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Energy saving analysis of a hybrid ground-coupled heat pump project

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Abstract: A hybrid ground-coupled heat pump (HGCHP) project in Nanjing, China is chosen to analyze the building energy-consumption properties in terms of different control strategies, building envelope and the terminal air-conditioning system. The HGCHP uses a supplemental heat rejecter to dissipate extra thermal energy to guarantee underground soil heat balance. The software EnergyPlus is employed to simulate the project and design the heat flow of the cooling tower and the borehole heat exchanger (BHE). Then two feasible control strategies for the cooling tower and the borehole heat exchanger are proposed. The energy-saving potential of the building envelope is analyzed in terms of the surface color of the wall/roof. With the same terminal system, it is found that in the cooling season the heat flow of the insulated building with black wall/roof is 1.2 times more than that with white wall/roof. With the same insulated building and gray wall/roof, it is concluded that the heat pump units for a primary air fan-coil system show an annual energy consumption increase of 44.7 GJ compared with a radiant floor system.

Key words: hybrid ground-coupled heat pump; borehole heat exchanger; energy saving

Nowadays, the energy demands increase annually in pace with economic development and the improvement of living standards. Building energy consumption occupies a very large proportion. The proportion of building energy consumption in America to its primary energy consumption is 35%, and the proportion is 25% to 30% in China[1]. With regard to the building energy consumption per unit of floor area, the average value in Europe is 8.75 kg of standard coal per square meter, but Chinese average value reaches up to 25 kg of standard coal per square meter. According to the building energy saving standards in Europe, the ratio of all the buildings in China that meet the standard is less than 1%. In the building energy consumption, energy consumption in HVAC (heating, ventilating and air conditioning) accounts for the maximum proportion[2]. So the energy saving, especially in terms of HVAC, has been placed in an important position. The study of energy saving is mainly carried out in the field of energy supply, the building envelope and indoor air-conditioning systems.

Ground-coupled heat pumps (GCHP) have a high energy saving potential and are considered as one of the most promising low carbon technologies for building HVAC applications[3]. The underground soil properties affect the operation efficiency of the GCHP system. In cooling-dominated areas, cooling loads are much greater than heating loads, and the temperature of the soil will rise annually if the soil is the only cold/heat source, which will decrease the efficiency of the GCHP system and even lead the BHE to invalid conditions after several years. One of available solutions to the problem is to employ the HGCHP, which uses supplemental heat rejecters, such as cooling towers, fluid coolers, or surface heat rejecters to reject extra thermal energy. There are many studies on the advantages[4] and the control strategies of the HGCHP system. But the hourly loads and the energy consumption of the heat pump units and the circulating pump are not accurately calculated, which obviously influences the proposed control strategies[5]. Most of the studies about the building envelope focus on the optimum insulation thickness and the corresponding building loads[6]. But little research on the building envelope is carried out to compare the energy-saving potential of different envelope surface colors.

This paper takes an HGCHP project as an example and employs the software EnergyPlus to simulate the air-conditioning system. The calculation results, including building hourly loads, building hourly heat flow, outdoor temperature changes and so on, provide a data foundation for the energy saving analysis in terms of the control strategies of the HGCHP system, the building envelope and the terminal air-conditioning system.

1 HGCHP Project

The HGCHP project is a factory building with a floor area of 5 100 m^2 and located in Nanjing, China. The daily occupation period of the building is from 08:00 to 17:00. The HGCHP system utilizes a cooling tower as a supplemental heat rejecter (see Fig. 1) and adopts radiant floor combined with a fresh air system as an indoor terminal air-conditioning system. The heating period is from December 1st to March 1st, and the cooling period is from June 1st to October 1st. During the heating and cooling periods, the HGCHP system

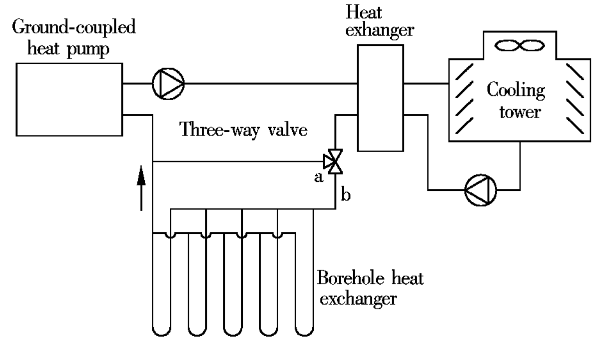

Fig. 1 The schematic diagram of the HGCHP

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is off on Sundays and holidays. Actually, the system carries out 76 d of heating and 103 d of cooling. The daily HVAC operating period from 06:00 to 16:00 is determined owing to the heat/cold storage capacity of the air-conditioning system and the building envelope.

The building envelope mainly includes the roof, the walls, the indoor floor, and the windows, which are all insulated. The insulation board with a thickness of 80 mm is added to the roof, and the one with a thickness of 60 mm is added to the walls and the indoor floor. The insulation board is extruded polystyrene foam board whose heat transfer coefficient is less than 0.03 $W/(m^2 \cdot K)$. The windowpane is double-glazed low-emission glass (6 mm + 12 mm + 6 mm) and its heat transfer coefficient is less than 1.8 $W/(m^2 \cdot K)$.

2 Heat Flow Design of BHE and Cooling Tower

This building is located in the hot summer and cold winter zone in China, and the total heat quantity absorbed from the external heat source in the heating season is less than the total heat quantity dissipated to the external cold source in the cooling season. So the building employs an HGCHP system, which is a ground-coupled heat pump system combined with a cooling tower, so as to avoid the unbalanced heat exchange between the borehole heat exchanger (BHE) system and underground soil. Using the cooling tower as a supplemental heat rejecter, the total heat quantity dissipated to the external cold source in the cooling season is divided into two parts. One part is dissipated to the air through the cooling tower and the other part, equal to the heat quantity absorbed from the underground soil in the heating season, is dissipated to the underground soil through a BHE system.

A correct calculation method of the heating load is required for the designs of the heat exchange between the BHE system and the soil and the heat exchange between the cooling tower and the air. In the heating season, the heating load is equal to the sum of the heat absorbed from the underground soil, the heat flow generated by the heat pump units, and the heat flow generated by the circulating pumps. While in the cooling season, the total heat quantity dissipated to the underground soil and the air is equal to the sum of the cooling load of the building, the heat flow generated by the heat pump units, and the heat flow generated by the circulating pumps. This paper adopts the whole building energy analysis tool EnergyPlus to simulate the HGCHP system. Through the accumulation of hourly heat flow, it is concluded that the total building heat flow in the heating and cooling seasons are 361 and 706 GJ, respectively.

The building uses two ground-coupled heat pump screw units. One of the heat pump units is used to supply hot/cold water for the floor radiation system and the other heat pump unit is used to supply hot/cold water for the fresh air system. The total energy consumption of the heat pump units for the insulated building is calculated by

$$Q = \int \frac{q_i}{\mathrm{COP}_i} \mathrm{d}\tau \tag{1}$$

where Q is the building heat flow; q_i is the building hourly load calculated by EnergyPlus; COP_i is the hourly coefficient of performance of the heat pump unit generated from heat pump manufacturers' software; τ is the time.

The calculation results are presented in Tab. 1. It is assumed that all the energy consumption of the heat pump units are converted into the heat flow generated by the heat pump units, so it can be obtained that for the insulated building the total heat flows of the two heat pump units in the heating and cooling seasons are 723 and 167 GJ, respectively.

Tab. 1 Energy consumption of heat pump units for insulated building GJ

Energy consumption	Floor radiant heat pump unit	Fresh air heat pump unit	Two heat pump units
Heating	47.6	24.7	72.3
Cooling	108.0	59.0	167.0

The building is equipped with four circulating pumps in operation. Four circulating pumps with the same type specifications have a shaft power of 7.5 kW, and it is assumed that all the shaft power is converted into the heat flow generated by circulating pumps. Based on the operation time and the shaft power, it can be calculated that the total heat flow of the four circulating pumps is 82 GJ in the heating season and 111 GJ in the cooling season.

According to the above calculation, it is concluded that the total heat flow absorbed from the heat source is 207 GJ, and the total heat flow dissipated to the cold source is 984 GJ. So in this HGCHP project, the design heat exchange quantity between the BHE and the underground soil is 207 GJ both in the heating season and in the cooling season. While the design quantity of heat exchange between the cooling tower and outdoor air is 777 GJ in the cooling season, which is about four times as much the design quantity of heat exchange between the BHE and the soil.

3 Energy Saving Analysis for HGCHP Project

Based on the simulation and calculation results for the insulated building, this paper carries out an energy-saving analysis in terms of control strategies of the HGCHP system, building envelope and the terminal air-conditioning system.

3.1 Control strategies for energy supply of HGCHP system

This building adopts a cooling tower as a supplemental heat rejecter in the cooling season. In order to give full play to the energy saving ability and guarantee the HGCHP system in high-efficiency operation, it is critical to make suitable control strategies for the BHE and the cooling tower in the cooling season. The most important thing is to determine the working times and non-working times of the BHE and the cooling tower in the cooling season. This paper presents two control strategies as follows:

Strategy 1 In the initial stage and the last stage of the cooling season, the HGCHP system makes use of the cooling tower to dissipate heat energy. The specific working time of the cooling tower is determined by the design heat flow. During the rest of the cooling season, the BHE is used to dissipate heat energy.

In the initial stage of the cooling season, the average outdoor dry bulb temperature is relatively lower and the heat dissipation efficiency of the cooling tower is higher than that at high outdoor temperature. Besides, the BHE still has the heat dissipation ability when the outdoor temperature is high. In the last stage of the cooling season, long usage of the BHE causes the underground soil temperature to rise and results in the heat exchange efficiency between the BHE and the underground soil to become low. During this period, the average outdoor dry bulb temperature is low, so the cooling tower is employed instead of the BHE to dissipate heat energy with high operational efficiency.

According to strategy 1, the whole cooling season from June 1st to October 1st can be divided into three stages. Based on the design heat flow(777 GJ) of the cooling tower and the outdoor dry bulb temperature changes in the cooling season obtained from EnergyPlus(see Fig. 2), the operation period of each stage is determined and the corresponding heat flow dissipated to the cooling tower or the BHE is obtained based on the calculation by EnergyPlus. The first stage using the cooling tower as a cold source is from June 1st to 7th and the corresponding heat flow is 297 GJ; the second stage using the BHE as a cold source is from July 8th to August 2nd and the corresponding heat flow is 219 GJ; the third stage using the cooling tower as a cold source is from August 3rd to October 1st and the corresponding heat flow is 468 GJ.

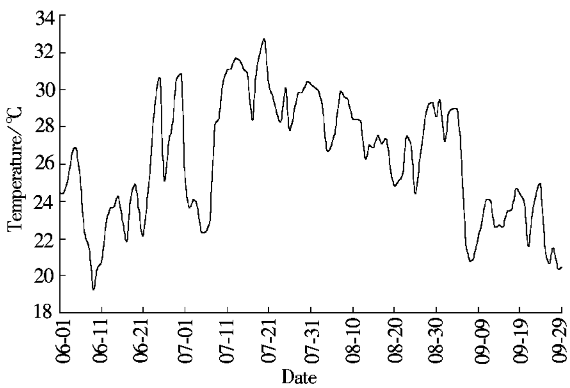

Fig. 2 Outdoor dry bulb temperature variation in cooling season

Strategy 2 Choosing an outdoor dry bulb temperature T_o as a baseline, the specific control policy is as follows: when the outdoor dry bulb temperature is less than T_o, the cooling tower is started and the BHE is shut down; when the outdoor dry bulb temperature is greater than or equal to T_o, the cooling tower is shut down and the BHE is started. This strategy creates an intermittent non-working period for the BHE to repair and alleviate the ability of storage heat, and provides enough time for the underground soil to dissipate the heat to distant soil.

In view of the outdoor dry bulb temperature variations (see Fig. 2) and the building daily heat flow in the cooling season(see Fig. 3), first, this paper selects T_o = 32 ℃. When the outdoor dry bulb temperature is greater than or equal to 32 ℃, the heat flow from the building, the heat pump units and the circulating pumps are calculated through the same computation steps introduced above. The total heat flow dissipated to the underground soil through the BHE is equal to 157 GJ. This quantity is less than the design heat flow(207 GJ) of the BHE. So it is necessary to decrease T_o in order to increase the heat flow of the BHE. Through several selections of T_o and calculation of the total heat flow dissipated to the underground soil(see Tab. 2), T_o is finally determined as 31. 2 ℃. Under strategy 2, the cooling tower should be started and the BHE should be shut down when the outdoor dry bulb temperature is less than 31. 2 ℃. When the outdoor dry bulb temperature is greater than or equal to 31. 2 ℃, the BHE should be started and the cooling tower should be shut down, and the total heat flow dissipated to the underground soil is 200 GJ, leading to 7 GJ of deviation and a 3% error compared with the design heat flow dissipation through the BHE.

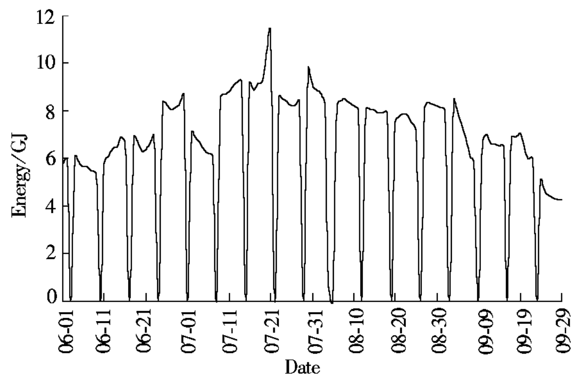

Fig. 3 Building daily heat flow variation in cooling season

Tab. 2 Heat flow dissipated to the underground soil at different T_o GJ

T_o/℃	Building heat flow	Heat pump units heat flow	Circulating pump heat flow	Total heat flow
30. 0	209	34. 1	25. 7	269
31. 0	168	28. 0	18. 8	215
31. 2	152	28. 7	19. 0	200
31. 3	149	27. 2	18. 1	194
31. 5	143	25. 2	15. 8	184
32. 0	127	17. 1	12. 4	157

3. 2 Energy saving potential of building envelope

According to the speech made by Zhu Diwen at the climate change seminar on May 26, 2009, supposing that the surface color of the roofs, roads and cars around the world turn into white, the decrease of the carbon emission is equivalent to stopping the usage of all the cars for 11 years. The surface colors of the wall/roof also have a great influence on the energy consumed in the air-conditioning system.

Three surface colors of the roof and wall for the building envelope are chosen to compare the heat flow from the building. The reflectivity and absorption of the three colors are listed in Tab. 3. With the same HGCHP system and the radiant floor combined with a fresh air system, an insulated building and an uninsulated building with white, gray and black are simulated through EnergyPlus. The uninsulated building is the building where the insulation boards are removed from the roof/wall/floor, and the air layer and single-layer glass are removed from the double-glazed low-emission windows of the insulated building. The heat flows of the building in the heating season and in the cooling season are listed in Figs. 4 and 5.

Tab. 3 Reflectivity and absorption of the wall/roof

Surface color	Reflectivity	Absorption
White	0. 80	0. 20
Gray	0. 35	0. 65
Black	0. 10	0. 90

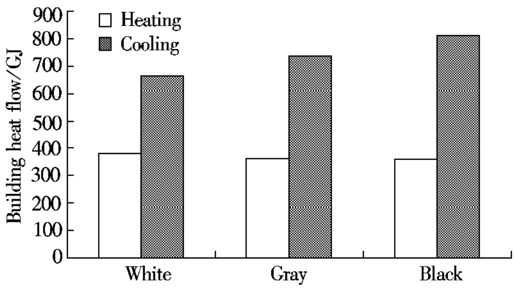

Fig. 4 Heat flow of insulated building with different surface colors

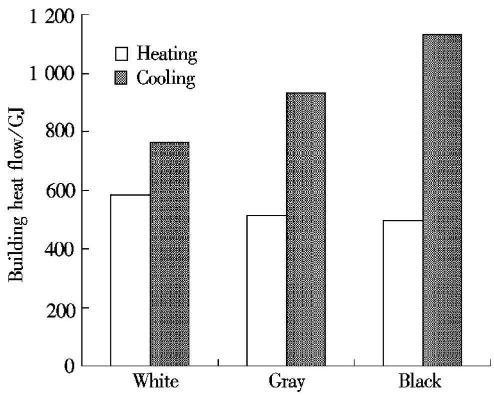

Fig. 5 Heat flow of un-insulated building with different surface colors

As can be seen from Fig. 4, in the cooling season for the insulated building, the heat flow of the building with black wall and roof is 1. 2 times greater than that with a white. For this actual HGCHP project, the color of the wall and roof is gray and the heat flow of this actual building is 1. 1 times greater than that with a white wall and roof. It can be seen from Fig. 5 that in the cooling season for the uninsulated building, the heat flow of the building with black wall and roof is 1. 4 times greater than that with white, and the heat flow of the building with a gray wall and roof is 1. 2 times greater than that with white. It is concluded that the influence of the surface color on the un-insulated building heat flow is greater than that on the insulated building.

3. 3 Energy saving analysis of terminal air-conditioning system

The building utilizing the radiant floor system combining a fresh air system as an indoor terminal air-conditioning system can realize a more comfortable indoor environment and shows an energy saving potential compared with the traditional air-conditioning systems[7]. For the insulated building and the HGCHP system, this paper compares the energy saving potential between the radiant floor combined with a fresh air system and a primary air fan-coil system.

For the primary air fan-coil system, two ground-coupled heat pump screw units are employed. One unit is used to supply cold and hot water for the primary air fan-coil system, and the other unit is used to supply cold and hot water for the fresh air system. The type of the units is the same as the units used in the radiant floor system combined with the fresh air system. It is assumed that the energy consumption of the fresh air heat pump unit in the primary air fan-coil system is the same as that of the radiant floor combined with the fresh air system. And based on the hourly load and COP_i of the heat pump unit, the energy consumption of the radiant floor heat pump unit for the primary air fan-coil system is calculated by Eq. (1), amounting to 52. 2 GJ in the heating season and 96. 5 GJ in the cooling season.

With the same insulated building and gray wall/roof, it is concluded that the total energy consumption of the heat pump units in the primary air fan-coil system is 1. 3 times greater than that of the radiant floor heating/cooling system (see Tab. 1), and shows an annual increase of 44. 7 GJ compared with the radiant system. Chosen 0. 85 yuan/(kW·h) as the industry electricity price, the annual operation costs of the primary air fan-coil system has an increase of 11 thousand yuan compared to the radiant floor system combined with the fresh air system.

4 Conclusions

This paper takes an HGCHP project as an example. The HGCHP uses a supplemental heat rejecter to dissipate extra thermal energy to guarantee an underground soil heat balance. Based on the simulation results from the software EnergyPlus, two feasible control strategies for the cooling tower and the borehole heat exchanger are proposed in this paper. The important conclusions are listed below:

1) Two control strategies of the BHE and the cooling tower are proposed. For strategy 1, the initial stage and the last stage of the cooling season choose the cooling tower to dissipate heat energy. For strategy 2, T_o is chosen as a baseline and the cooling tower is started when the outdoor dry bulb temperature is less than T_o.

2) With the same radiant floor cooling system, the building heat flow in the cooling season increases along with the absorption increase of the wall/roof surface color. The heat flow of the insulated building with a black wall and roof is 1. 2 times greater than that with white, and the heat flow of the un-insulated building with a black wall and roof is 1. 4 times greater than that with white.

3) With the same insulated building and the same gray wall/roof, the total energy consumption of the heat pump units for the primary air fan-coil system is 1. 3 times the amount of the radiant heating/cooling system.

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混合土壤热泵节能实例分析

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摘要:以南京某混合土壤热泵系统为例,分析比较不同冷热源运行策略、围护结构及空调末端系统对建筑能耗的影响.该混合土壤热泵系统以冷却塔为辅助散热设备,使得通过地埋管换热器向土壤散出的热量和从土壤中取出的热量相等.利用能耗模拟软件 EnergyPlus 对该厂房建筑进行了全能耗分析,并对冷却塔及地埋管换热器换热量进行计算.然后提出 2 种运行方法对冷却塔进行启停控制.比较墙面与屋顶不同颜色时建筑能耗特性,结果表明:供冷季节黑色外围护结构的建筑冷负荷是白色外围护结构的 1.2 倍;建筑保温性能相同时,以风机盘管为空调末端,热泵机组的年能耗比辐射地板系统大 44.7 GJ.

关键词:混合土壤热泵;地埋管换热器;节能
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