Build-up and long-term performance prediction of a hybrid solar ground source heat pump system for office building in cold climate

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Abstract

Maintaining annual ground thermal energy balance is one of the basic rules for the ground-source heat pump system (GSHPS). For a building with much larger heating load than cooling load, auxiliary energy should be added in the GSHPS. This paper presented a novel hybrid solar GSHPS (HSGSHPS), composed of a GSHPS and a solar assisted GSHPS (SAGSHPS), used in an office building for heating and cooling. The potential imbalance of the ground thermal energy could be avoided with convenience and economy. A simulation model was developed in TRNSYS to predict the long term (multi-year) performance of the proposed system. Simulation results showed that the proposed HSGSHPS was reasonably designed to resolve the ground thermal energy imbalance problem. A suitable control strategy for the solar collector and solar storage was sought according to the maximum overall annual coefficient of performance (COP) of the SAGSHPS. Long-term fifty-year performance prediction of the HSGSHPS was obtained. The results showed that the simulation study was very important for the proper design and determination of the suitable operational strategy of the HSGSHPS. Potential malfunction of the SAGSHPS could also be visualized through the simulation study.

1 Introduction

Ground source heat pump system (GSHPS) has been shown to be an efficient and popular technology for space conditioning because ground temperature below a few meters from the surface remains relatively constant year round, making it easier to extract heat in winter and cool in summer. GSHP systems are widely used around the world (Omer, 2008; Gao et al., 2009; McGuire, 2009; Sanner et al., 2003; Hepbasli and Kalinci, 2009; Zogou and Stamatelos, 2007; Lohami and Schmidt, 2010). The average coefficient of performance (COP) of GSHPS is at least 30% higher than that of comparable air source heat pump (USGAO, 1994). In GSHPS, soil is commonly used as the heat source and/or sink in order to meet building's heating and/or cooling requirements. However, the amount of heat rejected to or drawn from soil should be more or less balanced on an annual basis to ensure that the soil temperature does not change over time in the long-term. It is true that the ground can tolerate some degree of thermal imbalance especially with bigger borehole field. Issues may arise when space is limited and/or thermal imbalance between heating and cooling is large. Conventional GSHPS is bound by the balance of the ground thermal energy, which ultimately is based on the annual heating and cooling load of the building. Therefore, hybrid GSHPS must be employed when the heating load is far greater than the cooling load or vice versa.

In cold climates, heating requirement is much larger than that of cooling. An auxiliary heat source, such as a boiler or an electric heater, must be used to avert this annual energy imbalance. Solar energy, as a green and renewable energy, could be the ideal auxiliary energy source used in such hybrid system.

Several solar assisted ground-source heat pump systems (SAGSHPSs) used under various conditions appeared in the literatures in recent years (Ozgener and Hepbasli, 2007; Chapuis and Bernier, 2009; Rad et al., 2009; Kjellsson et al., 2010; Ozgener, 2010). Generally, solar thermal energy is stored in the ground during the non-heating season, and then extracted by the ground-source heat pump (GSHP) for heating in winter. SAGSHPSs are suitable for heating (water heating and/or space heating), but have limited application for space cooling (Rad et al., 2009; Zhang, 2010). It is difficult to design an exact solar system to complement the mismatch between heating load and cooling load, particularly for an office building, whose heating or cooling load is uncertain because of the number of occupants and the duration of occupancy. This paper presents a novel hybrid solar ground-source heat pump system (HSGSHPS) for heating and cooling of an office building. The performance of the overall HSGSHPS is estimated for the long-term multi-year manner.

2 Description of the HSGSHPS system

2.1 Building and load

The Energy Conservation Laboratory Center (ECLC), as a research and office building and a renewable energy demonstration building, is located in the new campus of Hebei University of Technology in Tianjin, China. The location of the ECLC is 39.238 °N and 117.066 °E. The ECLC has four stories above ground with a total floor area of 4953.4 m^2. There is a hollow space in the centre of the building from the second floor to the roof. The building is almost situated in the north-south orientation with a counter-clockwise rotation of 21 degrees from the north. The schematic of the ECLC is shown in Figure 1.

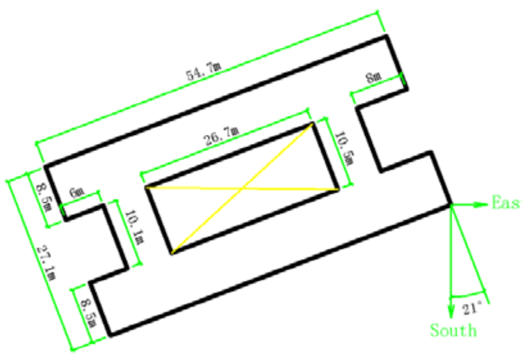


Figure 1 Shape and orientation of the ECLC building (dimensions in meter)

Table 1 Load of the ECLC

	Area (m^2)	Heating load (MJ)	Cooling load (MJ)
1st floor	1419.4	126251	17436
2nd floor	1375.4	112686	60032
3rd floor	1079.3	111836	61873
4th floor	1079.3	188098	84419
Total	4953.4	538871	223760

The first and second floor of the ECLC have mostly laboratories, and the third floor consists of staff offices while the fourth floor is used mainly for graduate student workplaces. Heating and cooling load of the ECLC were simulated by using TRNSYS 17 (Transient Systems Simulation Program) (SEL, 2011). The heating and cooling load for each floor and the whole building are shown in Table 1. The expected occupancy schedule of the ECLC considered in the simulation model is shown in Table 2.

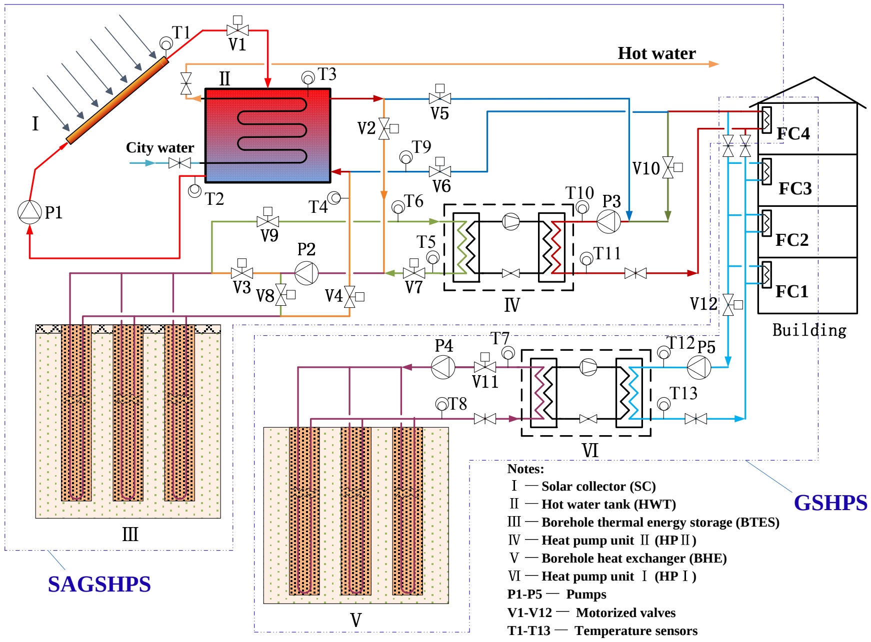
Table 2 Expected occupancy for various floors

	Weekday			Weekend/Holiday	
Time period	8:00-18:00	18:00-22:00	22:00-8:00	9:00-21:00	21:00-9:00
1st floor	22	11	0	11	0
2nd floor	34	17	0	17	0
3rd floor	40	10	0	10	0
4th floor	34	27	0	27	0
Total	130	65	0	65	0

2.2 HSGSHP system

A HSGSHPS, consisting of a GSHPS and a SAGSHPS, was designed to meet the building's heating and cooling requirement. The same solar collector system used in the HSGSHPs could also supply domestic hot water for students' shower and other minor uses in the building throughout the year. The schematic of the HSGSHPS is shown in Figure 2. Two HP units are used in the HSGSHPS. The first HP unit is used in a conventional GSHP manner to supply the entire building's cooling load requirement in summer and partial heating load requirement in winter. The second HP unit is used, coupled with a solar seasonal thermal storage system, in a SAGSHPS to supply the remaining heating load requirement of the building. Two borehole heat exchangers (BHEs) were designed corresponding to each of the two HP units. Because the function and construction of the BHEs corresponding to the two HPs are very different (to be discussed in the later section), the BHEs of GSHPS and SAGSHPS will be referred to as BHE and BTES (borehole thermal energy storage) respectively, as shown in Figure 2. The HPs are water-to-water type. Fan-coils are used as the terminal units.

In this system, the GSHPS is relative simple, while the SAGSHPS is more complex. As shown in Figure 2, the SAGSHPS consists of a solar collector (SC), a hot water tank (HWT), a solar circulation pump (P1), a borehole thermal energy storage (BTES), a heat pump (HP II), a storage circulation pump or source circulation pump (P2), a load circulation pump (P3), a fan-coils (FC4) and several valves. All the working fluid in the HSGSHPS is water. There are five loops in the SAGSHPS while there are two loops in the GSHPS. The water can be supplied through water treatment equipment (not shown in Figure 2). All the loops can be controlled by motorized valves and pumps. In the SAGSHPS, the solar seasonal storage loop and the ground heat extraction loop have the same pump (P2). But the pump circulates the fluid through the BTES in reverse direction controlled by the valves V3, V4, V8 and V9. During non-space-heating seasons (i.e., the cooling season (summer) and two shoulder seasons (spring and autumn)), solar thermal energy is stored in the soil of the BTES via the storage loop. Thus, the non-space-heating season is also called storage season for the SAGSHPS. In winter, heating is provided by the fan-coils with the hot water coming from solar storage tank if the temperature is high enough, or else with the hot water heated by HP II, using the stored solar thermal energy in the BTES. The SAGSHPS was designed as a direct system in order to improve the heat transfer efficiency. Water, as the working fluid in the whole HSGSHPS, which is supplied by water treatment equipment, can flow through the solar collector, the hot-water-tank, the BTES and heating distribution system. A serpentine tube heat exchanger is immersed in the storage tank. City water is heated by flowing through the serpentine tube heat exchanger inside the hot water tank for the production of domestic hot water.



Five recirculation loops in SAGSHPS:		Two recirculation loops in GSHPS:
Solar collection loop:	I-V1-II-P1-I	Source loop: VI-V11-P4-V-VI
Solar seasonal storage loop:	II-V2-P2-V3-III-V4-II	Load loop: VI-FCs-V12-P5-VI
Solar space heating loop:	II-V5-P3-FC4-V6-II	
GSHP space heating loop:	IV-FC4-V10-P3-IV	
Ground heat extraction loop:	IV-V7-P2-V8- III-V9-IV	

Figure 2 Schematic of the HSGSHPS

2.3 Determination of heating load for the GSHPS

Determining the load of the GSHPS is the key to design a HSGSHPS. In order to balance the ground thermal energy on an annual basis, it is required to estimate the amount of heat extracted from and rejected into the ground through the BHE. However, it is difficult, or even impossible, to design the heating and cooling system with an exact balance because of many uncertainties including HP cannot always operate under rated condition resulting in varying coefficient of performance of HP unit (COP_{HP}); building's heating or cooling load cannot be determined exactly if the air conditioning terminal unit can be turned on/off by people in every room; and extreme weather conditions affects the building's heating and cooling load.

In order to keep the balance of the soil temperature on an annual basis, the heat extraction should be equal to the heat injection of the BHE. This can be estimated based on the COP_{HP} of GSHP unit in heating mode and cooling mode. According to the definition of COP of HP unit, the relationship of R_L (the ratio of heating load to cooling load on an annual basis) and R_S (the ratio of heat extraction to injection of the BHE on an annual basis) can be obtained as,

$$R_L = \frac{COP_{HP,H}(COP_{HP,C}+1)}{COP_{HP,C}(COP_{HP,H}-1)} R_S \qquad (1)$$

Where $COP_{HP,H}$ and $COP_{HP,C}$ are COP_{HP} in heating mode and cooling mode, respectively.

The rated COP_{HP} of a GSHP (model: PSRHH1201-Y manufactured by Climaveneta (China) company), used in the GSHP system, is 4.53 in heating mode and 5.22 in cooling mode. To guarantee the heat extraction equal to the heat injection, i.e., R_s is 1 in Equation (1), the ratio of heating load to cooling load on an annual basis should be,

$$R_L = \frac{COP_{HP,H}(COP_{HP,C}+1)}{COP_{HP,C}(COP_{HP,H}-1)} = \frac{4.53 \times (5.22+1)}{5.22 \times (4.53-1)} = 1.53$$

In other words, the ground thermal energy can be balanced on an annual basis if the heating load is 1.53 times of the cooling load. Simulation results showed that the ECLC's heating load was 2.4 times of its cooling load (Table 1). It means that for this building with conventional GSHP, auxiliary energy has to be used for space heating. According to the load calculation, the sum of the heating load of the first, second and third floor is 1.56 times of the total cooling load. So the heating load of the fourth floor is separated from the GSHPS, and supplied by the SAGSHPS. Furthermore, some fan-coils can be switched to connect with the GSHPS or SAGSHPS to provide flexibility in operation. As a result, it may be able to minimize/eliminate the effect of any discrepancy between the actual load and the designed load of GSHPS, if the above fan-coils are switched between GSHPS and SAGSHPS in the heating season based on the actual requirement.

2.4 Solar collector area and the hot-water-tank volume

In the proposed HSGSHPS, all the auxiliary heat is supplied by SAGSHPS. The space heating can be derived from three different ways: solar thermal energy in winter, seasonal thermal storage in ground extracted by heat pump, and electricity power conversion of the HP. There is a principle to determine the minimum solar collector area. The solar thermal storage can maintain the soil temperature on an annual basis if,

$$Q_{SH} + Q_{HP} \geq Q_{HL} \quad (2)$$

Where Q_{SH} is heating through solar thermal energy in heating season; Q_{HP} is heating through HP; Q_{HL} is the total required heating load of the SAGSHPS. Q_{HL} can be obtained from the design standards manual or from simulation results. Q_{SH} and Q_{HP} can be calculated from the following equations.

$$Q_{SH} = A_c H_{T,h} \eta_{c,h} (1 - \eta_{loss,h}) \quad (3)$$

$$Q_{HP} = \frac{COP_{HP,h}}{COP_{HP,h}-1} A_c H_{T,s} \eta_{c,s} (1 - \eta_{loss,s}) \quad (4)$$

Where A_c denotes solar aperture area; $H_{T,h}$ and $H_{T,s}$ denote the global radiation incident based on aperture area of the tilted collector surface during heating season and storage season respectively; $\eta_{c,h}$ and $\eta_{c,s}$ are thermal efficiency of the collector based on aperture area during heating season and storage season respectively; $\eta_{loss,h}$ and $\eta_{loss,s}$ are the loss rates during heating season and storage season respectively; $COP_{HP,h}$ is coefficient of performance of heat pump during heating season.

In the proposed HSGSHPS, a total of 280m^2 of the evacuated tube solar collector area was installed, accounting for the requirements of space heating, domestic hot water heating, and some other minor uses.

The principle to determine the volume of the hot water tank is that the maximum temperature of the solar collector never exceeds 90°C. The collector temperature is affected by the tank temperature and the solar radiation. The tank temperature is also affected by the storage temperature or space heating temperature. In fact, the amount of available solar energy in the heating season is much lower than that in the storage season. The tank volume was designed in terms of thermal energy storage conditions. The storage turn-on temperature (the tank temperature) is assumed to be 50°C, and the average heat transfer rate per unit borehole depth during the storage season is 50W/m. The volume of the hot water tank can be determined based on the heat gain of solar collector and heat storage in soil per day in the storage season. The maximum local global irradiation per day in Tianjin is 32.5MJ/m^2 (the peak irradiance is

1193W/m^2 on collector surface). The volume of the hot water tank was designed as 20m^3. The maximum possible temperature of the solar collector was estimated to be 86°C under such condition.

2.5 Construction of BHE and BTES

The BHE and BTES consist of several tens of high-density polyethylene U-pipes buried in vertical boreholes. The BHE was formed by 66 vertical boreholes with individual depth of 120m and spacing of 4m apart. For the purpose of seasonal storage, the BTES should consist of boreholes with smaller spacing and swallower depth. The BTES was formed by 25 vertical boreholes with individual depth of 50m and spacing of 2.5m apart. The number of the boreholes should match the HP's capacity. To decide the number of boreholes of BHE or BTES, different operation characteristics between GSHP and SAGSHP should be considered. The former should base on cooling load, whereas the latter should base on heating load. Another difference between the BHE and BTES is the connection relationship of the boreholes. In the BHE, all boreholes are connected in parallel. On the other hand, in the BTES, there are 3 groups of parallel boreholes connected in series with 8 or 9 boreholes for each group. The fluid is circulated through the boreholes in the following manner to optimize the overall system performance. The fluid circulates from the centre to the edge of the BTES volume during heat injection process. Otherwise, the fluid circulates in the reverse direction during heat extraction process. Moreover, the top of the BTES is covered with polyurethane foam insulation of 48mm thickness to reduce heat loss.

2.6 Heat pump

The heat pumps in the HSGSHPS were selected based on the rated capacity and rated power. According to the calculation of the building load, the maximum cooling and heating loads of the ECLC are 361.8kW and 259.9kW, respectively. The peak heating load of the fourth floor is 87.3kW. The HP types were selected based on 80% of the maximum cooling load of the entire building for the GSHPS (HP I) and peak heating load of the fourth floor for the SAGSHPS (HP II). Such information is shown in Table 3.

Table 3. The parameters of GSHP in rated condition

GSHP	HP in GSHPS	HP in SAGSHPS
GSHP type	PSRHH1201-Y	HRHH0252
The rated source temperature in cooling mode (°C)	25/30	-
The rated load temperature in cooling mode (°C)	12/7	-
The rated source temperature in heating mode (°C)	10/5	7/3.8
The rated load temperature in heating mode (°C)	40/45	40/45
The rated source flow rate/ load flow rate in cooling mode (m^3/h)	65.6/55.6	-
The rated source flow rate/ load flow rate in heating mode (m^3/h)	46.2/58.3	16.4/14.2
The rated cooling capacity/ cooling power (kW)	323.2/61.9	-
The rated heating capacity/heating power (kW)	339.2/74.9	82.8/19.7

The other equipments such as fan-coils, circulation pumps, fresh air units, and so on were designed and determined as conventional building heating and cooling system. Such information are available in many manuals and/or literatures (ASHRAE, 2007; ASHRAE, 2008; Kavanaugh et al., 1997).

3. Simulation

3.1 Simulation program

A numerical model was created for the proposed HSGSHPS based on TRNSYS 17 (SEL, 2011) simulation program. The building was simplified to four zones with one zone per floor, but the walls and windows were modeled as the real building using the component model Type 56. Correspondingly, four fan-coil models (Type 928) were used in the system to simulate the dozens of fan-coils used in the four floors with the same total flow rate and power. The ventilation of the building was achieved by the fan-coils with flow rate and temperature considered as the actual conditions of the building. An evacuated tube solar collector model (Type 71) and a flat bottomed storage tank model (Type 531) were used for the solar collection system. All the pumps were modelled by component Type 114. The main pipes were modelled by component Type 31. Weather model of Type 109 was used. Weather data of Tianjin, China, was produced by the Meteonorm 5.1 software.

The HP unit was modeled using component Type 927, water-to-water HP. Parameters, such as flow rate, power, and capacity at the rated condition, of the GSHPs, shown in Table 3, were based on the manufacturer's specification. The power and capacity of the HPs vary with flow rate, exit water temperature (EWT) of evaporator and EWT of condenser. The EWT of evaporator is the load EWT in cooling mode, while the EWT of condenser is the load EWT in heating mode. Two user-supplied data files were created as external files in Type 927 containing catalogue data for the capacity and power draw which were based on the entering load and source temperatures. Then, the cooling or heating capacity and power draw information of the HPs could be read from these two external files during the TRNSYS simulation.

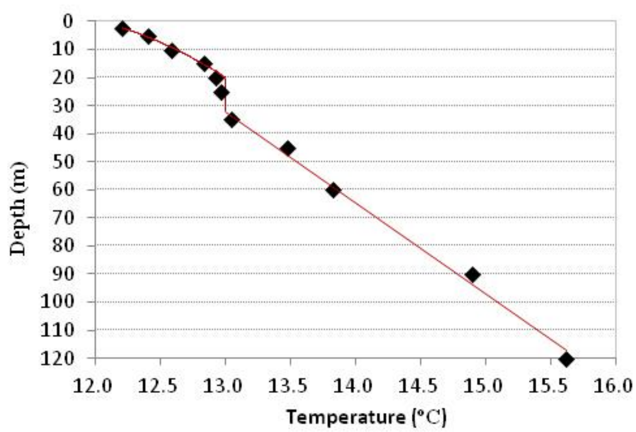


Figure 3 Undisturbed temperature of soil with depth of boreholes in winter

Component Type 557 was used to model the BHE and BTES together in TRNSYS. A "new" or "fake" type was created, based on Type 557, for the simulation of the BTES while regular Type 557 was used for the BHE. The soil thermal physical parameters were set in the soil models based on the experimental data shown in Table 4. The thermal physical parameters of soil changed with depth because of the variation of the water content and composition in soil with respect to depth. The maximum number of soil layers in the component Type 557 is 10. A simplified soil model, based on the conductivities of ten layers, was used in the simulation. The thickness, heat capacity, and thermal conductivity of the soil in every layer are shown in Table 4. Average soil properties were used in the Type 557 storage volume. The undisturbed soil temperature profile with depth, based on measurement, is shown in Figure 3. The temperature distribution in the soil from 0-120m depth can be plotted into three partitions: environmental impact layer (0-20m below the surface), constant temperature layer (20-

30m of depth) and varying temperature layer (30-120m). The undisturbed soil temperature between 20 and 30m deep is constant of 13.0°C, while it increases 0.3°C/m with depth after 30m deep. The average initial soil temperature between 0 and 120m deep is 14.1°C.

Table 4 Properties of the soil

Number of ground layer	Thickness of layer (m)	Thermal conductivity (W/(m·K))	Heat capacity (kJ/(m^3·K))
1	6	1.127	3351.1
2	19	1.428	3174.5
3	12	1.572	3019.8
4	14	1.299	2928.2
5	22	1.456	3003.1
6	8	1.770	2920.6
7	10	1.318	2739.5
8	14	1.699	2868.8
9	6	1.103	3043.8
10	9	1.600	2984.5

3.2 Simulation process

The building is designed for graduate students and faculty staff to conduct research work or study. The operating hour of the HSGSHP system is different during weekdays, weekends, or holidays. The distinction between daytime and night-time is considered as well. During the daytime of the weekday, there are 130 persons in the building, and the system operates from 8:00am to 6:00pm normally. However, during night-time of the weekday from 6:00pm to 10:00pm, only half of the occupancy is considered, and the fan-coils are turned on/off according to the floor's occupancy level. The system is turned off during other time from 10:00pm to 8:00am. The system operates as half occupancy during weekend from 9:00am to 9:00pm, otherwise the system is turned off at other time. Two holidays (January 25 to February 20 and July 22 to August 29) every year are modelled in this system. The number of persons and the operating hours in the holidays are assumed to be the same as the weekend except the number of operating fan-coils is only 1/3 as the weekend. The expected occupancy for each floor is shown in Table 2. Generally, the load circulation pump is turned on based on the described schedule.

During the simulation, each year is divided into four seasons: heating season, cooling season and two shoulder seasons, as shown in Figure 4. The heating season is set from 0:00 on November 15 to 0:00 on next year's March 16 (121 days), while the corresponding simulation time is from 7632h to 10536h (1776h from 0:00 on next year's January 1). The cooling season is set from 0:00 on May 20 to 0:00 on September 8 (111 days), while the corresponding simulation time is from 3336h to 6000h. The other times belong to the two shoulder seasons respectively, with no heating and cooling.

The average temperature of the BHE or BTES would vary with the first-operation time (FOT) of the HSGSHPS. The average soil temperature would increase or decrease according to the first operation time chosen in different time of the year. For detailed analysis on the effect of FOT on the BTES temperature, please refer to Wang et al. (2012). In this study, the first operation time is at the end of heating season (1776 hours from 0:00 on January 1). All simulation was done with a time step of 3 minutes.

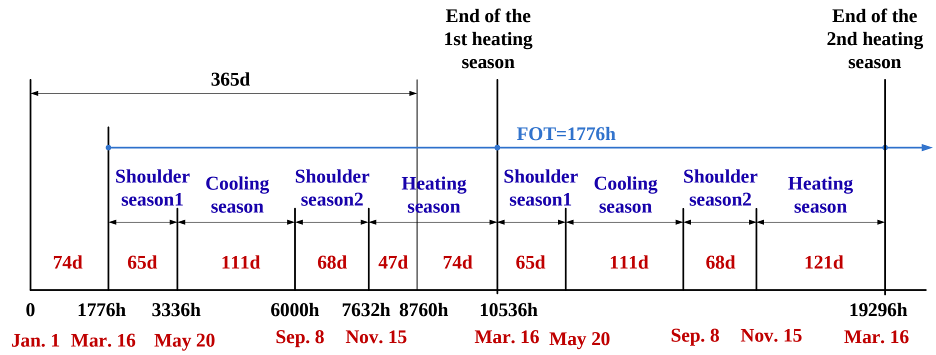


Figure 4 The schematic of simulation time and FOT

This paper predicts the coefficient of performance of the systems (COP_{sys}) and of HP units (COP_{HP}) under the selected control strategy for the solar collection and storage circulation pumps. Different temperatures or temperature differences were tested and analyzed for the proper control of the solar collection loop and/or solar seasonal storage loop. The control signals tested were water temperature difference between solar collector outlet and inlet (ΔT_{SC}), temperature of tank outlet in the storage loop ($T_{ST,out}$), and temperature difference between tank outlet and tank inlet in the storage loop (ΔT_{ST}).

The temperature difference ΔT_{SC} and ΔT_{ST}, can be defined as,

$$\Delta T_{SC} = T_{SC,out} - T_{SC,in} \quad (5)$$

$$\Delta T_{ST} = T_{ST,out} - T_{ST,in} \quad (6)$$

Where the subscript in and out denote inlet and outlet respectively. $T_{SC,out}$, $T_{SC,in}$, $T_{ST,out}$ and $T_{ST,in}$ are based on the temperature sensors T_1, T_2, T_3 and T_4 as shown in Figure 2.

The control strategies are the pump turn-on and turn-off operating limits. Four limits are defined for the control strategy: collection upper limit (CUL), collection lower limit (CLL), storage upper limit (SUL) and storage lower limit (SLL). CUL is the upper limit of ΔT_{SC} while CLL is the lower limit of ΔT_{SC}. SUL is the upper limit of $T_{ST,out}$ while SLL is the lower limit of ΔT_{ST}.

System COP, COP_{sys}, is defined as,

$$COP_{sys} = \frac{Q_L}{W_{tot}} \quad (7)$$

Q_L can be calculated from the heating or cooling heat transfer from the fan-coil to indoor return air in the computation period. W_{tot} is the total electrical energy consumed in the computation period by all of the pumps, fans, compressors and so on. The chosen computation periods are one year, cooling season or heating season, depending on requirement. For the SAGSHPS, the computation period should be an entire year even though it is only used for space heating. The electricity consumption in SAGSHPS for calculating the COP_{sys} should include the annual energy consumption by the solar circulation pump (P1 in Figure 2), storage circulation pump (P2 in Figure 2), source circulation pump (P2 in Figure 2), load circulation pump (P3 in Figure 2), compressor of HP II unit, and the 4th floor fan-coils. The COP_{sys} defined here is an average value in the computation period. It is not a power rate but an energy rate.

Similarly, the COP_{HP} is defined as,

$$COP_{HP} = \frac{Q_{L,HP}}{W_{HP}} \quad (8)$$

Where $Q_{L,HP}$ is thermal energy transferred to load of HP unit; W_{HP} is the electrical energy consumed by HP unit.

Based on the control strategy studied, the suitable case was determined with CUL=15°C, CLL=2°C, SUL=50°C and SLL=5°C. The load circulation pump control strategy (LCPCS) and the FOT=1776h were used for this case study. For further details, please refer to Wang et al. (2012).

4. Results and discussion

The average temperature of the BHE and BTES, COP_{HP}, COP_{sys}, heat loss and heat extraction of the BTES were studied. Figures 5 to 9 illustrate the results of 50-year operating performance of the proposed HSGSHPS for the chosen suitable control case. The average temperature of the BHE or BTES refers to the average temperature of the ground in the storage volume. The ratio of heat loss to heat storage (LRS) and the ratio of heat extraction to heat storage (ERS) in BTES are defined to describe the characteristics of BTES. The heat loss of the BTES is the total heat lost from the sides, bottom and top of the storage volume to the surrounding ground or the ambient. The heat extraction is the heat transferred from the source fluid by the HP. The heat storage is the energy removed from the tank through the specified outlet port minus the energy added to the tank through the corresponding inlet port of the seasonal storage loop.

Figure 5 illustrates that the average temperature of the BHE or BTES varies in a periodical manner annually. The temperature of BTES increases year by year because of the solar seasonal storage effect. The temperature increase in the storage season is larger than the temperature reduction in the heating season each year. The temperature of the BTES increases by 2.3°C after the first year. Soil temperature increases by 7.9ºC in 50 years. It increases quickly in the first 5 years and then increases gradually. Soil temperature increases very slowly after 20 years. It only increases by 0.4ºC in 25 years from 25th to 50th year. The average temperature in BHE decreases gradually and very slowly. It decreases 1.0ºC after 25 years. This estimated change of soil temperature in BHE hardly affects the characteristic of GSHPS in the long run. Some literatures reported problem of operation in SAGSHPS for cooling and heating using only one borehole heat exchanger. Zhang (2010) found that the heat storage capacity should be reduced appropriately to make the soil heat balance after 3 years of running. Rad et al. (2009) also detected system malfunctioning in the cooling season because the soil temperature was too high in the summer due to solar energy storage.

Figure 6 illustrates that the heat loss and heat extraction of the storage increases mostly in the first 5 years. It results in small internal energy variation of the BTES which causes its temperature to increase annually. The ratio of internal energy variation to heat storage (1-(LRS+ERS) in Figure 6) is less than 10% of the heat storage after 9 years. The LRS keeps constant after the first 20 years. However, the ERS continues to increase with time. Thus the sum of LRS and ERS increases while the quantities for the average temperature increase slow down. The average soil temperature is nearly constant during the last 25 years.

Figures 7 and 8 illustrate the annual COP variation with time (year). The SAGSHPS operates only in heating mode. The GSHPS is responsible for the total cooling load of the building. So the COP_{sys} of SAGSHPS represents heating mode only, while the COP_{sys} of GSHP in cooling mode is the same as that of HSGSHPS in cooling mode. The COPs of HSGSHPS shown in Figures 7 and 8 represent whole year of heating and cooling modes. The COP_{HP} of SAGSHPS increases with the average temperature in BTES. The annual COP_{HP} of SAGSHPS and average temperature of BTES show similar trend with time. COP_{sys} of SAGSHPS or HSGSHPS increases as a result of the increase of COP_{HP}. However, the range of increase is different. Annual COP_{HP} of SAGSHPS increases by 12% and the COP_{sys} of SAGSHPS improves by 8.5% after 50 years while annual COP_{sys} of HSGSHPS increases by 1.3% for the same period. These performance improvements are mainly due to the increase in average temperature of BTES annually. The COP_{sys} of SAGSHPS increases to 3.44 from 3.17 while COP_{sys} of HSGSHPS increases to 2.99 from 2.95 at the end of 50 years. The increase of the average temperature in BTES results in very small increase in COP_{sys} of HSGSHPS because the load of SAGSHPS is a small part (about 1/4) of the total load of HSGSHPS. The increase in COP_{sys} of HSGSHPS is only about 1.3% after 50 years. The solar collection and storage control strategies have no effect on COP_{sys} of GSHPS, and the overall annual value is about 2.87. The value of the COP_{sys} of HSGSHPS is affected by the SAGSHPS only in the first 10 years and there is no noticeable effect afterward.

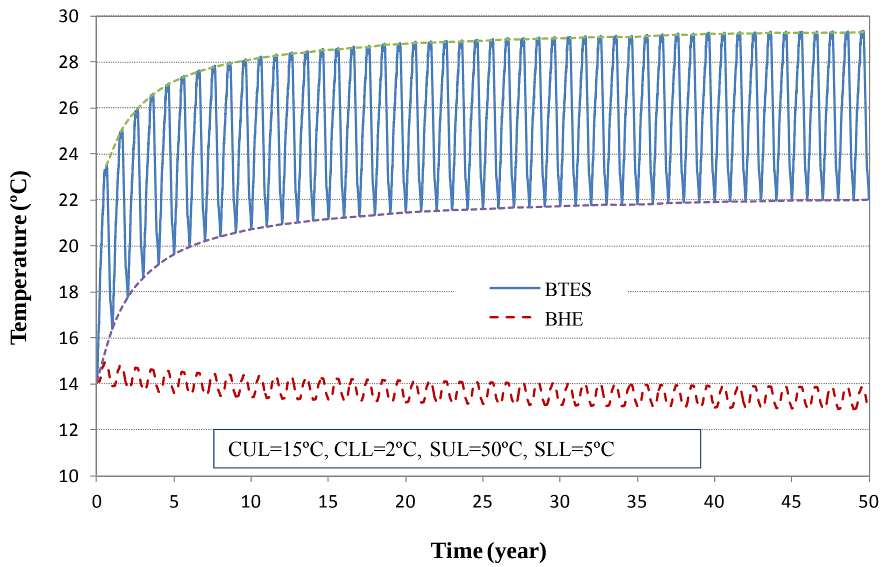


Figure 5 Variation of average temperature in BTES and BHE with time

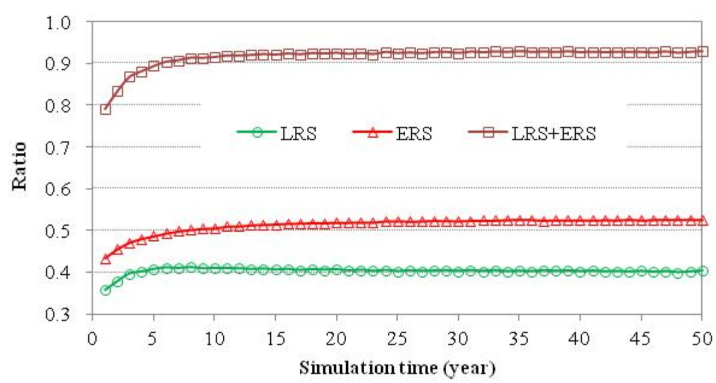


Figure 6 Variation of energy ratios with time

As mentioned above, the designed R_L is a little larger than it should be. There is a little more heat extraction from than injection into the BHE of GSHPS. The temperature of BHE reduces very slightly year after year (1.2°C in 50 years) as shown in Figure 5. The variation of average temperature of BHE in a given year is small (only 0.8°C) due mainly to the large spacing between boreholes. The COP_{sys} of GSHPS hardly changes year over year. The results verify that the distribution of the heating load for GSHPS and SAGSHPS in the proposed HSGSHPS is acceptable. In summary, the proposed HSGSHPS has the capability of resolving the problem of imbalance of heat extraction and injection while having higher COP_{sys} than that of conventional GSHPS under the same condition.

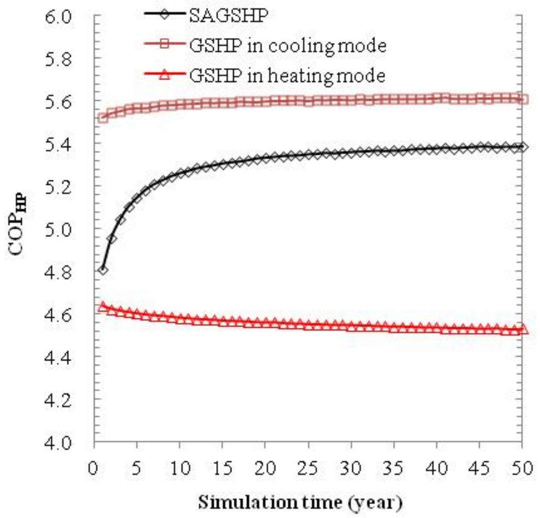


Figure 7 Variation of HP COPs with time

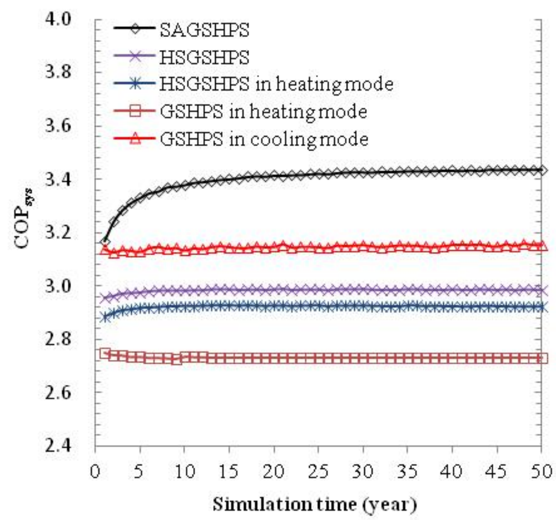


Figure 8 Variation of system COPs with time

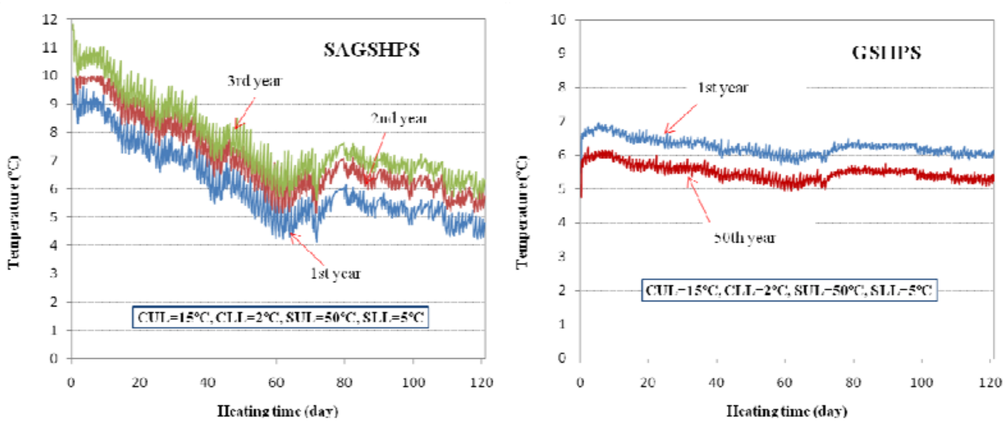


Figure 9 Fluid temperatures out of evaporators of HP of SAGSHPS and GSHPS

The minimum temperature of the evaporator's outlet should be determined based on the source fluid in order to protect the HP unit. The fluid used in the U-shape pipes of the boreholes of the proposed system is water. The minimum temperature is 5°C based on the manufacturer's specification. The minimum temperature can drop to -8°C, if the water is mixed with antifreeze (such as ethylene alcohol). Figure 9 shows that there are some instances when the outlet temperature of the evaporator in SAGSHPS are lower than 5 °C which is the limit of HP when water is used as the heat transfer fluid. However, the average soil temperature in BTES increases year by year. The outlet temperature of the evaporator is higher than 5°C during the whole heating season in the second year. The chosen suitable case cannot absolutely resolve the problem of the temperature limit of the HP used in SAGSHP in the first year. However, the amount of time with evaporator exit temperature below 5°C is only a small fraction of the whole heating season. Because the distribution system of GSHP and SAGSHPS connects together, the problem of temperature limit can be resolved by diverting part of the load from SAGSHPS to that of GSHPS. The GSHPS can provide majority of/total heating load when the HP of SAGSHPS cannot function due to low evaporator exit temperature. The heating load would then be supplemented by SAGSHPS in the following year to maintain the balance of the BTES of GSHPS.

For the GSHPS, the outlet temperature of the evaporator is never lower than the limit of 5ºC even in the 50th year. The distribution of the heating load for SAGSHPS and GSHPS in the proposed HSGSHPS is suitable.

5 Conclusions

A hybrid solar ground-source heat pump system (HSGSHPS) was proposed for an office building whose heating load is far larger than cooling load. The performance of the HSGSHPS was predicted by a simulation model developed in TRNSYS. The soil temperature, evaporator temperature, average annual coefficient of performance of heat pump (COP_{HP}) or system (COP_{sys}), and so on were simulated, analyzed and discussed. It is important to conduct simulation prediction of the system for proper design and determination of the control strategy. Suitable operation control strategies were also assessed, by using simulation, to provide directions for the operation of HSGSHPS. The conclusion can be drawn as follows:

(1) The distribution of heating load between HSHPS and SAGSHPS is appropriate. The average soil temperature of the BHE of GSHPS decreases 1.2ºC after 50 years. It hardly affects the performance characteristic of GSHPS in the long run. Otherwise, the average soil temperature of BTES of SAGSHPS increases annually resulting in the increase in COP_{sys} of both SAGSHPS and HSGSHPS.

(2) The HP will not work due to low evaporator temperature if insufficient thermal energy is injected into the BTES before extraction. As the heat exchange fluid in the source of the SAGSHP is water, even though the FOT is at the end of the heating season in the first year, there are still a few occasions when the evaporator temperature is lower than the limit during the first year of operation. The result shows that the outlet temperature of the evaporator is never lower than the limit (5ºC) for GSHPS during the life span of the BHE (50 years).

(3) The proposed HSGSHPS can be used in a building whose heating load is far greater than cooling load. The hybrid system of SAGSHPS and GSHPS resolves the thermal imbalance problem of the BHE in GSHPS while increasing the COP_{sys} of SAGSHPS.

The parameters used for the model components such as soil, solar collector, heat pump, and fan-coils correspond to that of the actual building itself. The accuracy of the simulation results should/and will be validated by the monitoring data obtained in the future. Furthermore, optimization study will be conducted for the entire system.

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