Long-term performance analysis of a hybrid ground source heat pump system in Finland

TIANCHEN XUE
Doctoral candidate,
Aalto University
tianchen.xue@aalto.fi

RISTO KOSONEN
Full-Professor,
Aalto University

JUHA JOKISALO
Senior researcher,
Aalto University

This study investigated methods for improving the long-term performance of a hybrid GSHP system coupled to district heating and an air-cooled chiller. These methods include adjusting indoor air setpoints and dimensioning air handling unit (AHU) cooling coils. The system performance was analysed based on 25-year simulations in IDA ICE 4.8. By using the studied methods, the minimum outlet brine temperature was increased by around 3°C in the last heating season, the average heat pump COP in the last heating season was increased by 3 % and the share of the GSHP heating energy in the last heating season was improved by 2 percentage points. However, ensuring long-term operation still required extra solutions.

Keywords: Hybrid ground source heat pump, district heating, borehole free cooling, long-term performance analysis.

Introduction

Ground source heat pumps (GSHPs) as high-efficiency solutions for providing heating and cooling have been widely used in European countries (Menegazzo et al. 2022). However, in cold regions, as buildings have the dominating heating demand, GSHP systems face the challenge of ground thermal imbalance. If the GSHP system is not designed properly, the ground temperature will be overcooled and lead to deterioration of the heat pump performance in a long run. In this context, hybrid GSHP systems with auxiliary heat source are proposed especially for cases with a limited land for drilling boreholes. Many studies revealed that integrating auxiliary heat source with the GSHP can assist to maintain a more stable ground temperature and generate a higher coefficient of performance (COP) of the heat pump (Xi et al. 2011; Naranjo-Mendoza et al. 2019; Liu et al. 2017). However, some existing hybrid GSHP systems could still have imbalanced ground load if the system was controlled unproperly.

Therefore, this study aims to investigate different methods for improving the long-term performance of a hybrid GSHP system in Finland with a risk of overcooled ground. The investigated methods include adjusting indoor heating and cooling setpoints and dimensioning air handling unit (AHU) cooling coils. The whole system was modelled and simulated in IDA Indoor Climate and Energy (IDA ICE) 4.8. The results of this paper could be helpful to the design and practical implementation of hybrid GSHP systems.

Method

Description of building model

In this study, the simulation software IDA ICE 4.8 (Sahlin 1996) was used for the modelling and simulation of the building and the hybrid GSHP system.

The case building is a new 4/5-storey educational building with hundreds of rooms in Espoo, Finland. The total heated net floor area is around 47,500 m². The original building was designed in an irregular shape. The studied building was simplified as a rectangular building with five zones in the building model.

In the building model, U-values of the external wall, the roof and the base floor were set as 0.17 W/(m²K), 0.09 W/(m²K) and 0.18 W/(m²K), respectively. Each wall was equipped with one window featuring a U-value of 0.6 W/(m²K), solar heat transmittance of 0.49 and direct solar transmittance of 0.41. The total window to envelope ratio was 17.3 %. The air leakage rate of the building was 2 m³/(h, m²) under a pressure of 50 kPa.

The heating and cooling were distributed by a hydronic four-pipe radiant ceiling panel system. The indoor heating and cooling setpoints were set as 21.5°C and 25°C. The dimensioning supply/return water temperatures for space heating were 45/30°C. The supply water temperature for space heating was controlled by the outdoor air temperature. The dimensioning supply/return water temperatures for space cooling were fixed at 15/18°C. The domestic hot water (DHW) was heated to 55°C. In the model, the annual heating energy demand of DHW was set as 4 kWh/(m², a).

The ventilation system was a mechanical balanced ventilation system with heat recovery. The supply/return water temperatures for AHU cooling were set as 10/16°C. The supply air temperature was controlled between 16-18°C according to the outdoor air temperature. More details about the settings in the model can be found in the study by Xue et al. (2023).

Description of hybrid GSHP system model

The main components of the hybrid GSHP system are the GSHP, the district heating substations, the air-cooled chiller and the storage tanks. The COP of the GSHP was 3.94 at rating conditions of 0/35°C. The energy efficient ratio (EER) of the air-cooled chiller was 3.04 at rating conditions of 35/7°C. The volumes of the hot and cold-water storage tanks were 5 m³ and 3 m³, respectively.

Figure 1 shows a simplified schematic of the hybrid GSHP system. As the figure shows, the heating energy

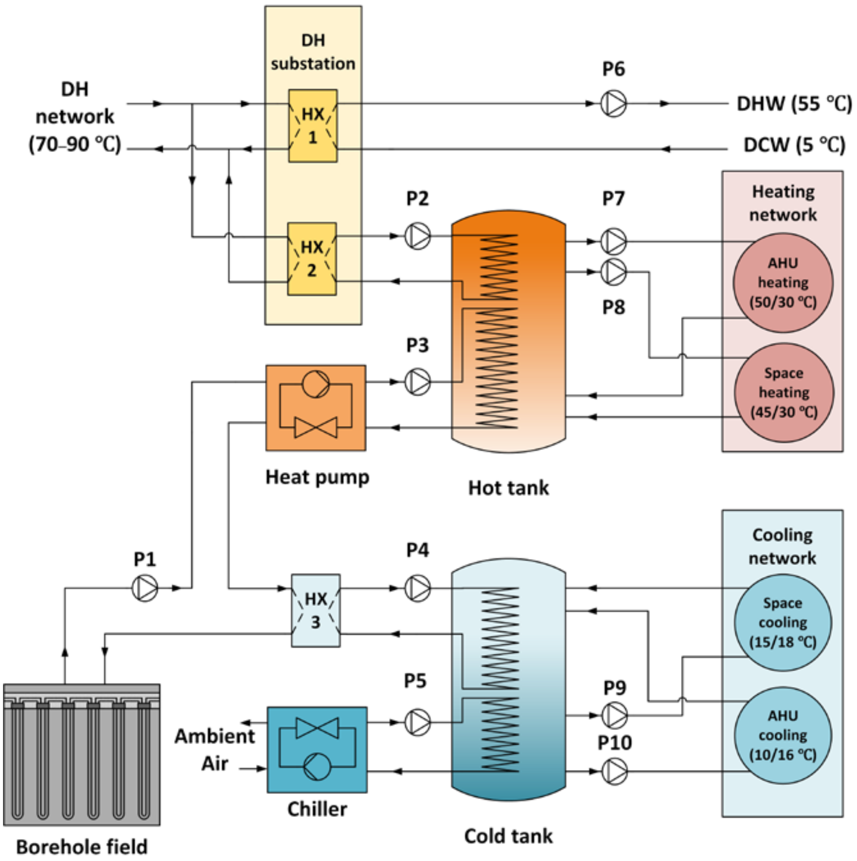

Figure 1. Simplified schematic of the hybrid GSHP system model.

to the heating network is supplied from the hot water storage tank which is primarily heated by the heat pump. If the water temperature of the top layer is lower than the required temperature for the heating network, the district heating will be used additionally. Besides, the district heating is also used for generating the DHW via a separate heat exchanger. The cooling network is connected to the cold-water storage tank in which the water is mainly cooled by free cooling from the borehole field. When the water temperature of the cooling tank bottom layer is lower than the required temperature for the cooling, the air-cooled chiller will be used as the back-up cooling.

The borehole field in this study was modelled by IDA ICE ground heat exchanger (IDA ICE GHX) module. There are 74 groundwater-filled boreholes in the borehole field with an average length of 310 m. The borehole heat exchangers are single U-tubes filled with 28% ethanol-water. In the modelling, the original borehole field layout (see **Figure 2(a)**) was simplified as a double-symmetry layout (see **Figure 2(b)**). The borehole field models were described detailly by Xue et al. (2022). In their work, the simplified borehole field model was validated against the measured brine temperature.

Definition of simulated cases

Four different cases were designed to compare different performance-improving methods. Case 1 is the reference case with settings from the actual design. In Case 2, the AHU cooling water supply/return temperatures were increased to 15/18°C to use more free cooling in summer. However, it also implies larger cooling coils in the AHUs. Case 3 is designed based on Case 2, while the cooling setpoint is reduced to 22.5°C to further increase the ground cooling load. In Case 4, a lower heating of 21°C is used for purpose of reducing the ground heating load.

The long-term simulations were conducted separately for each studied case. The simulation period was from July 2019 to June 2044. To generate the 25-year weather data, the measured weather data from 2019 to 2021 was used periodically for 25 years. The measured weather data was obtained from the nearest weather station.

Results

Brine temperatures

Figure 3 shows the curves of inlet and outlet brine temperatures of the borehole field from Case 1 (reference case). As the figure shows, inlet and outlet brine temperatures of the borehole field drop significantly after 25 years.

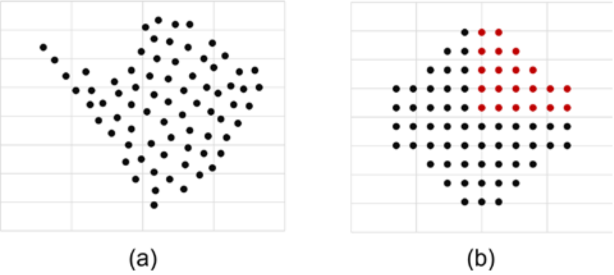

Figure 2. Borehole field layouts, (a) original layout, (b) simplified layout.

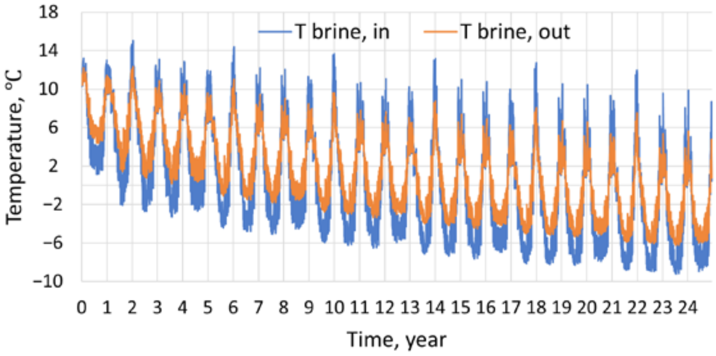

Figure 3. Borehole field inlet and outlet brine temperatures (reference case).

Table 1. *Properties of studied cases.*

Case	AHU cooling water temperatures, °C	Heating setpoint, °C	Cooling setpoint, °C
Case 1 (ref)	10/16	21.5	25
Case 2	15/18	21.5	25
Case 3	15/18	21.5	22.5
Case 4	15/18	21	22.5

Table 2 shows the inlet and outlet brine temperatures in the first and last years. In Case 1, the minimum outlet brine temperature during the heating season drops from 4.4°C to −6.0°C after 25 years. In Case 2, by increasing the AHU cooling water temperature level, the minimum outlet brine temperature in the last year has no change while the maximum outlet brine temperature is reduced compared to Case 1. The reason for this could be the accumulated injected heat is decreased as the condensation in AHUs is reduced because of a higher AHU cooling water temperature level. In Case 3, the lower indoor air cooling setpoint results in higher brine temperatures in the last cooling season. However, it is also noticed the brine temperatures are higher in the last heating season, which could be due to the seasonal storage effect. In Case 4, further reducing the heating setpoint can further increase the brine temperatures in the last heating season. However, the minimum outlet brine temperature in the last heating season of Case 4 can only reach to −3.1°C, which is still lower than the required minimum outlet brine temperature of 0°C for Nordic countries (Gehlin et al. 2016).

Hybrid GSHP performance

Tables 3 and 4 show the hybrid GSHP performance of different cases in the first and last years, respectively. It can be seen the average COP of GSHP in the heating season decreases after 25 years. In Case 1, the average COP in the last heating season is 3.42, which is 9 % lower than that in the first heating season. The COP reduction leads to the deterioration of the GSHP heating capacity. The share of GSHP heating energy reduced from 95 % to 90 % after 25 years. However, in the cooling season, the free cooling is benefited from the reduced brine temperature which is presented by the increased share of borehole free cooling in the last year.

Table 2. *Comparison of inlet and outlet brine temperatures.*

Case	1st year				25th year			
	Heating season		Cooling season		Heating season		Cooling season	
	$T_{in, min}$, °C	$T_{out, min}$, °C	$T_{in, max}$, °C	$T_{out, max}$, °C	$T_{in, min}$, °C	$T_{out, min}$, °C	$T_{in, max}$, °C	$T_{out, max}$, °C
Case 1 (ref)	1.1	4.4	13.2	12.2	−8.9	−6.0	9.9	5.6
Case 2	1.1	4.4	14.6	12.8	−8.9	−6.0	9.4	5.3
Case 3	1.8	4.9	15.2	13.1	−6.1	−3.4	12.4	8.5
Case 4	2.0	5.1	15.2	13.1	−5.7	−3.1	12.4	8.3

Table 3. *Comparison of hybrid GSHP performance in the first year.*

Case	Heating season					Cooling season			
	Average COP of GSHP	GSHP heating energy, MWh	Back-up District heating energy, MWh	Total heating energy, MWh	Share of GSHP heating energy, %	Borehole free cooling energy, MWh	Chiller cooling energy, MWh	Total cooling energy, MWh	Share of borehole free cooling energy, %
Case 1 (ref)	3.76	2984	154	3139	95	217	212	429	51
Case 2	3.76	2983	151	3134	95	290	94.7	385	75
Case 3	3.78	3168	180	3348	95	392	154	546	72
Case 4	3.78	2966	139	3106	96	389	155	544	72

Table 4. *Comparison of hybrid GSHP performance in the last year.*

Case	Heating season					Cooling season			
	Average COP of GSHP	GSHP heating energy, MWh	Back-up District heating energy, MWh	Total heating energy, MWh	Share of GSHP heating energy, %	Borehole free cooling energy, MWh	Chiller cooling energy, MWh	Total cooling energy, MWh	Share of borehole free energy, %
Case 1 (ref)	3.42	2801	321	3122	90	420	11.6	432	97
Case 2	3.42	2799	317	3117	90	384	0.1	384	100
Case 3	3.51	3011	332	3343	90	547	4.9	552	99
Case 4	3.51	2840	255	3095	92	546	5.4	551	99

Compared with the reference case, it can be noticed that among three proposed methods, only reducing the cooling setpoint (Case 3) presents an improved heat pump COP. In Case 2, increasing the AHU supply water temperature level only leads to an increase on the share of borehole free cooling in the total supplied cooling energy. In Case 4, the reduced heating setpoint only benefits the share of GSHP heating energy in the system. Finally, in Case 4 in which all three improving methods was applied, the average heat pump COP in the last heating season was increased by 3 % and the share of GSHP heating energy in the last heating season was improved by 2 percentage points.

Conclusion

Different methods for improving the long-term performance of a hybrid GSHP were investigated based on 25-year simulations in IDA ICE 4.8 The conclusions are summarized as follows:

a) The reference case showed a significant decrease in the borehole field outlet brine temperature after 25 years. The brine temperature drop led to decreases in the COP of GSHP and the share of GSHP heating energy after 25 years. However, the decreased brine temperature caused a substantial increase in the borehole free energy.

b) The overcooling of the ground can be alleviated by the studied methods. In the case with a higher AHU cooling water temperature level and lower cooling and heating setpoints, the minimum outlet brine temperature in the last heating season was increased by around 3°C compared to the reference case. As a result, the average heat pump COP in the last heating season was increased by 3 % and the share of the GSHP heating energy in the last heating season was improved by 2 percentage points.

c) Considering the overcooling cannot be eliminated by the proposed methods, additional solutions, such as reducing the GSHP power or adding more back-up heating, could be still needed for ensuring the sustainable operation of the hybrid GSHP system. ■

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