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Solar Assisted Ground Source Heat Pump for Heating System

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Abstract:

In the winter heating system, the long-term operation of the ground source heat pump (GSHP) will cause the average soil temperature to drop, and the performance of the GSHP will decrease. This paper proposes an integration of solar collectors into the GSHP for assisting the long-term operation of heating system. The thermodynamic models of solar collector, hot water storage tank, heat pump, ground heat exchanger are constructed. The operation modes of the solar-assisted GSHP are presented. To minimize the annual total cost considering investment cost and operation cost, an optimization model considering soil heat balance is presented to optimize the system configurations, in which enumeration method is employed to solve the optimization problem. The match of suitable solar collectors with GSHP is discussed. Taking a residential area of 70,000 square meters in northern China as an example, the optimization and operating performance of solar-assisted ground-source heat pumps were studied. By comparing several typical operation modes, the optimal operation mode of the system is obtained, which reduces the investment cost..

Keywords —Ground source heat pump (GSHP); solar collector; operation mode; optimization

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I. INTRODUCTION

Ground source heat pump (GSHP) is a kind of high efficiency, energy saving and environmental protection air conditioning system that utilizes shallow underground geothermal resources for heating and cooling. However, the heat pump unit could be impaired under short-time continuous operation modes or long-term imbalanced-load conditions [1].What is more, the average temperature of soil would decrease and the coefficient of performance of the heat pump would decrease. Degradation of the heat pump performance is avoided by offsetting the annual load imbalance in the borefield [2].

Compared to the GSHP, solar assisted GSHP has a higher COP and a less cost. For example, solar energy can be stored in the daytime for radiation heating at night. A studied result from Verma and Murugesan [3] The results show that the additional thermal energy extracted from the ground by the system at night is 2.8-3.2 times as much as the operating input of the solar collector, and the the system capital is improved by 23%. The solar assistance in the GSHP based on shallow well buried pipe heat exchanger reduces the borehole length [4].

Improving the performance of solar assisted GSHP requires appropriate technologies, design methods and operation modes, in which system optimization is one of the effective methods. Weeratunge et al. [5] put forward a linear programming optimization method, which can reduce the operation cost of solar assisted GSHP system combined with peak valley electricity price. Sun et al. [6] proposed a novel SACSHP system that considers thermal cascade utilization. Ji et al [7] proposed a simplified method to determine the optimal solar energy collecting area of solar assisted GSHP system based on the soil heat balance and system economy. Kegel et al. [8] proposed a system combining GSHP system with vacuum tube solar collector in the research of energy end use of solar assisted GSHP. Reda et al. [9] established a solar assisted GSHP combined with heat storage and cold storage system, and compared with the traditional GSHP system for energy evaluation. Jiang [10] established a three-dimensional borehole heat conduction model, and analyzed the system energy transfer process, soil heat transfer process and building heat transfer process. Han et al. [11] established a heat transfer calculation model based on dynamic load and complex geological conditions. The influence of seasonal solar energy storage assisted GSHP seepage on operation performance is analyzed, and the seepage effect of seasonal heat storage is quantitatively analyzed. Besagni et al. [12] proposed a new type of solar assisted heat pump system, which coupled a hybrid photovoltaic / thermal (PVT) panel with a multifunctional reversible heat pump. The heat pump is equipped with "air source" and "water source" evaporator. According to the environmental conditions, the system parameters and operation mode are connected in series and operated alternately.

Moreover, the solar assisted GSHP system with heat injection has a better performance in soil thermal environment. Compared to the system with heat injection, the average temperature of soil decreases 0.8 K in the system without heat injection after a year operation [13]. Paiho et al. [14] studied the impact of solar energy storage on local self-sufficiency of heating energy and the impact of solar heating on the environment. The heat collected by the solar collector in summer is stored in the buried pipe, and the heat stored in the buried pipe is used for heating in winter, which can achieve 60% self-sufficiency of heat and reduce 50% carbon dioxide emissions. Carlosnaranjo-mendoza et al. [15] introduced a household SACSHP shallow drilling technique for seasonal underground energy storage. The results showed that solar energy injected into the surface not only helps to restore the soil from thermal imbalance, but also contributes to heat storage. Yang and Liu [16] simulated the operation of one year with and without supplementary heat. The results show that the conditions with supplemental heat are better than those without supplemental heat, and the supplemental heat can improve the quality of soil thermal environment and the performance of the solar-assisted GSHP system. Youssef et al. [17] designed and implemented a detailed control strategy for the system to operate efficiently in different modes and maintain a constant load water supply temperature during operation. Hirvonen et al. [18] put forward a solar community located in Finland, which was optimized with respect to energy demand and life cycle cost.

Energy management of solar-assisted GSHP is an important research direction to improve energy efficiency. Energy management of solar-assisted GSHP is an important research direction to improve energy efficiency. Li et al. [19] used a project in Tianjin to design and analyze the problem of cross season heat storage. In this paper, the solar collector's heat collection power and the underground heat storage power of the buried tube heat exchanger are simulated, which proves the feasibility of cross season heat storage. Wang et al. [20] established the solar assisted GSHP system, proposed the control logic of heating season and non-heating season, and studied the influence of the temperature difference of the start-up of the heat collection.

The operation mode of solar-assisted GSHP is of great significance for improving energy utilization efficiency and reducing economic cost. Ji et al. [21] constructed a system composed of solar energy storage water tank, GSHP and solar collector. A dual heat source combining a heat pump and a heat storage tank is used for heating, and the operation mode is selected according to the temperature of the heat storage tank. Li [22] of Beijing University of architecture proposed in his master's thesis that the solar energy heat source and soil source heat source operate in parallel and are configured according to the ratio of 1:1, and the system performance coefficient is the highest. The operation mode designed by Nam et al. [23] for residential building system is divided into 20:00-5:00 heating mode and

6:00-18:00 solar energy heat storage mode. Chen and Yang [24] presents the numerical simulation of GSHP system which can provide both space heating and domestic hot water (DHW). The optimization process is completed on the TRNSYS based platform by simulating the influence of solar collector area on the total borehole length and system performance.

In order to solve this problem, the long-term operation of the ground source heat pump system causes the soil temperature to drop, and can not continue to heat . This paper presents a solar assisted ground source heat pump heating system, using solar collector and ground source heat pump heating in winter, in summer and transition seasons using solar collector to heat stored in the soil, the soil heat from the rising to thermal equilibrium, and describes in detail the structure and operation mode of the system, and the simulation analysis on the actual engineering.Finally, relevant optimization results are given.

II. SOLAR ASSISTED HEAT PUMP SYSTEM

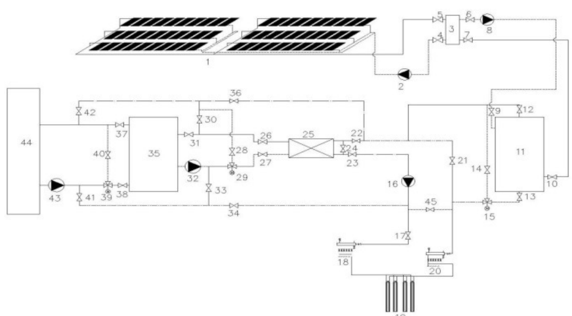


Fig.1 Heating system diagram of solar GSHP

1—Solar collector; 2—Solar hot water pump; 3—Plate heat exchanger; 8—Solar heat storage pump; 11-Solar thermal storage tank; 15-Electric three-way valve; 16-Ground source side circulating water pump; 18- Manifold; 19-Buried pipe heat exchanger; 20-Collector; 25-Heat pump unit; 29-Electric tee valves; 32-Reservoir circulating pumps of heat pump units; 35-Heat pump thermal storage tank; 39—Electric three-way valve; 43—User-side circulating water pump; 44—Building. Other states—Valves.

Fig. 1 displays the energy flows of solar assisted GSHP heating system, which is mainly composed of a solar collector, a solar thermal storage tank, a buried tube heat exchanger, a heat pump unit, and a heat pump thermal storage tank. During the day, the heat collected by solar collector is stored in the solar thermal storage tank. The solar thermal storage tank is the heat source of heat pump units and users. During the night, the heat produced by heat pump unit is stored in heat pump thermal storage tank, which is the heat source of users. The heat absorbed by buried pipe heat exchanger is transferred to the heat pump units for heating. In winter, the solar collector and the GSHP supply heat together. In summer and transition seasons, the heat collected by the solar collector accumulates the heat to the soil, which makes the balance between heat extraction and heat supplement.

A. *System operating modes*

A solar collector uses solar radiation to generate heat. When solar radiation is available, the solar collector starts to operate. The temperature of the water in the solar heat storage tank is always changing due to the influence of the operating state of the solar collector. Different operation modes are opened according to the temperature of the hot water during heating.

(1) When the temperature of solar thermal storage tank is greater than or equal to 40℃, the solar thermal storage tank provides direct heating.

(2) When the temperature of the solar thermal storage tank is between 25 °C and 40 °C, the water from solar thermal storage tank is mixed with the effluent from the buried pipe heat exchanger and flows into the evaporator of the heat pump unit for heating.

(3) When the temperature of the solar thermal storage tank is between 10 °C and 25 °C, the hot water of the solar thermal storage tank directly flows into the evaporator of the heat pump unit, and the heat pump provides heating.

(4) When the temperature of the solar water storage tank is less than 10 °C, the buried pipe heat exchanger is used as the evaporator of the heat pump unit.

A1. System operation mode in winter

The control mode of the system has been stated in the previous part. In winter, in order to reduce the operating cost of the system, solar collectors and off-peak power policies should be fully utilized, so different operating modes of the system should be adopted. When the solar radiation intensity is greater than zero, the solar collector accumulates heat to the solar energy storage tank. When the temperature of the solar energy storage water tank is higher than 10 ℃, the heat in the solar thermal storage water tank is preferred for heating. When the temperature of the solar thermal storage tank is lower than 10 ℃, the buried pipe heat exchanger is used as the heat source of the heat pump unit.

(1) Mode one: Heat storage of heat pump unit

During the period of 1: 00-5: 00, the heat pump unit accumulates heat by means of off-peak electricity.

(2) Mode two: Heat storage tank heating of heat pump unit

During the period of 6: 00-11: 00, the heat storage tank of the heat pump unit uses the heat stored in the water tank to provide heating to users.

(3) Mode three: Solar thermal water storage tank

When the solar radiation intensity is greater than zero, the solar collector collects heat and stores the heat in a solar thermal storage tank.

(4) Mode four: Direct heating by solar water storage tank

When the temperature of the solar thermal storage tank is 40 °C or higher, the solar thermal storage tank directly supplies heat.

(5) Mode five: The mixed water of the solar water storage tank and the buried tube heat exchanger is used as the heat source of the evaporator, and the heat pump unit is used for heating

When the temperature of the solar thermal storage tank is between 25 °C and 40 °C, the solar thermal storage tank is mixed with the effluent of the buried tube heat exchanger and flows into the heat pump unit evaporator to heat the heat pump.

(6) Mode six: Solar water storage tank is used as the heat source of the evaporator, and the heat pump unit is used for heating

When the hot water of the solar thermal storage tank directly flows into the evaporator of the heat pump unit, the temperature of the solar hot water storage tank heated by the heat pump is greater than 10 □ and lower than 25 □, and the hot water of the solar thermal storage tank directly flows into the evaporator of the heat pump unit to heat the heat pump.

(7) Mode seven: Heat pump unit heating

When the temperature of the solar thermal storage tank is 10 □ or lower, the buried tube heat exchanger is used as the evaporator of the heat pump unit, and the heat pump unit is turned on to supply heat to the user.

A2. System operation mode in summer and transition season

In summer and transition season, solar collectors only serve as the system's heat supplement device since there is no need to provide heat to users. When the solar radiation intensity is greater than zero, solar collectors collect heat and store heat in the soil, so as to ensure a balance between taking heat and releasing heat from the soil throughout the year, so that the system can operate stably for a long time.

(1) Solar collector heat collection: When the solar radiation intensity is greater than zero, the solar collector collects heat and stores the heat in the solar thermal storage tank.

(2) Solar thermal storage tanks store heat in the soil: When the temperature of the solar thermal storage tank is higher than the soil temperature, the solar thermal storage tank stores heat in the soil.

B. Modelling

Taking winter as an example, this paper simulates and calculates the operation plan of the solar-assisted geothermal heat pump heating system, which is an economic optimization plan that meets the user's heat load and soil heat balance. In this paper, the thermodynamic models of components are established and， in order to facilitate the calculation, the following assumptions are made:

(1) The temperature distribution inside the solar thermal storage tank is uniform, and there is no temperature stratification.

(2) The temperature of the solar thermal storage tank is as same as the internal water temperature.

(3) Ignore the heat loss from the bottom and sides of the solar collector.

(4) The solar radiation intensity is calculated in hours, and the change of solar radiation intensity within one hour is ignored.

(5) Ignore the heat loss of the system pipes.

B1. Solar collector model

The amount of heat collected by a solar collector is related to the area of the collector, the efficiency factor of the collector, solar radiation, the heat loss coefficient of the collector plate, and thetemperature difference between the collector and the environment. The formula is as follows [10]:

$$m=\sqrt{\frac{U_L}{k\delta}} \tag{1}$$

$$F=\frac{\tanh[m(W-D)/2]}{m(W-D)/2} \tag{2}$$

$$F'=\frac{\frac{1}{U_L}}{W[\frac{1}{U_L[D+(W-D)F]}+\frac{1}{C_b}+\frac{1}{\pi D_i h_{fi}}]} \tag{3}$$

$$Q_C=A_C F'[G_t(\tau\alpha)-U_L(T_p-T_a)] \tag{4}$$

Where A_C is the area of solar collector(m^2); $G_t(\tau\alpha)$ is absorbed solar radiation(W/m^2); $(\tau\alpha)$ is generally 0.7-0.75; G_t is the irradiance, which is replaced by the radiant product I_t; $I_s=I_t/\cos\theta$,Where I_s is the intensity of solar radiation projected onto the collector at each moment , I_t is the solar radiation intensity at the horizontal plane at each moment; U_L is the total heat loss coefficient of the heat collecting plate (W/(m^{2}K)); T_p is the inlet fluid temperature (K); T_a is the ambient temperature(K); F' is the collector efficiency factor; m is the fluid flow rate(m/s); C_p is the specific heat capacity of the fluid(J/(kg*K)); W is the distance between the collector tubes(m); D is the diameter of the collector tube(m); C_b is the adhesion conductivity; h_{fi} is the heat transfer coefficient between the fluid and the pipe wall(W/m^2 K); D_i is the inner diameter of the pipe(m); F is the efficiency of flat collector ribs; k is the thermal conductivity of the solar collector(W/(m*K)); δ is the thickness of the solar collector sheet(m).

As the heat collector is installed on the bottom and sides of the flat-plate collector, the heat loss is negligible. The total heat loss coefficient mainly considers the heat loss coefficient on the top of the collector. The calculation formula is as follows [11]:

$$U_L=\{\frac{N}{\frac{c}{T_{p,m}}[\frac{T_{p,m}-T_a}{(N+f)}]^e}+\frac{1}{h_w}\}^{-1}+\frac{\sigma(T_{p,m}+T_a)(T_{p,m}^2+T_a^2)}{(\varepsilon_p+0.00591Nh_w)^{-1}+\frac{2N+f-1+0.133\varepsilon_p}{\varepsilon_c}-N} \tag{5}$$

$$c=520(1-0.000051\beta^2) \tag{6}$$

$$e=0.43(1-100/T_{p,m}) \tag{7}$$

$$f=(1+0.0892h_w-0.1166h_w\varepsilon_p)(1+0.07866N) \tag{8}$$

$$h_w=5.7+3.8u_w \tag{9}$$

Where U_L is coefficient of heat loss(W/(m^{2}K)); N is the number of layers of glass cover, take 1; ε_c is the emissivity of glass, take 0.88; ε_p is the emissivity of the collector plate, take 0.5; $T_{p,m}$ is the average temperature of the collector plate; T_a is the ambient temperature; β is the tilt angle of the collector, which is 45 °; h_w is convective heat transfer coefficient (W/(m^2□)); u_w is the environmental wind speed (m).

B2.Solar thermal storage tank model

The heat balance of the thermal storage tank can be expressed as:

$$Q_T=Q_C-Q_U-Q_{HL} \tag{10}$$

Where Q_T is the heat of hot water in the hot water storage tank(W); Q_C is the heat collected by the solar collector(W); Q_U is the heat that the thermal storage tank supplies to the user(W); Q_{HL} is the heat lost by the thermal storage tank(W).

The heat that the thermal storage tank supplies to the user is calculated as:

$$Q_U=C_W m_S(T_o-T_i) \tag{11}$$

Where is the specific heat capacity of water(J/(kg•K)) is the quality of the water in the thermal storage tank(kg); is the outlet temperature(K); is the inlet temperature(K).

The heat lost by the thermal storage tank is calculated as:

$$Q_{HL} = U_T A_T (T_T - T_a) \tag{12}$$

Where is heat loss coefficient(W/m^2 K)，and it is set to 0.03; is the external surface area of the thermal storage tank(m^2); is the temperature of the tank of the thermal storage tank(K); This article approximates that the water temperature in the water tank is the same as the temperature of the tank. is the ambient temperature(K).

B.3 Heat pump model

According to conservation of energy, heat output of heat pump is the sum of input heat and its power. The heat generation capacity of the heat pump can be calculated by [21]:

$$Q_{heating} = Q_{source} \text{-} P_{hp} \tag{13}$$

$$Q_{source} = C_{p,source} m_{source} (T_{source,in} - T_{source,out}) \tag{14}$$

Where is the heat supply to user, is the heat transferred from source, is the consumed power by the heat pump, is the specific heat of source fluid, is the source water mass flow rate, is the inlet source water temperature and is the outlet source water temperature.

B.3Buried pipe heat exchanger model

The heat absorbed by buried pipe in soil is calculated as:

$$Q_{bp} = C_{p,bp} m_{bp} (T_{bp,out} - T_{bp,in}) \tag{15}$$

Where is the heat absorbed from the ground(W); is the specific heat of fluid(J/(kg•K)); is the fluid mass flow rate(kg/s); is the inlet fluid temperature(K); is the outlet fluid temperature(K).

III. OPTIMIZATION METHOD

A. Decision variables

In the solar assisted GSHP heating system, the volume of the solar energy storage water tank is a function of the area of the solar collector, and the solar collector mainly plays the role of heat supplement to the soil in summer and transition season. During the non-heating seasons, the amount of heat transferred into the ground by the system depends on the area of the solar collector.

As shown in Fig. 1, the system is composed of solar collector, solar storage water tank, buried pipe heat exchanger, heat pump unit and heat pump unit storage water tank, among which solar collector and heat pump unit are used to produce heat. As the area of solar collector increases, the more heat the solar collector produces, the less cost it takes to operate the heat pump unit. However, the initial investment cost of the system increases with the increase of solar collector area. The area of solar collector determines the total cost of the system, so the area of solar collector is a decision variable.

B. Objective function

The area of solar collector plays a decisive role in the total cost of the system and the balance of heat absorption and heat release of the system, so the cost objective function is established.

The cost goals of this article include investment costs and operating costs. The total annual cost is the sum of the two. The lowest total cost within the service life is the best solution.

The annual investment cost is calculated as:

$$C_C = C_{UC} A_P CRF \tag{16}$$

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1} \tag{17}$$

Where is the annual investment cost of solar collector(yuan / year); is the investment cost per unit area of solar collectors(yuan / m^2); is the area of solar collector(m^2); is the capital recovery factor; is the discount rate, this article is calculated at 8%;n is the service life, this article is calculated based on 15 years. The area of the flat plate collector is 2m^2, and the price of each collector is 900 yuan / piece; The value of is 450 yuan / m^2.

The annual investment cost of solar thermal storage tanks is calculated as:

$$C_{CST} = C_{UST} V_{ST} CRF \tag{18}$$

Where is the annual investment cost of solar thermal storage tanks(yuan / year); is the investment cost per unit volume of the thermal storage tank(yuan / m3); is the volume of the thermal storage tank(m3).

The volume of the thermal storage tank is calculated as:

$$V_{ST} = \varphi A_P \times 10^{-3} \tag{19}$$

Where is the volume of the water tank per unit area collector (L / m^2), collector area, this article takes 75 L / m2 , the cost per unit volume is 560 yuan / m^3.

The annual investment cost of the heat pump unit is calculated as:

$$C_{HEAC} = C_{HPUC} CRF \tag{20}$$

Where is the annual investment cost of the heat pump unit(yuan / year); is the cost of heat pump unit(yuan); . is the capital recovery factor.

$$C_{BP} = C_{UBP} L_W CRF \tag{21}$$

Where is the annual investment cost of buried pipe; is the length of the buried tube heat exchanger needed in winter (m); is the investment cost per underground meter of underground pipes (yuan / year).

The annual investment cost of the pump is calculated as:

$$C_P = (C_{SP1} + C_{SP2} + C_{GP} + C_{UP}) CRF \tag{22}$$

Where C_P is the annual investment cost of the pump (yuan / year); C_{SP1} is the initial investment of heat pumps to extract solar energy (yuan); C_{SP2} is the initial investment of heat pumps to store solar energy (yuan); C_{GP} is the initial investment of ground source side circulating water pump (yuan); C_{UP} is the initial investment of the user-side circulating water pump (yuan).

The annual investment cost of the plate heat exchanger is calculated as:

$$C_{HE} = C_{UHE} A_{HE} CRF \tag{23}$$

Where C_{HE} It is the annual investment cost of the plate heat exchanger(Yuan / year); C_{UHE} It is the cost per unit area of plate heat exchanger(yuan / m^2); A_{HE} It is the area of the plate heat exchanger(m^2).

Annual investment cost of solar-assisted GSHP system can be calculated by following equation.

$$C_I = C_C + C_{CST} + C_{HPAC} + C_{BP} + C_{HPST} + C_P + C_{HE} \tag{24}$$

C. Restrictions

C1. Conservation of energy

During the operation of the system, the heat collected by the heat pump unit and the solar collector meets the total heat load of the users.The total power when the heat pump unit is turned on is equal to the total heat load in winter minus the total heat collection of the solar collector in summer, transition seasons and winter.

$$P_{hp} t_p = Q_h - Q_c t_d - Q_c t_{xg} \tag{25}$$

Where P_{hp} is the power of the heat pump unit(kW); t_p is the time of the heat pump unit(h); Q_h is the total load of the system in winter(kWh); Q_c is the heat collection of solar collectors (kW); t_d is the running time of the solar collector in winter (h) ; t_{xg} is the running time of solar collectors in summer and transition season (h).

C2. Collector area constraint

The minimum value of the solar collector area is greater than zero, and the maximum value is the sum of the roof areas of all buildings, so the area of the solar collector is in between.

$$0 < A_c \le A_r \tag{26}$$

Where A_c is the total area of solar collector; A_r is the total area of the building roof.

C3. Constraints on working hours of solar collectors

The working time of the solar collector depends on the solar radiation intensity. When the radiation intensity is greater than 0 and the output temperature is greater than the output temperature of the solar collector, the solar collector starts to operate. In the winter, the solar collector running time is less than the total time of heating; in the summer and transition season, solar collectors running time is less than the total time of non-heating season.

$$0 \le t_d \le N_g \times 24 \tag{27}$$

$$0 \le t_{xg} \le N_{fg} \times 24 \tag{28}$$

Where N_g is the number of heating days in winter, this article takes 151; N_{fg} It is the number of non-heating days in summer and the transition season.，this article takes 214.

D. Solution method

The enumeration method enumerates all possible answers to the question, and then judges whether the answer is appropriate according to the conditions, keeps the appropriate, and discards the inappropriate. The enumeration algorithm flowchart shows in Fig. 2.

Solution steps in this paper are as follow:

1) The area of solar collector that starts from 1 square meter increases by 1 square meter each time.

2) Determine whether the area of solar collector is lower than the area of roof of the building.

3) Calculate the annual cost with every area of solar collector, and output the lowest annual cost.

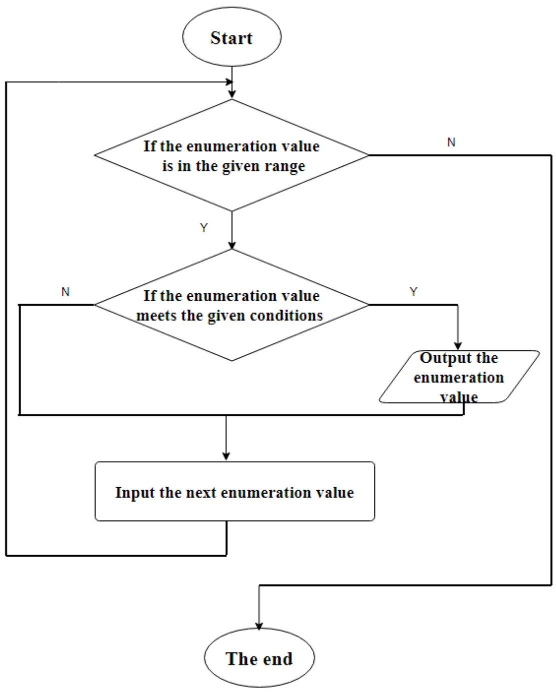


Fig.2Enumeration algorithm flowchart

IV. RESULTS AND ANALYSIS

This article takes a residential area of 70,000m^2 in Zhangjiakou, China, as an example, carries out equipment selection and objective function optimization to determine the area of solar collectors in the system.

The system is optimized according to the enumeration method, and the relationship between the total system cost and the area of the solar collector is obtained. As shown in Fig. 2, with the increase of the area of the solar heat collector, the total system cost decreases rapidly and then increases slowly. When the area of the solar heat collector is 2181m^2, the total system cost is a minimum of 2,225,977.6 yuan.

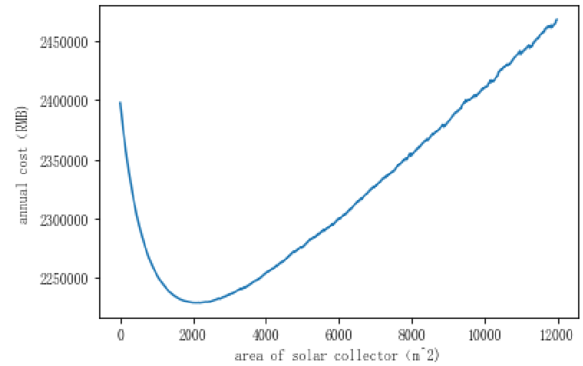


Fig.3Total cost of the system

The solar collector is a flat-plate collector with a size of 2000 × 1000 × 80mm and a total of 1091 heat collector plates.

The solar thermal storage tank is a cylindrical thermal storage tank with a volume of 164 m3, a radius of 3 m, and a height of 5.8 m.

The heat storage tank of the heat pump unit is a cylindrical heat storage tank with a volume of 608 m3, a radius of 5.5 m, a height of 6.5 m.

Because the main heating equipment of this system is a heat pump unit, the selection of the heat pump unit is based on the user's thermal load. The building area is 70,000 square meters. The design thermal index is 60 W/m^2 and the total load is 4200 kW. Two heat pumps of type FOCSWH7204 are selected.

The plate heat exchanger is located between the solar collector and the solar water storage tank. The inlet and outlet temperatures of the hot fluid side are 45 ℃ and 30 ℃, and the inlet and outlet temperatures of the cold fluid side are 25℃ and 35 ℃. The temperature difference is 7.2 ℃, and the area of the plate heat exchanger is 221 m^2.

TABLE ISystem water pump parameters

Name	Flow (m^3/h)	Head (m)	Power (kW)	Quantity (station)
Solar water heater	138	24	15	2
Solar water storage pump	138	24	15	2
Ground source side circulating	174	38	30	3

water pump				
Circulating water pump for heat storage tank of heat pump unit	400	32	55	2
User-side circulating water pump	400	32	55	2

There are four types of circulating water pumps in the system, namely: solar water heating pump, solar water storage pump, ground source side circulating water pump and user side circulating water pump. The selection parameters of each water pump are shown in Table 1.

A. *Typical daily operation mode*

This paper selects the intensity of solar radiation with minimal winter solstice (December 22), the lowest outdoor temperature Day (January 22), solar radiation intensity greater day (March 25) and the outdoor temperature is higher day (November 6th) to simulate the operation of the system and determine the hourly operating mode.

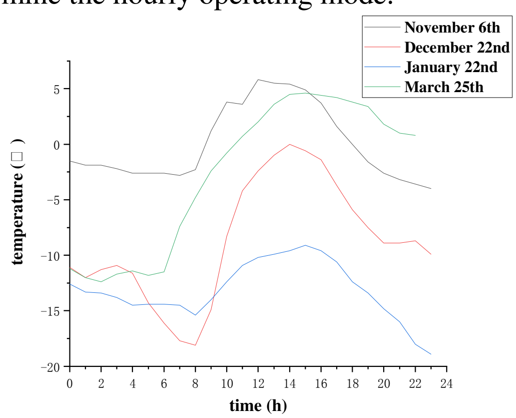


Fig.4Outdoor temperature change

As can be seen from Figure 4, the outdoor temperatures are low at around 6:00, reaches a maximum at around 14:00. December 22 and January 22, in the middle of the heating season, the outdoor lower temperature stage, while November 6 and March 25, respectively, the beginning and end of the heating phase, a higher temperature at this stage outdoors.

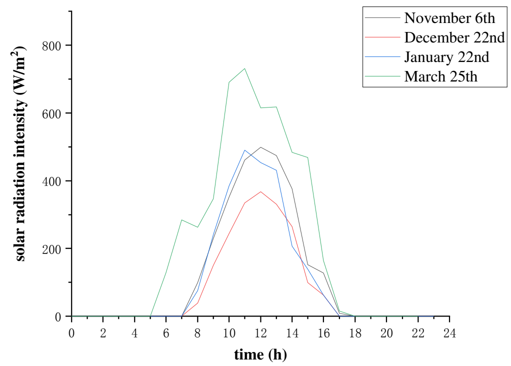
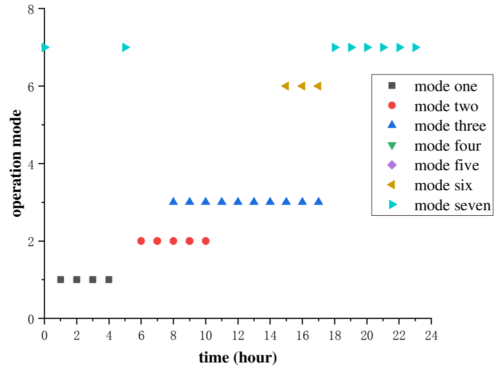


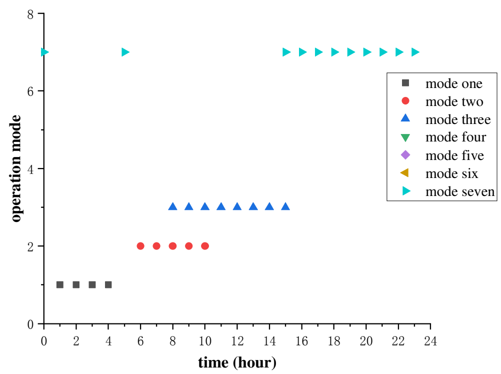
Fig.5Solar radiation intensity changes with time

Available from Figure 5, which outdoor temperature and solar radiation intensity minimum of four days each comprise heating season, the data also includes the beginning and end of the heating season, so you can use this analysis four days as a typical day.

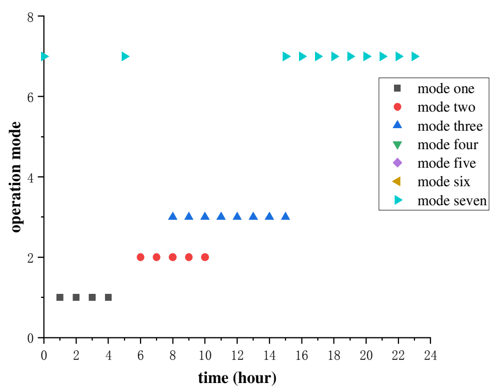
Fig. 6 shows the operating modes of solar-assisted ground-source heat pump heating systems at various times on November 6th, December 22nd, January 22nd, and March 25th. As can be seen from the table, select the same solar radiation intensity of 22 December minimum outdoor temperature and the lowest mode of operation of January 22, the operation pattern of November 6 at the beginning of the heating season is similar to that of March 25 at the end of the heating season. During the heating season, due to the use of trough electricity, the heat pump unit stores heat for 4 hours and the heat pump unit supplies heat for 1 hour during the 1: 00-6: 00 trough electricity period, during parity and peak hours, the heat pump unit stores hot water .The box is heated for 5 hours. In the period when the solar radiation intensity is greater than zero, the solar collector collects heat, in the period after 15:00, different modes of heating are performed according to the temperature of the solar thermal storage tank.



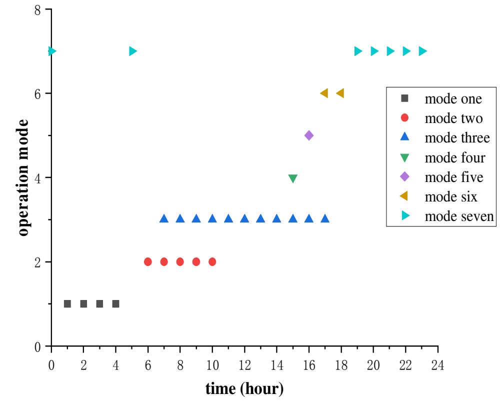
a) November 6th



b) December 22nd



c) January 22nd



d) March 25th

Fig.6Hourly operation mode of solar assisted GSHP heating system

For November 6th at the beginning of the heating season, due to the longer period of solar irradiation and greater solar radiation intensity at this stage, the operating time of mode three is 8: 00-17: 00, during which the solar collectors have been running. In the heating mode after 15:00, because the water temperature of the solar thermal storage tank is not high, mode four and mode five are not running, mode six is running for three hours, and the remaining 7 hours are mode seven.

For December 22nd, when the solar radiation intensity is the lowest in the heating season, the operating time of mode three is 8: 00-15: 00, and the operating time of the solar collector is 8 hours. All are in mode seven, and the heat supply time of the heat pump unit is 10 hours.

For January 22nd, the lowest outdoor temperature in the heating season, the operating time of mode three is 8: 00-15: 00, and the operating time of the solar collector is 8 hours, in the heating mode after 15:00, all in mode seven, the heating time of the heat pump unit is 10 hours.

For March 25th with high solar radiation intensity, the operating time of mode three is 7: 00-17: 00, and the operating time of solar collectors is 10 hours. In heating mode after 15:00, mode four run for one hour, mode five for one hour, mode six for two hours, and the remaining six hours are mode seven.

As can be seen from figure 5, the operating modes on December 22nd and January 22nd are similar. The operating time of mode three is shorter, and there is no operation of mode five and mode six. The operating mode on November 6th is similar to that on March 25th. In the case of high outdoor temperature and strong solar radiation, the operating time of mode three is longer, and the operating time of mode five and mode six is 1-2 hour. The solar assisted GSHP heating system makes full use of solar energy in the condition that the soil is recharged in winter, and the heat stored in the solar thermal storage tank is provided to users in different operating modes.

B. Heating season operation mode

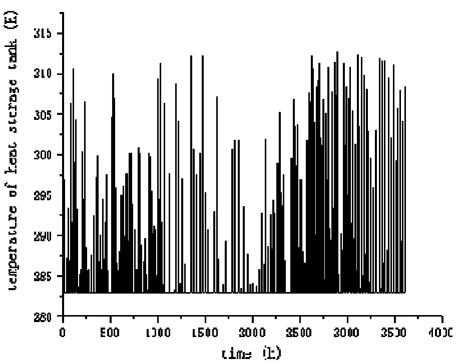


Fig.7Temperature change of solar thermal storage tank

As shown in Fig. 7, the maximum temperature of the solar thermal storage tank can reach 335 K, and only a few hours to meet the heating demand of 313 K. Therefore, the operating mode of the solar thermal storage tank directly to the user is the shortest on time. The solar thermal storage tank is affected by the solar radiation intensity and outdoor temperature. The temperature of the solar thermal storage tank first decreases and then rises. In November, the solar radiation intensity is high and the outdoor temperature is high. At the beginning of the heating season, the temperature of the solar thermal storage tank is high. The solar radiation intensity is the highest in March and the outdoor temperature is high, and the temperature of the solar thermal storage tank is the highest at the end of the heating season. In January, the coldest month, the solar radiation intensity is low and the outdoor temperature is low, The temperature of the solar water storage tank is low.

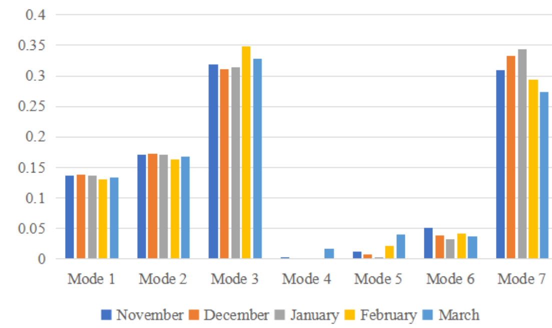


Fig.8Proportion of system operation mode

It can be seen from Fig. 8 that the proportion of operation time of mode 1 and mode 2 has basically no change in the five months of the heating season. The proportion of operation time of mode 3 is higher in November, February and March than that in December and January. In Particular, in February, the proportion of the mode 3 reached a high of nearly 35%, and in December, the proportion of the mode 3 reached a low of 31%. As solar collectors transfer heat to soil in summer and transition season, operation time of mode 4 is the shortest operation time in heating season, only in November and March, and zero in the other three months. Operation time of mode 5 is the longest in March and the shorter operation time in the other four months due to the smaller solar radiation intensity. The operating time of Mode 6 is the shortest in January and can reach about 5% in November. Operation time of mode 7 is longer in December, January and February, and shorter in November and March. It can be seen that mode three and mode seven take up more than half of the heating season.

The operation of mode 5 and mode 6 makes the temperature cascade utilization of solar energy storage tank. When the temperature of solar energy storage tank is in the range of 25 ℃ to 40 ℃, mode 5 starts. When the temperature of solar energy storage tank is in the range of 10 ℃ to 25 ℃, mode 6 starts. Mode 7 takes the ground as the heat source of the heat pump unit. The operation of mode 5 and mode 6 reduces the operation time of mode 7. The utilization of the residual heat of the solar energy storage tank reduces the heat supplement to the soil in summer and transition season, which reduces the area of the solar energy collector and the number of the underground heat exchange.

TABLE Ⅱ Average daily operation time of each mode (h)

	November	December	January	February	March
mode one	4.00	4.00	4.00	4.00	4.00
mode two	5.00	5.00	5.00	5.00	5.00
mode three	9.33	9.00	9.13	10.68	9.77
mode four	0.3	0	0	0	0.53
mode five	0.37	0.23	0.03	0.68	1.19
mode six	1.50	1.13	0.97	1.29	1.13
mode seven	9.10	9.65	10.00	9.04	8.16

As can be seen from table 2, the operation time of mode 1 and mode 2 basically remains the same, because during the period of 1:00-5:00 at night, the heat pump unit uses the low electricity to store heat in the heat pump heat storage tank for 4 hours. During the next 5 hours of flat and peak periods, the heat pump heat storage tank provides heat to the user for another 5 hours. In this way, it not only uses the low-level electricity to store heat, but also makes the heat loss to the environment at least. Due to the overlap of the operation modes of the solar-assisted GSHP heating system, the total daily operation time of each mode is greater than 24 hours each month.

In the 5 months of system operation, the operating time of mode three first decreases and then increases, and the operating time of mode three is the shortest in December, because the solar radiation intensity reaches the minimum in December and the time with solar radiation also reaches the minimum Then, the solar radiation intensity gradually increased, and the solar radiation time also prolonged. Mode 3 is the longest running time in the whole heating season, especially in February, when it reached a maximum of 10.68.

The running time of mode 4 is the shortest in the whole heating season, which is 0 in December, January and February, because the system is a solar-assisted ground source heat pump heating system, and the heat pump unit is the main heating device. The purpose of the solar collector is to meet the heating needs of the system for one year. The area of solar collector is not large. In addition, Zhangjiakou is located in a cold area and the outdoor temperature is relatively low. Therefore, it takes very little time for the water temperature of the solar thermal storage tank to reach above 40 ° C in the heating season, and the running time of mode four is the shortest.

Operation time of mode five is the longest in March, which is shorter in November, December, January, and February. Because the solar radiation intensity is larger in March and the solar irradiation time is longer, the solar energy storage takes the longest time for the water temperature of the hot water tank to reach above 25 ° C. The operating time of mode six decreases first and then increases.

The operation time of mode 6 decreases first and then increases. In January, the operation time of mode 6 is the shortest, while in February, the operation time is the longest. Because the solar radiation intensity decreases first and then increases, and the time when the temperature of solar energy storage tank is higher than 10 ℃ decreases first and then increases. In March operating of mode 5 reduces the operation time of mode 6, but the total operation time of mode 5 and mode 6 is the longest.

The operating time of mode 7 increases first and then decreases. The changing trend of operating time of mode 7 is opposite to the changing trend of mode 5 and mode 6. In February, the operating time of mode 7 is the longest. The warmest time is the longest, and the operation time of mode 7 is the shortest in March. The operating of Mode 5 and Mode 6 reduces the running time of Mode 7.

TABLE□Heating equipment costs

Device	Unit price (Yuan)	Quantity	Investment costs (ten thousand Yuan)
Heat pump unit	700000	2Piece	
Buried pipe heat exchanger	3000	215wells	
solar collector	450	2181m^2	

Solar water storage tank	560	164m^3	9.2
Heat pump water storage tank	560	608m^3	34.05
Solar water heater pump	5860	2Piece	1.17
Solar water storage pump	5860	2Piece	1.17
Ground source side circulating water pump	10220	3Piece	3.06
Circulating water pump for heat storage tank of heat pump unit	10220	2Piece	2.04
User-side circulating water pump	10220	2Piece	2.04
total			355.39

The service life of the equipment is calculated according to 15 years. The discount rate is 8%. The annual equipment cost for heating in this paper is 415,000 Yuan.

TABLE Annual operating costs of heating

Device	Power(W)	operation hours(h)	Electricity price (Yuan)	Operating costs (Yuan)
Heat pump unit（1）	1219.8	1062	0.6	777098.38
Heat pump unit（2）	1219.8	453	0.82	453106.91
Heat pump unit（3）	1219.8	587	0.85	608619.21
total				1838824.5

The annual operating cost of the solar-assisted ground-source heat pump heating system proposed in this article is 1.839 million Yuan, the total annual cost is the sum of the annual equipment cost and the annual operating cost, and the annual cost is 2.254 million Yuan. When the system is running, the operation of solar collectors and solar thermal storage tanks makes full use of solar heat, the operation of the heat pump thermal storage tanks allows the system to fully store heat during periods of low electricity prices, saving system operating costs.

In the operation mode of the system, the power of the heat pump unit is calculated according to the rated power, without considering the case of variable power, and without considering that the power of the heat pump unit changes with the soil temperature.

V. CONCLUSION

This paper takes a residential area of 70,000 m2 in Zhangjiakou area as an example, conducts research on the heating performance of solar-assisted ground-source heat pump systems, and establishes a solar-assisted ground-source heat pump system. A mathematical model of equipment costs and operating costs is proposed. The electricity price optimizes the system's operating mode, so that the system's equipment costs and operating costs are the lowest. This article draws the following conclusions:

1) The total cost of the solar-assisted ground source heat pump system is related to the area of the solar collector. With the increase of the area of the solar collector, the total cost of the system first decreases and then increases gradually.

2) Through the analysis of seasonal heating operation mode, it can be found that the heating mode of regenerative heat pump using solar heat storage tank accounts for more than 65% of the total operation mode.Heating using a heat pump storage tank operated up to 10.68 hours per day in February.

3) It is suggested that the annual operating cost of the solar-assisted ground source heat pump heating system is 1.839 million yuan, and the annual operating cost is 2.254 million yuan. During the operation of the system, the existence of solar collector and solar heat storage tank can make full use of the solar energy, so as to effectively reduce the operating cost of the system.

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