Optimal control of cooling tower in hybrid ground-source heat pump system for hotel buildings

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Abstract. The control strategy of the cooling tower is an important factor in the optimal operation of hybrid ground-source heat pump systems (HGSHPS). This paper selected a hotel building of cooling-dominated area as the research object. We selected multiple control operating points of two commonly used control strategies (i.e., the highest temperature control strategy and the temperature difference control strategy) for simulation. The optimal control operating points under different control strategies were then obtained on the basis of the minimum energy consumption of the HGSHPS in 20 years.

Introduction

The ground-source heat pump (GSHP) has gained increasing intention as high efficiency and environmental protection characteristics [1–3]. Cities such as Wuhan, cooling-dominated area, generally use HGSHPS [4–9], which are systems that adopt the combined operation of GHE and cooling towers. A long cooling tower operation time will result in the large energy consumption of the cooling tower fan and the water pump. Therefore, in this scenario, the system doesn't have the energy saving advantage of the GSHP. By contrast, if the cooling tower operation time is too short, then the GHE will undertake too much heat load and will result in high soil temperature and entering fluid temperature (EFT) of the heat pump unit, which will then increase the energy consumption of the heat pump system. Therefore, matching the operation of the GHE and the cooling tower poses a difficulty.

Among the many problems of the matching operation of the GHE and the cooling tower, the control strategy of the cooling tower is considered as the core problem. In 2000, Yavuzturk and Spitler first studied the cooling tower control strategies by using the same office building in two different climates in the United States as an example [10]. On the basis of their study, domestic and foreign scholars conducted related research on cooling tower control strategies [11–15]. Yavuzturk and Spitler directly proposed specific operating points as reference for each control strategy when choosing a control point temperature. They chose 35.8 °C as control point temperature for the highest temperature control strategy and chose 2 °C/1.5 °C and 8 °C/1.5 °C as control point temperature for the temperature difference control strategy [10]. However, they didn't prove that the operating points are the optimal operating points for the control strategy. Subsequent studies didn't adjust their assumptions according to different climate regions and geotechnical conditions. These studies also didn't analyze the optimal operating point of every control strategy, but directly used the operating points mentioned above. Therefore, the conclusions of these studies were needed to be improved.

In this paper, a hotel building in Wuhan is chose as the research object. First, we selected some control operating points of two control strategies (i.e., the highest temperature control strategy and the temperature difference control strategy) for simulation. Then, we investigated the influence of different control strategies on soil temperature increase and a 20-year energy consumption. Finally, the optimal control operating points of different control strategies were obtained.

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Design of the HGSHPS

Building load calculation. This study selected a 16-floor hotel building with a total area of approximately 18,048 m^2 located in Wuhan City, China.

The building loads were simulated by Designer's Simulation Toolkit (DeST) software developed by Tsinghua University. The hotel operates 24 hours every day. On the basis of the requirements of the cooling and heating periods of the Wuhan region, the cooling period was set to last from June 1 to September 30, whereas the heating period was set to last from December 1 to February 28.

Simulation shows that the maximum cooling load was 1,838 kW in the cooling period, whereas the maximum heating load was 954 kW in the heating period. The ratio of the maximum cooling and heating load was 1.93. The cumulative cooling and heating loads reached 2,174,626 and 688,206 kWh, respectively. The ratio of the cumulative cooling and heating loads was 3.16.

Heat pump system design. An auxiliary cooling device was adopted to undertake the load difference between cooling and heating loads during the cooling period. The cooling tower is usually utilized as the auxiliary cooling device. The GHE and the cooling tower in the HGSHPS are commonly connected in parallel or in series. The proposed system adopts the parallel connection form. The system schematic is shown in Fig. 1.

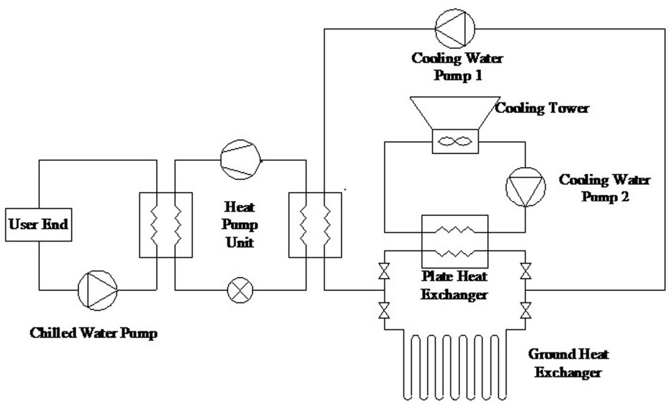

Fig. 1. Schematic of HGSHPS

The soil thermal properties of the Wuhan region are investigated and stated in reference [16]. Considering that the circulation fluid of the GHE is not allowed to freeze under winter conditions, this study used 7% NaCl solution as the circulation fluid for GHE. The GHE used polyethylene (PE) pipe. The design parameters of the cooling and heating conditions are shown in Table 1.

Table 1. Design parameters of the cooling and heating conditions

EFT and EXFT of GHE [°C]		Temperature of supply and return water of user [°C]		Energy efficiency ratio of design condition	
Summer	Winter	Summer	Winter	EER	COP
37/32	0/5	7/12	45/40	3.7	3.35

On the basis of the calculation [17], the designed tube length of GHE was 20,601 m, the number of boreholes was 103, the circulation liquid flow of GHE was 120 m^3/h, and the circulating water flow of the cooling tower was 286 m^3/h.

According to the selection calculation, the main water pump capacity was 417 m^3/h in summer and 120 m^3/h in winter, and the pump head was 25 m. The water pump capacity of the cooling tower was 268 m^3/h, and the pump head was 16 m. The heat exchange amount per Kelvin temperature difference of the plate heat exchanger was 833 kW/K.

The cooling tower control strategy setting

Highest temperature control strategy. This control strategy is based on the local climate conditions and air conditioning load characteristics. The highest temperature of the EFT (or ExFT) of the heat pump units were set in advance. If the temperature exceeds this value during operation, then the cooling tower is activated for auxiliary heat dissipation. The setting of the control operating points of this control strategy are shown in Table 2.

Table 2. Highest temperature control strategy of the EFT(or ExFT) of heat pump units

	EFT[°C]		EXFT[°C]	
	Open	Close	Open	Close
Strategy 1	26	25	29	28
Strategy 2	27	26	30	29
Strategy 3	28	27	31	30
Strategy 4	29	28	32	31
Strategy 5	30	29	33	32
Strategy 6	31	30	34	33
Strategy 7	32	31	35	34
Strategy 8	33	32	36	35
Strategy 9	34	33	37	36
Strategy 10	35	34	38	37

Temperature difference control strategy. This control strategy is based on the temperature difference between the EFT (or ExFT) of heat pump units and the outdoor air wet-bulb temperature. If the temperature difference exceeds the setting range, then the cooling tower is activated for auxiliary heat dissipation until the temperature difference returned to the setting range. The setting of the control operating points of this control strategy are shown in Table 3.

Table 3. Temperature difference control strategy of the EFT(or ExFT) of heat pump units

	EFT[°C]		EXFT[°C]	
	Open	Close	Open	Close
Strategy 1	2	1.5	4	3.5
Strategy 2	3	2.5	5	4.5
Strategy 3	4	3.5	6	5.5
Strategy 4	5	4.5	7	6.5
Strategy 5	6	5.5	8	7.5
Strategy 6	7	6.5	9	8.5
Strategy 7	8	7.5	10	9.5

TRNSYS-based model establishment

The initial soil temperature was set to 17.3 °C [16]. The time step was set to 1 hour. To conduct a 20-year simulation, we adopted the HGSHP system model for each control operating point of the above strategies. A total of 175,200 steps were simulated.

Simulation results and control strategy analyses

The cold and heat source sides of the heat pump system adopted the constant flow operation. The main water pump energy consumption was similar under every control strategy, and its 20 years' energy consumption was 3,357,982 kWh. The values will not be restated in the sections below.

The highest temperature control strategy of the EFT of heat pump units. The energy consumption of this control strategy are shown in Table 4 and Fig. 2, the maximum soil average temperature of this control strategy is shown in Fig. 2.

Table 4. Energy consumption of the highest temperature control strategy of the EFT of heat pump units on a full lifecycle

	Heat pump units [kWh]	Water pump of cooling tower [kWh]	Fan of cooling tower [kWh]	Total energy consumption [kWh]
Strategy 1	14,057,637	976,275	473,198	18,865,092
Strategy 2	14,116,025	887,676	430,254	18,791,937
Strategy 3	14,204,510	811,036	393,107	18,766,635
Strategy 4	14,312,735	717,512	347,776	18,736,005
Strategy 5	14,482,174	608,555	294,965	18,743,676
Strategy 6	14,702,521	505,340	244,937	18,810,780
Strategy 7	14,950,039	425,864	206,415	18,940,300
Strategy 8	15,241,927	353,718	171,446	19,125,073
Strategy 9	15,551,408	299,705	145,266	19,354,361
Strategy 10	15,879,181	267,024	129,426	19,633,613

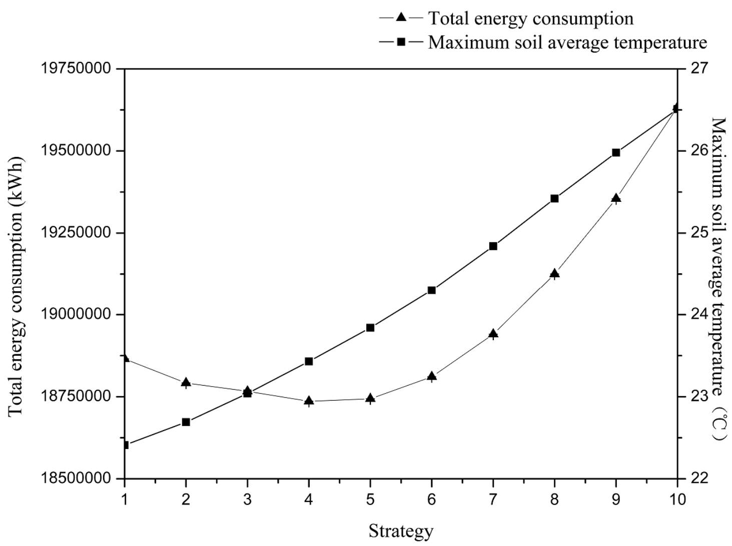

Fig. 2. Total energy consumption and maximum soil average temperature of the highest temperature control strategy of the EFT of heat pump units

The highest temperature control strategy of the ExFT of heat pump units. The energy consumption of this control strategy are shown in Table 5 and Fig. 3, the maximum soil average temperature of this control strategy is shown in Fig. 3.

Table 5. Energy consumption of the highest temperature control strategy of the ExFT of heat pump units on a full lifecycle

	Heat pump units [kWh]	Water pump of cooling tower [kWh]	Fan of cooling tower [kWh]	Total energy consumption [kWh]
Strategy 1	14,137,023	896,300	434,434	18,825,739
Strategy 2	14,211,939	820,976	397,925	18,788,822
Strategy 3	14,309,245	743,202	360,228	18,770,657
Strategy 4	14,444,775	654,625	317,295	18,774,677
Strategy 5	14,632,448	562,417	272,602	18,825,449
Strategy 6	14,859,237	475,429	230,439	18,923,087
Strategy 7	15,088,327	410,999	199,210	19,056,518
Strategy 8	15,367,299	358,007	173,525	19,256,813
Strategy 9	15,677,845	311,483	150,975	19,498,285
Strategy 10	15,990,628	273,878	132,748	19,755,236

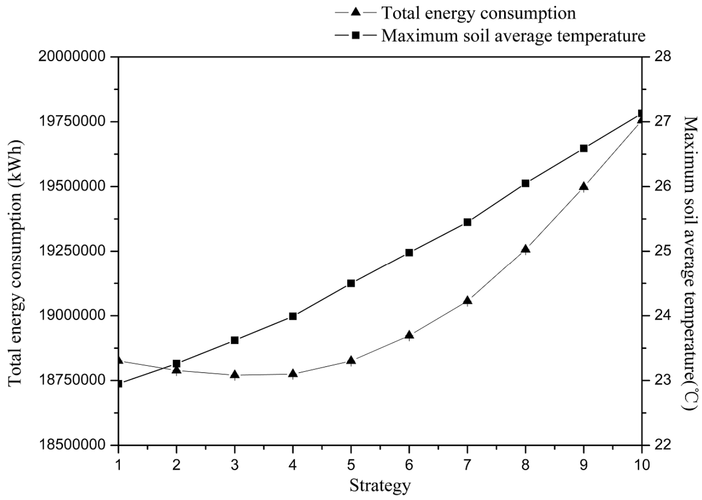

Fig. 3. Total energy consumption and maximum soil average temperature of the highest temperature control strategy of the ExFT of heat pump units

The temperature difference control strategy of the EFT of heat pump units. The energy consumption of this control strategy are shown in Table 6 and Fig. 4, the maximum soil average temperature of this control strategy is shown in Fig. 4.

Table 6. Energy consumption of the temperature difference control strategy of the EFT of heat pump units on a full lifecycle

	Heat pump units	Water pump of cooling tower	Fan of cooling tower	Total energy consumption
	[kWh]	[kWh]	[kWh]	[kWh]
Strategy 1	14,001,362	1,117,640	541,717	19,018,701
Strategy 2	14,117,612	933,224	452,331	18,861,149
Strategy 3	14,288,622	745,176	361,185	18,752,965
Strategy 4	14,484,506	554,338	268,686	18,665,512
Strategy 5	14,715,891	438,210	212,399	18,724,482
Strategy 6	14,953,514	367,425	178,090	18,857,011
Strategy 7	15,227,421	322,535	156,332	19,064,270

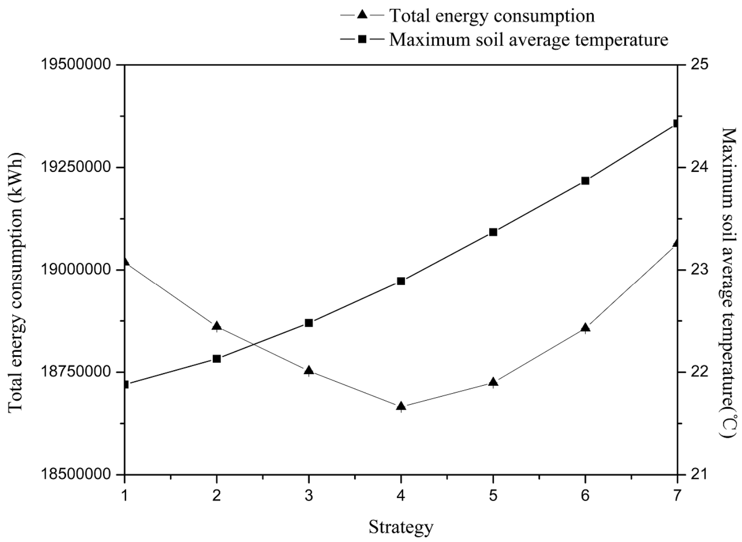

Fig. 4. Total energy consumption and maximum soil average temperature of the temperature difference control strategy of the EFT of heat pump units

The temperature difference control strategy of the ExFT of heat pump units. The energy consumption of this control strategy are shown in Table 7 and Fig. 5, the maximum soil average temperature of this control strategy is shown in Fig. 5.

Table 7. Energy consumption of the temperature difference control strategy of the ExFT of heat pump units on a full lifecycle

	Heat pump units	Water pump of cooling tower	Fan of cooling tower	Total energy consumption
	[kWh]	[kWh]	[kWh]	[kWh]
Strategy 1	13,999,872	1,070,549	518,892	18,947,295
Strategy 2	14,069,430	927,051	449,339	18,803,802
Strategy 3	14,179,731	766,192	371,371	18,675,276
Strategy 4	14,342,805	609,690	295,515	18,605,992
Strategy 5	14,535,336	493,403	239,151	18,625,872
Strategy 6	14,769,799	404,031	195,833	18,727,645
Strategy 7	15,009,337	343,846	166,661	18,877,826

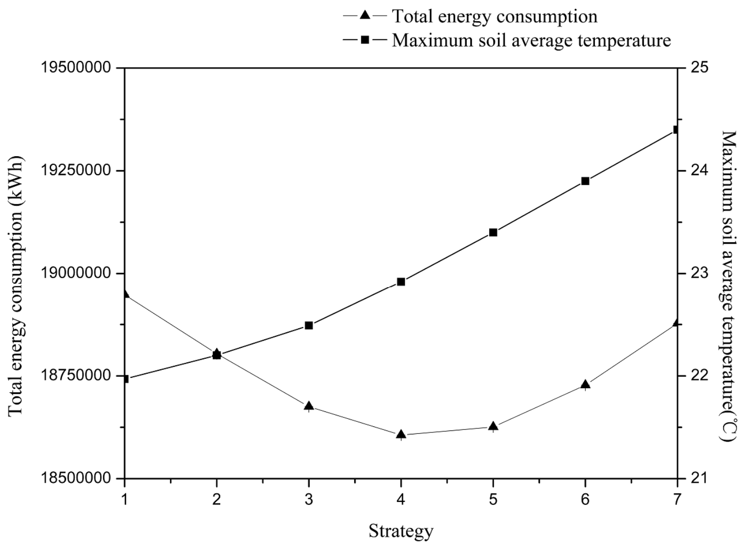

Fig. 5. Total energy consumption and maximum soil average temperature of the temperature difference control strategy of the ExFT of heat pump units

Simulation result analysis and conclusion

Analysis of the highest temperature control strategy. Simulation results show that when the highest temperature control strategy is adopted to control either the EFT or the ExFT of the heat pump units, the energy consumption of the heat pump units will increase, whereas the energy consumption of the cooling tower fan and the cooling water pump will decrease when the temperature of the control operating points increases. The total energy consumption during 20 years of the heat pump system first decreases and then increases, and the maximum average temperature of the soil increases.

For the highest temperature control strategy of the EFT of heat pump units, the optimal control operating point is as follows: when the EFT of the heat pump units is higher than 29 °C, the cooling tower is activated; when the value is lower than 28 °C, the cooling tower is shut down. The total energy consumption during 20 years of the heat pump system is 18,736,005 kWh, and the maximum soil average temperature is 23.43 °C.

For the highest temperature control strategy of the ExFT of heat pump units, the optimal control operating point is as follows: when the ExFT of the heat pump units is higher than 31 °C, the cooling tower is activated; when the value is lower than 30 °C, the cooling tower is shut down. The total energy consumption during 20 years of the heat pump system is 18,770,657 kWh, and the maximum soil average temperature is 23.62 °C.

On the basis of the comparison, we found that when the highest temperature control strategy is adopted, controlling the EFT of the heat pump units is better than controlling the ExFT of the heat pump units.

Analysis of the temperature difference control strategy. Simulation results show that when the temperature difference control strategy is adopted either to control the EFT or the ExFT of the heat pump units, the energy consumption of the heat pump units increases, whereas the energy consumption of the cooling tower fan and the cooling water pump decreases when the temperature of the control operating points increases. The total energy consumption during 20 years of the heat pump system first decreases and then increases, and the maximum average temperature of the soil increases.

For the temperature difference control strategy of the EFT of the heat pump units, the optimal control operating point is as follows: when the temperature difference between the EFT of the heat pump units and the outdoor air wet-bulb temperature is higher than 5 °C, the cooling tower is activated; when the value is lower than 4.5 °C, the cooling tower is shut down. The total energy consumption during 20 years of the heat pump system is 18,665,512 kWh, and the maximum soil average temperature is 22.89 °C.

For the temperature difference control strategy of the ExFT of the heat pump units, the optimal control operating point is as follows: when the temperature difference between the ExFT of heat pump units and the outdoor air wet-bulb temperature is higher than 7 °C, the cooling tower is activated; when the value is lower than 6.5 °C, the cooling tower is shut down. The total energy consumption during 20 years of the heat pump system is 18,605,992 kWh, and the maximum soil average temperature is 22.92 °C.

On the basis of this comparison, we found that when the temperature difference control strategy is adopted, controlling the ExFT of the heat pump units is better than controlling the EFT of the heat pump units.

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