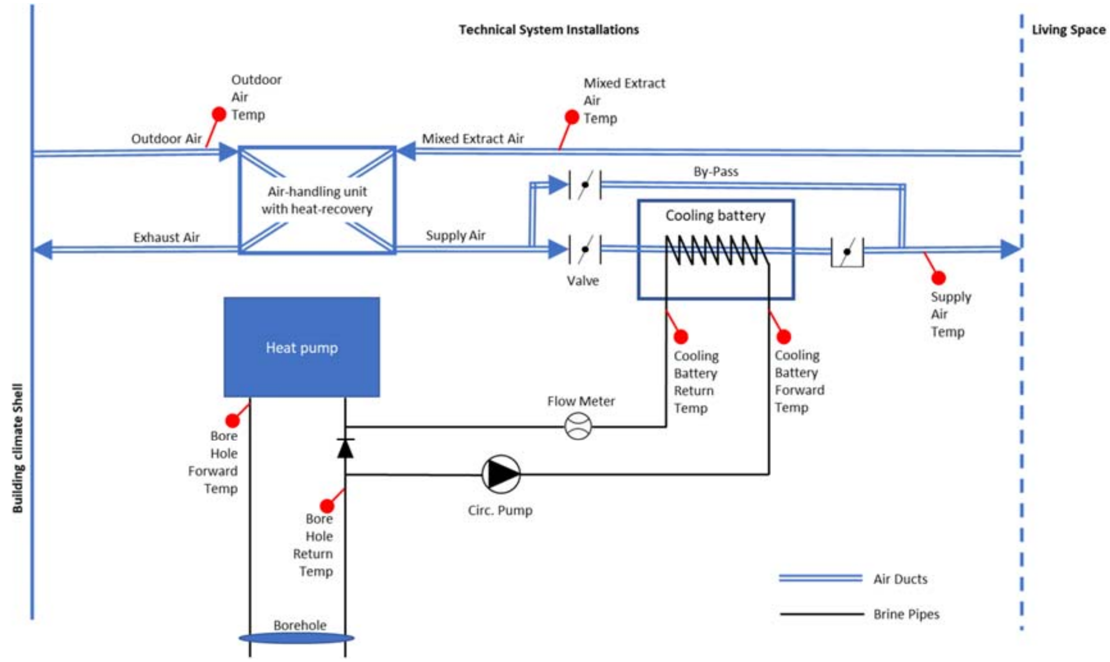

Figure 2. The system setup of the installation of the cooling battery in the Research Villa.

3 RESULTS AND DISCUSSION

3.1 Simulations

Results from the IDA simulations are presented and discussed in this section.

3.1.1 Required cooling capacity

The required cooling capacity for case 1, 2 and 3 (see case description in Table 2) to keep the maximum room temperature below 24 °C during the whole cooling season is presented in Figure 3. As shown in the figure the peak cooling demand for all three cases is nearly the same, about 2000 W, while the number of hours required for the same amount of cooling demand is decreased by increasing ventilation flow rate or opening window.

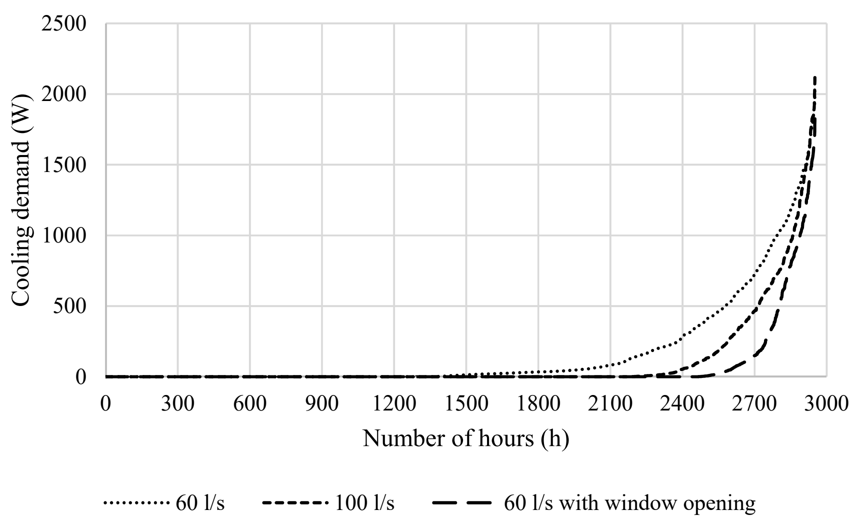

Figure 3. Duration diagram of cooling demand for case 1 – 3 during the whole cooling season.

3.1.2 Cooling potential in ventilation system

According to IDA calculation, the maximum cooling power (both sensible and latent) provided by the ventilation flow rate of 60 l/s and 100 l/s is about 1.2 kW and 1.9 kW, respectively. These values are valid for an outdoor temperature of 26 °C, relative humidity of 54 % and supply air temperature of 16 °C. In the IDA model, the temperature for entering liquid and leaving liquid is assumed to be 5°C and 10°C (IDA default value), respectively.

3.1.3 Reduction of hours of overheating

In Figure 4 the indoor temperature of the modelled house is shown for a sunny day in July at 16:00. The contour plot of temperature is based on the simulation results for case 1 (base case). The temperatures for the living room and kitchen, bedroom 1 and bedroom 2 are at about 27, 29 and 30°C, respectively. In general, the air temperature in the first-floor is lower than that in the second-floor; and bedroom 2 in the second-floor is warmer than bedroom 1 due to more incoming solar radiation in the afternoon. Therefore bedroom 2 has a longer overheated period than bedroom 1 as shown in Figure 5.

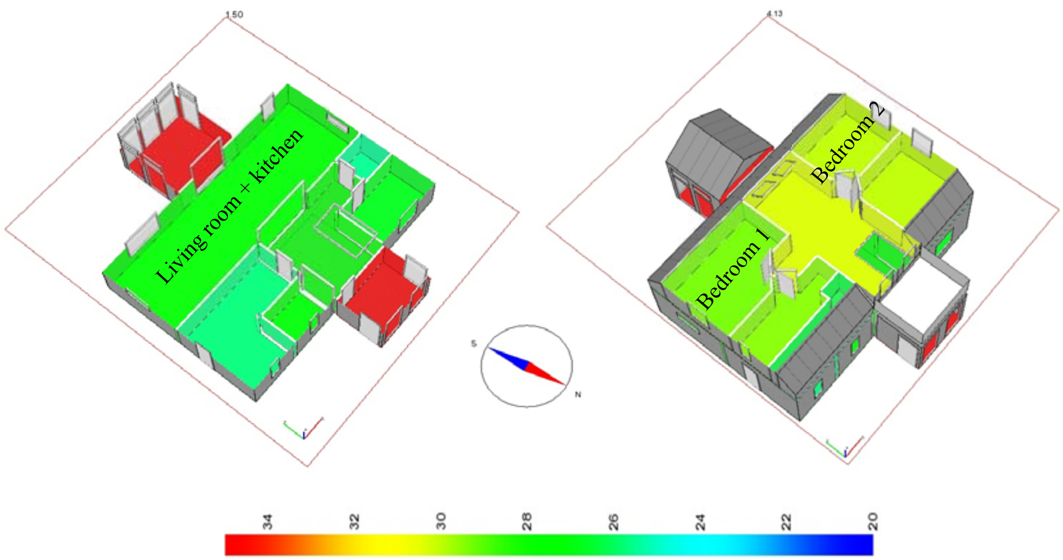

Figure 4. contour plot of room temperature of the modelled house for a sunny day in July at 16:00

Figure 4 shows the total number of hours when the room air temperature above 24°C during the whole cooling season for different cases, including increased ventilation flow rates (case 2 and 5), opening window (case 3 and 6) and using a free cooling system (case 4,5 and 6). As can be seen, increasing ventilation flow rate, opening windows, and connection to free cooling system helps to decrease extent of overheating in house, in terms of reducing the overheating hours. But of course, the changes also have in impact on the average room temperature. For example, the average room temperature for the living room and kitchen for case 1 and case 4 (with free cooling) is about 24 and 23°C, respectively; for bedroom 1, the average room temperature for case 1 and case 3 is about 25 and 23°C, respectably.

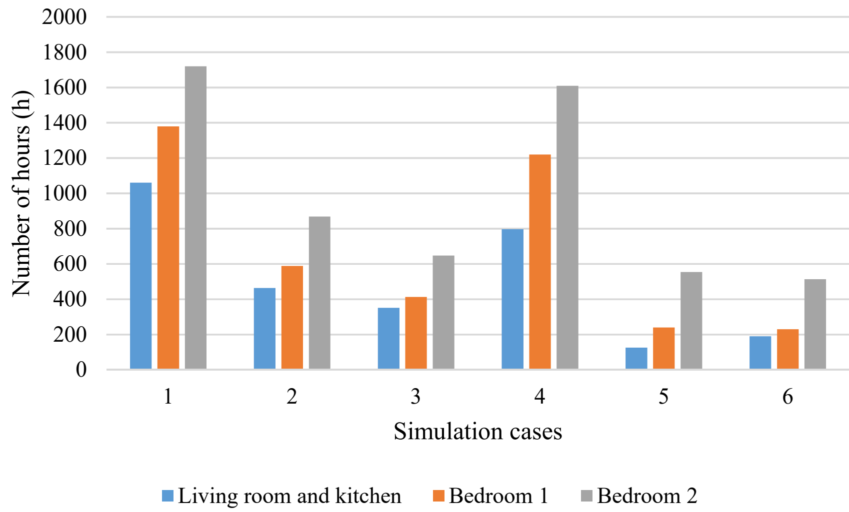

Figure 5. Total number of hours when the room temperature is above 24 °C for living room and kitchen and two sleeping rooms during the whole cooling season based on simulation.

3.2 Measurements

In Figure 6 below the temperature of the mixed extract air is shown during the three different evaluation periods. This temperature is assumed to represent an average indoor temperature. No (or very few) window openings were done during the evaluation period since the measurements were performed in a research villa with no people living in the house. Occupancy is only simulated by electrical thermal loads. Due to restrictions in fan capacity, it was only possible to increase the air flow rate to 70 l/s (and not up to 100 l/s). As can be seen, temperatures over 24 °C are registered for a large amount of the time, even at moderate outdoor temperatures. After setting the cooling coil into operation, the temperature of the extract air is reduced significantly, even more than expected, since the ventilation air flow was reduced due to the additional pressure drop over the cooling coil. According to the default setting of the heat pump, the heat pump operates in heating mode during night time, if the outdoor temperature drops below a certain level. It can be seen that lower temperatures are obtained if the heat pump operation is blocked, and nevertheless, the mixed indoor temperature never drops below 20 °C.

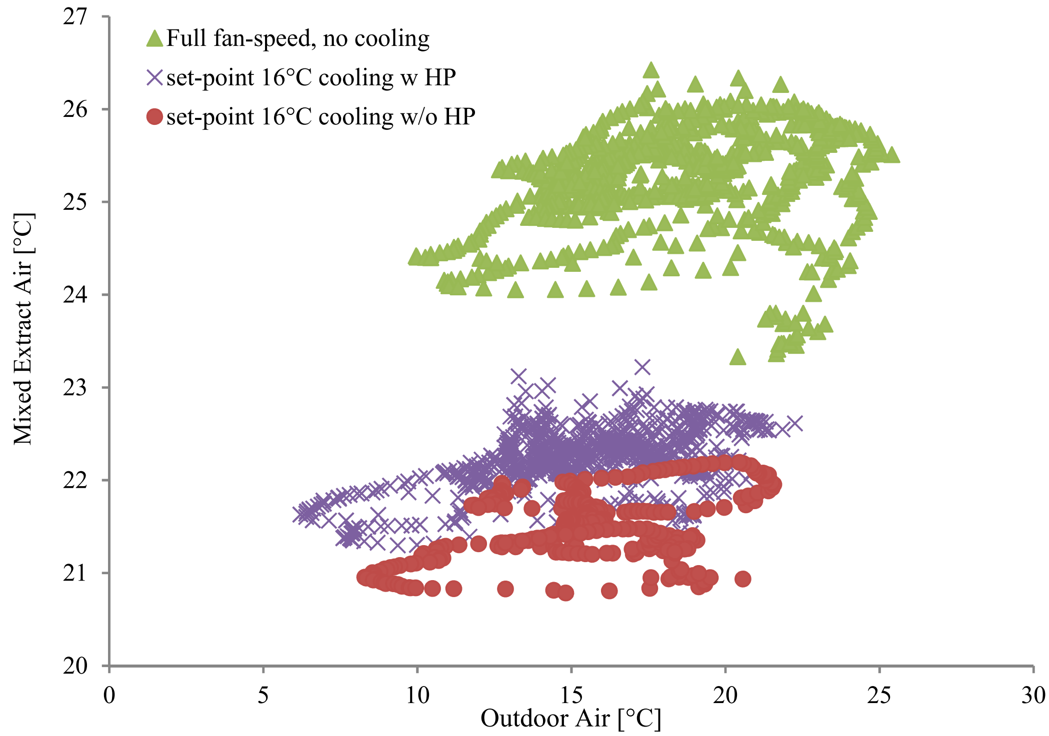

Figure 6. Temperature of the mixed extract air during different evaluation periods with and without free cooling and heat pump operation.

3.3 Lessons learned from measurements

Some lessons learned from the measurement evaluation periods are listed below.

- In order to limit the additional pump power, the cooling pump should not be oversized and equipped with variable flow control.
- In order to reduce the fan energy used during the whole year it is beneficial if the system has a bypass for the airflow to prevent the air from passing the cooling coil during the heating system.
- The control should include a summer and winter period to prevent the heat pump to heat the house during nighttime when there is a cooling need in the daytime.
- The system should have a valve to shut-off the cooling coil when the heat pump is operating. Otherwise there is a risk that too cold air (below 16°C) is distributed by the ventilation system.

4 DISCUSSION

As an alternative to distributing the chilled air through the ventilation system, separate fan coils could be installed in one or several rooms of the house. If only one is installed, it will be a challenge to distribute the cool air in the house, and if several are installed, it will lead to considerable extra cost, both for material, work and fan power. Therefore, the alternative if distributing the air by the already existing ventilation system is a cost-efficient alternative, even though the available cooling capacity is restricted by the ventilation air flow rate and a lowest permitted discharge temperature of 16°C.

5 CONCLUSIONS

- It is possible to lower the indoor temperature significantly with a cooling could connected to the borehole of a ground source heat pump and a bidirectional ventilation.
- The IDA model used in this study shows reasonable predictions of indoor thermal conditions for a typical summer based on the comparison results with the measurement data.
- Since the cooling capacity is limited in the free cooling system a good control scheme is required i.e. one must start cooling before the actual cooling need (high indoor temperatures) to prevent overheating.
- Increasing the ventilation flow rate is efficient to reduce the number of hours of overheating. Therefore, this should be the first step, if possible, before installing the cooling system.

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