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Study on performance of solar energy interseasonal heat storage ground source heat pump system in cold region

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Abstract: In order to solve the problem of soil heat imbalance caused by winter heat load much higher than summer cooling load in severe cold areas of China, TRNSYS simulation software was used to analyze the performance of solar energy interseasonal regenerative ground source heat pump system in a hospital in Baotou City. The results show that COP and EER of the two heat pump units have little difference on a typical day, and the heating and cooling effect of the heat pump is relatively stable. Within ten years of operation of the inter-seasonal heat storage system, the soil temperature increased from 10℃ to 10.68℃, and the soil temperature of the solar-ground source heat pump composite system decreased to 5.62℃. At this time, the COP of interseasonal heat storage model was 3.25, up 2.2% year-on-year. It can be concluded that the solar energy cross-season heat storage mode can effectively alleviate the soil heat imbalance and improve the heat performance coefficient of the heat pump.

Keywords: cold region, TRNSYS, solar energy, interseasonal thermal storage, ground source heat pump

1. Introduction

According to the United Nations Environment Programme 2022 Report released by the Global Renewable Energy Status (UNEP), the higher the proportion of renewable energy consumption, the higher the degree of energy independence and security. Therefore, "reducing expenditure" and "increasing source" in the construction field has become one of the key tasks for China to realize the national major strategic decisions on energy conservation and emission reduction[1]. However, China is facing the dual pressure of energy shortage and environmental pollution, so seeking long-term, effective, clean and pollution-free renewable energy to solve the problem of building heating and cooling has become an important research direction in China[2]。

Ground source heat pump is one of the important technologies to achieve the goal of "double carbon", and also an important way to achieve energy conservation and emission reduction in the construction field in China. The definition was first explicitly proposed by Zoelly, using the soil as an environmentally friendly source of sustainable heating and cooling[3]. However, in cold areas where the heat load is much greater than the cold load, a single ground source heat pump system (GSHP) operates independently for several years, which will lead to soil thermal imbalance[4-6]Excessive soil heat exchange attenuation, which leads to poor heating effect and reduces the performance coefficient of the system[7-8]。

In recent years, with the continuous exposure of the disadvantages of ground source heat pump, solar energy-ground source heat pump composite system (SGSHP) has been widely used as a superior to a single source heat pump combination form[9]. The system was first proposed by P enrod in 1956, which can replace the traditional heating method in winter, can reduce the use of fossil energy and harmful gas emissions, and is one of the measures to achieve energy conservation and emission reduction in China's buildings[10]. However, the solar energy in the solar energy-ground source heat pump composite system can only reduce the proportion of heat supply of the heat pump units, and can not effectively alleviate the thermal imbalance in the cold areas[11-13]。

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Therefore, this paper proposes to use solar energy cross-season heat storage ground source heat pump to solve the problem of soil heat imbalance. Solar energy cross-season heat storage ground source heat pump system (SAGSHP) is on the basis of SGSHP system, added the solar energy in the transition season to buried pipe heat storage link, used to supplement the heating season ground source heat pump to the soil excessive heating. Taking a hospital building in Baotou city as an example, T RNSYS software was applied to establish a SAGSHP simulation model, and compared with the SGSHP system to analyze the changes of the heating performance coefficient, cooling energy efficiency ratio and soil temperature of the SAGSHP system, and determined that this system can solve the problem of soil thermal imbalance.

2. Building overview and load calculation

2.1 Architecture overview

In Baotou city, Inner Mongolia, the building covers a total area of 2,340 m2. The building is divided into three independent main bodies, namely, the second floor of the old building on the west side is the outpatient department, the second floor of the east side new building is the inpatient department and the bungalow on the west side is the fever clinic. Each floor is 3.3m high, and the layout of each floor is roughly the same. The ratio of window to wall is designed to be outpatient department 0, inpatient department 0 and fever clinic 0..36.31.33

The hospital is located in a severe and cold category C area, with an outdoor temperature range of between-23.05℃ and 34.4℃. According to GB 50189-2015 Energy Saving Design Standard for Public Buildings[14]Set the thermal parameters of the envelope, as shown in Table 1; according to J GJ26-2018[15], Set the internal disturbance parameters, as shown in Table 2.

Table 1 Thermal parameters of the envelope structure

building	Exterior wall heat transfer coefficient ($W/m^2\cdot k$)	Roof heat transfer coefficient ($W/m^2\cdot k$)	Building heat resistance ($W/m^2\cdot k$)	Heat transfer coefficient of outer window ($W/m^2\cdot k$)	Solar heat gain coefficient of outer window ($W/m^2\cdot k$)
fever clinics	1.11	0.61	1.12	2.60	0.53
Outpatient building	1.11	0.61	1.12	2.60	0.53
in-patient department	0.32	0.28	1.54	2.10	0.53

Table 2. Internal disturbance parameters

building	Personnel density ($person/m^2$)	Equipment power density (W/m^2)	Lighting power density (W/m^2)
fever clinics	0.125	20	8
Outpatient building	0.125	20	8
in-patient department	0.04	15	6

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2.2 Load calculation

The heating time of Baotou city is from October 15 to April 14, about 180 days; the cooling time is from June 15 to August 31, accumulated 77 days. TRNBuild software is used to build a building model and simulate the annual time-to-time load of buildings as shown in Figure 1.

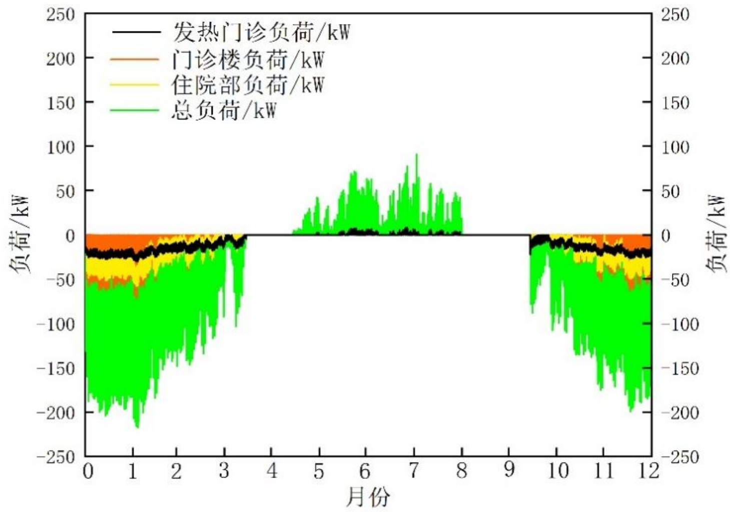

Figure 1 Time-by-year load of the building

It can be seen from Table 3 that the coldest month of the whole year is December, and the total heat load is 73646.52kWh. The simulation results here are slightly inaccurate. According to the local meteorological data of Baotou, the maximum heat load of that year appeared in January, mainly caused by rain and snow for several consecutive days in January. The hottest month of the year is June, with a cumulative cold load of 11663.32kWh.

Table 3 Monthly load for the whole year

Month	Fever clinic load / kWh	Outpatient department load / kWh	Inpatient department load / kWh	Overall load /kWh
January	15767.38	31685.45	24768.81	72221.64
February	13724.64	28637.94	21643.92	64006.50
March	9714.85	18154.89	10888.64	38758.38
April	2603.74	3857.63	1349.62	7810.66
May	70.15	491.04	2594.62	3155.81
June	719.11	2946.54	7997.68	11663.32
July	556.82	1518.73	8083.29	10158.84
August	215.10	516.32	5826.53	6557.95
September	0.00	0.00	0.00	0.00
October	2604.61	2979.81	516.25	6100.67
November	10133.81	20251.61	12866.01	43251.43
December	15435.72	33037.02	25161.79	73634.52

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3. System and model establishment

3.1 System design

This paper designs the SAGSHP system, which is divided into four subsystems. They are collector subsystem, ground source heat pump heating and refrigeration subsystem, buried pipe heat exchange subsystem and user terminal subsystem. The SAGSHP system adds the solar energy-assisted heating function, making full use of the advantages of rich solar energy resources in Inner Mongolia, and then reducing the running time of the heating season of the ground source heat pump unit. The schematic diagram of the SAGSHP system is shown in Figure 2.

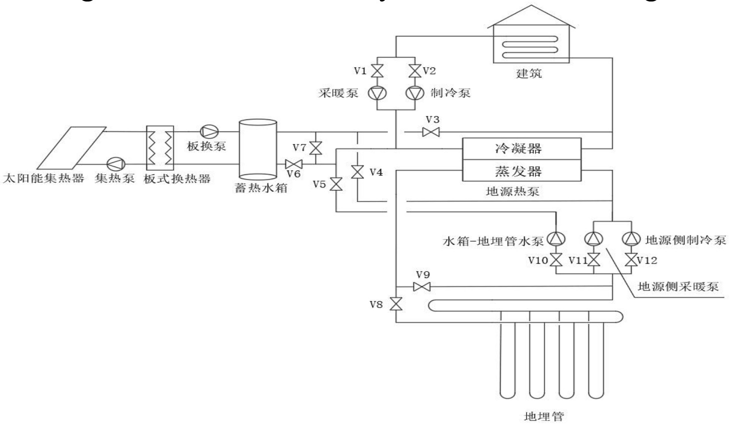

Figure 2. Schematic diagram of the SAGSHP system

This paper mainly studies the SAGSHP system heating storage, heating, cooling three working states. The operation control strategy of applying TRNSYS, medium temperature difference controller module, calculator module, seasonal control module and plotter module is given as follows:

1) Heat collection control: when the outlet temperature of the collector is 8℃ higher than the water temperature at the bottom of the water tank, the collector pump runs. When the outlet water temperature of the collector is minus the bottom water temperature of the water tank, the collector pump is closed than 2℃. When the collector has heated the tank to 90℃, the collector pump is forced off.

2) Heating control of the heating water storage tank on the buried pipe (non-heating season): when the top water temperature of the top of the water tank is 5℃ higher than the water outlet temperature of the buried pipe, the heating replenishment shall start. When the water temperature of the top of the water tank minus the outlet water temperature of the buried pipe is less than 2℃, the heating replenishment shall stop.

3) Ground source side heat storage tank for buried pipe heating control (heating season): in the early and late heating, due to the heat load is small, the collector heat collection, can start the heating control, specific control scheme is: in the heating season, when the water tank top temperature is higher than 85℃, start the buried pipe heating control, when the tank top water temperature is lower than 75℃, stop to buried pipe heating.

4) Ground source side heat storage water tank heating control: when in the heating season, the top temperature of the water tank is higher than 60℃, the water tank starts to start to the building heating, when the water temperature at the top of the water tank is lower than 55℃, the water tank stops the direct heating volume to the building.

5) Ground source side heat storage tank heating water mixing control: when the tank temperature is higher than the heating design temperature of 55℃, water mixing control, part of the heating return water is bypass, not into the ground source side heat storage tank, the remaining heating return water into the ground source side heat storage tank heating return water is mixed with the heating return water, by controlling the bypass water temperature stabilized at 55℃.

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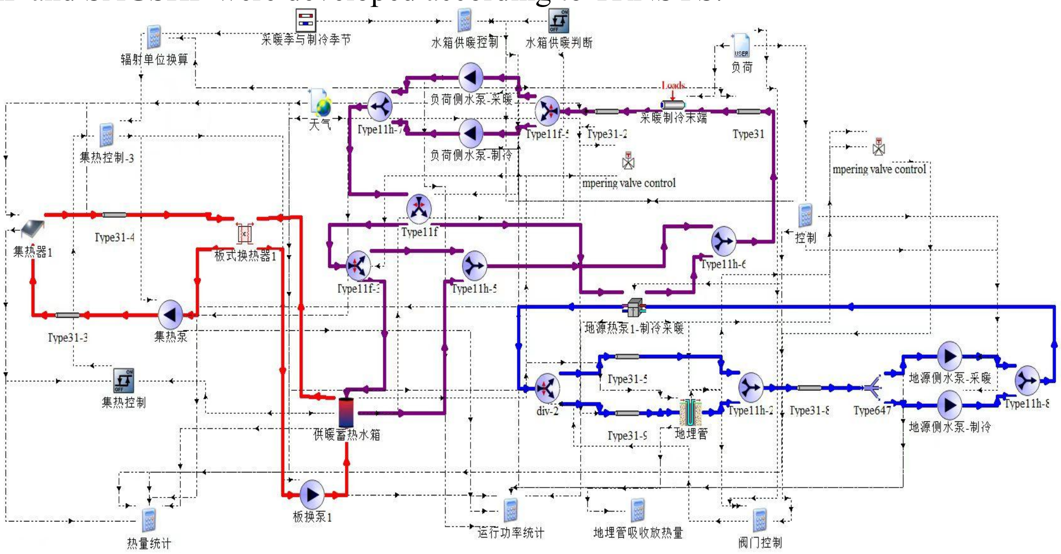
6) Heat pump heating and refrigeration control: when there is a heat load and the water tank is not in direct heating, the heat pump out of 55℃ of hot water, start heating, the corresponding pump also begins to operate, otherwise, the heating stops, the corresponding pump turns off. When there is a cold load, the heat pump starts to produce 7℃ of cold water and begins to cool down. The corresponding pump is opened. When there is no cold load, the heat pump cooling is closed, and the corresponding pump is also closed.

7) Summer cooling water bypass control at the buried pipe: in summer refrigeration, in order to prevent the outlet water temperature of the buried pipe is too low, resulting in the unit can not be normal cooling, so a bypass control is adopted. During operation, if the outlet water temperature of the buried pipe is less than 16℃, the partial cooling water is bypassed without heat dissipation through the buried pipe. The partial bypass cooling water is mixed with the buried pipe outlet water, and the mixed water is stabilized at 16℃ through the bypass water control. If the outlet water temperature of the buried pipe is higher than 16℃, then close the bypass.

3.2 Model building

The TRNSYS Simulation Software is a transient process modular energy consumption simulation software, jointly developed by researchers at the Institute of Building Technology and Solar Energy Reuse at the Wisconsin-Madison College, USA. Contains software such as Simuiation Studio, TRNEdit, TRNOPT, and TRNBuild. As shown in Figure 3, two system simulation models of SGSHP and SAGSHP were developed according to TRNSYS.



a SGSHP system

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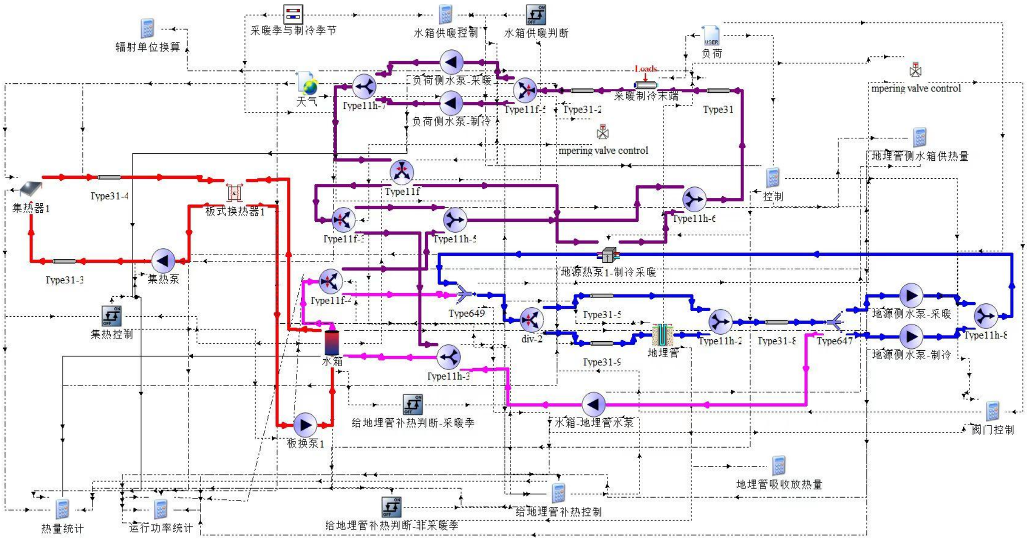

b SAGSHP system

Figure 3. Heating system model

TRNSY divides the parts of the system with different functions into different modules between which separate digital models are input in the form of subroutines. This model mainly uses the weather module(type 15-2), plate heat exchanger module(type91), single U-shaped buried pipe module (type557a), temperature controller module(type165), heating season and cooling season control module(type515), load reading(type9e), formula converter(equation), water tank module(type158), user terminal(type682), water pump(type114) and result display(type65a), etc. In addition, C++ is also used to create a ground source heat pump module(type216) that meets the requirements.

4. Analysis of the simulation results of coupling system

4.1 Analysis of typical daily simulation results

According to the typical meteorological data of Baotou City, February 3 is the coldest day, and the average outdoor temperature is lower than -15℃; June 21 is the hottest day, and the average outdoor temperature is higher than 25℃. Two typical days of the coldest days and the hottest days were selected to analyze the COP and EER of the heat pump units of the two systems.

Figure 4 shows the change trend chart of the COP and EER of the hourly heat pump units on February 3rd and June 21st, respectively. Because SGSHP and SAGSHP systems are solar energy as auxiliary heat source to ground source heat pump in heating season, so the COP change of heat pump unit is very small and kept at 3.30; both cooling season are directly cooled by ground source heat pump, so the EER of heat pump unit is basically consistent and kept at 7.55, so the heating and cooling of heat pump unit have high stability.

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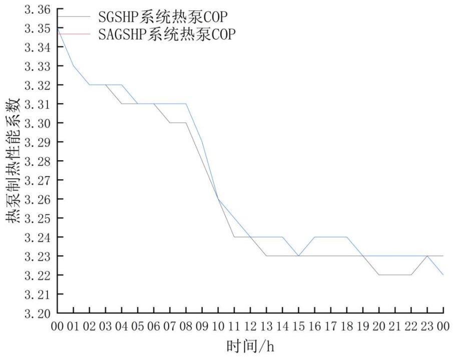
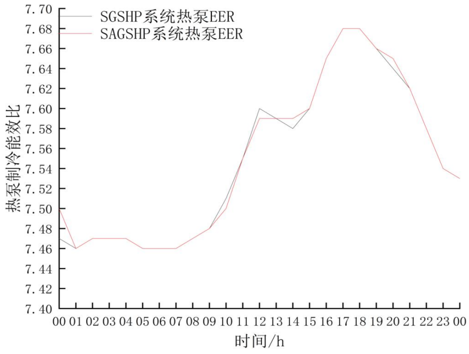




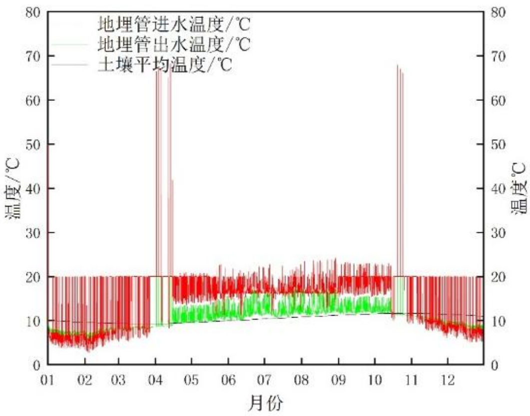
a COP analysis b EER analysis

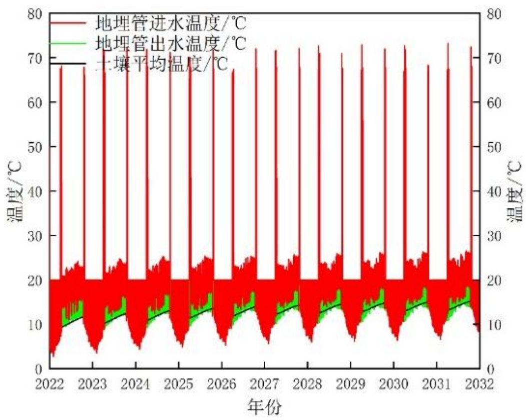
Figure 4. Analysis of the typical daily simulation results

4.2 Analysis of the simulation results

4.2.1 Average soil temperature

The change of soil average temperature is an important parameter to monitor the operation of the heat storage system. The simulation model of the above two systems is simulated for one year and ten years respectively to output the inlet and outlet temperature of the buried pipes and the average soil temperature. As can be seen from Figure 5, for the SAGSHP system, the average soil temperature gradually drops within one year, and the temperature rises after heat storage, and then drops again. However, because the heat storage is greater than the heat extraction, the temperature rises to 10.16℃. The trend of soil temperature change remained consistent within ten years and within one year, with repeated circulation.





a temperature trend in the first year b temperature trend in ten years

Figure 5 Soil temperature trends

As shown in Figure 6 are the soil temperature changes of SGSHP system and SAGSHP system. For the SGSHP system, the soil temperature has dropped from 10℃ to 5.62℃ due to the excessive heat extraction during the heating season. It follows that the hospital building is not suitable for the system. Under the SAGSHP system, the soil temperature rose from 10℃ to 10.68℃, up by 0.68℃, or by 6.8%. It fully shows that the SAGSHP system can effectively solve the problem of soil thermal imbalance.

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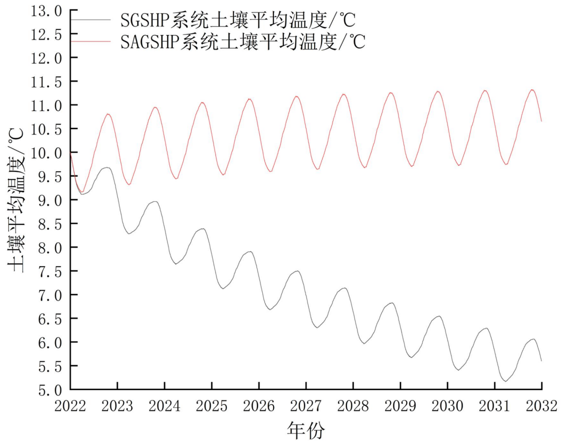

Figure 6 Soil temperature change in the past decade

4.2.2 Performance Coefficient

Ground source heat pump is by inputting a small amount of electric energy, the shallow geothermal energy into heat energy, can be used for the building heating and can be used for cooling. The heating performance coefficient (COP) of the heat pump unit (EER) is calculated according to the following formula[16]：

$$COP = \frac{Q}{N_i} \quad (1)$$

$$EER = \frac{Q}{N_i} \quad (2)$$

$$Q = \frac{V\rho c\Delta t_w}{3600} \quad (3)$$

In Equation (1), (2) and (3) above:COP——Heat performance coefficient of heat pump unit；EER——Refrigeration energy efficiency ratio of heat pump unit；Q——Average heating (cooling) of a unit，kw；N_i——Average input power of the unit，kw；V——Average user side flow of heat pump unit，m3/h，ρ——Average density of hot (cold) medium，kg/m3；c——Average specific heat at constant pressure of hot (cold) medium，kj/(kg.℃)；Δt_w——Average temperature difference between inlet and outlet medium at user side of heat pump unit。Coefficient of heating performance of heat pump system（COP_{sys}）,Refrigeration energy efficiency ratio of heat pump system（EER_{sys}）.It shall be calculated according to the following formula according to the test results [16]：

$$COP_{sys} = \frac{Q_{SH}}{\Sigma N_i + \Sigma N_j} \quad (4)$$

$$EER_{sys} = \frac{Q_{SC}}{\Sigma N_i + \Sigma N_j} \quad (5)$$

$$Q_{SH} = \sum_{i=1}^{n} q_{hi}\,\Delta T_i \quad (6)$$

$$Q_{SC} = \sum_{i=1}^{n} q_{ci}\,\Delta T_i \quad (7)$$

$$q_{h(c)i} = V_{i\rho_i c_i}\Delta t_i/3600 \quad (8)$$

In Equation (4), (5), (6), (7) and (8) above:Q_{SH}——Cumulative heat system，kw·h; Q_{SC}——Total system cooling capacity，kw·h；ΣN_i——Cumulative power consumption of all heat pump units，kw·h；ΣN_j——Total power consumption of all pumps，kw·h；$q_{h(c)i}$——Period I heating (cooling) of a heat pump system，kw；V_i——Average traffic on the user side in time period I，m3/h；

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Δt_i——Temperature difference between inlet and outlet media at user side during period I of heat pump system，℃；ρ_i——Average density of cold media at time I，kg/m3；c_i——Average specific heat of cold medium at constant pressure in period I，kj/(kg.℃)；ΔT_i——Duration of period I，h；n——Number of collected data groups.

It can be seen from Table 4 that compared with SGSHP operation mode, the COP of heat pump units increased by 2.2% vs. EER increased by 0.13% year on year. The difference between C OP and E ER of the two systems is small, mainly because the solar auxiliary ground source heat pump heating method is used in the heating season, and the ground source heat pump is independently cooled, which has no great impact on the heat performance coefficient and cooling energy efficiency ratio of the heat pump units.

COP_{sys} In the heating season, the SAGSHP system stores heat to the buried pipe, and the power consumption of the water pump unit increases, so it is slightly lower than the SGSHP system, but it has little impact on the heating effect of the system. The system still has a strong heating capacity, and can effectively alleviate the problem of soil heat imbalance. EER_{sys} In the refrigeration season, SAGSHP system is not significantly different compared with SGSHP system, which does not affect the refrigeration effect.

Table 4 Performance coefficient and energy efficiency ratio of the two systems

system	COP	COP_{sys}	EER	EER_{sys}
SGSHP	3.18	3.26	7.54	4.96
SAGSHP	3.25	3.24	7.55	4.97

4.2.3. System power consumption

As can be seen from Table 5, the power consumption of the cross-season heat storage unit is 374kw·h lower than the non-heat storage system in one year, and the energy consumption of the unit is about 1.2%. However, because the SAGSHP system needs to open the pump heat storage in the transition season, the final total power consumption is higher than that of the SGSHP system, with a difference of 10.19%.

Table 5 Energy consumption in the first year

system	Unit power consumption	Heat pump power consumption	Heat storage consumes electricity	The total power consumption
SGSHP	30561kw·h	69684kw·h	0kw·h	100245kw·h
SAGSHP	30187kw·h	68767kw·h	11510kw·h	110464kw·h

According to Table 6, it shows the energy consumption analysis of the heating and cooling system of the two systems over the past ten years. The power consumption of the cross-season heat storage mode is 1548kw·h less than that of the non-heat storage mode, and the energy consumption of the unit is reduced by about 0.5%. However, because the cross-season heat storage mode needs to open the pump heat storage in the transition season, the final total power consumption is basically consistent, with a difference of 1.79%.

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Table 6. Energy consumption of the system in ten years

system	Unit power consumption	Heat pump power consumption	Heat storage consumes electricity	The total power consumption
SGSHP	309474kw·h	740232kw·h	0kw·h	1049706kw·h
SAGSHP	307926kw·h	660972kw·h	99603kw·h	1068501kw·h

5. Conclusion

1) The SAGSHP system is suitable for severe cold areas. The system stores the solar energy to the underground heat in the transition season to supplement the excessive heating to the soil in winter, which can effectively solve the problem of soil thermal imbalance. The difference between COP and EER between SAGSHP system and SGSHP system is small, keeping around 3.30 and 7.55 respectively, which can provide relatively stable heating and cooling effect.

2) When the initial soil temperature is 10℃, the average soil temperature of SAGSHP system increases by 0.68℃. At this time, COP of SGSHP system is 3.18, EER is 7.54; COP of SAGSHP system is 3.25, up 2.2% year on year, and EER is 7.55, up 0.13% year on year.

3) Comparing the two operation modes, it is found that SAGSHP system can be significantly improved compared with SGSHP system, and the heating effect of heat pump unit is improved. In one year, the difference in energy consumption between the two systems is 10.19%; in ten years, the difference in energy consumption between the two system mode is less than 1%.

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