SIMULATION AND OPERATION CONTROL STRATEGY OF GROUND SOURCE THERMAL ENERGY MANAGEMENT SYSTEM BY COLD AND HEAT AUXILIARY TECHNOLOGY

by

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To explore the performance of the ground source thermal energy management system under the cold and heat sources, based on the cold and heat auxiliary technology, a ground source thermal energy composite management system is constructed and simulated. The constructed ground source heat pump-refrigeration unit-hybrid heating management system of urban heating networks, as well as the simple system, are analyzed and investigated in terms of power consumption and underground temperature control. The research results show that the constructed ground source heat pump-refrigeration unit-hybrid heating management system of the urban heating network has lower power and energy consumption than a simple system during the same period, which meets the economic requirements and guarantees the system with relatively low energy consumption. For underground temperature control, the constructed system is more stable than a simple system without excessive temperature fluctuations. The operation control strategy of the constructed system is mainly for chiller units, heat pump units, cooling towers, source side, and side circulation water pump modules. In summary, the constructed ground source heat pump-refrigeration unit-hybrid heating management system of an urban heating network based on the ground source heat pump meets the requirements for energy consumption and temperature control and can operate the control strategy normally. The results are significant for subsequent researches on the ground source thermal energy management system based on cold and heat auxiliary technology.

Key words: *cold and heat source, composite, centralization, energy consumption, refrigeration*

Introduction

Along with the continuous consumption of fossil energy worldwide, the available natural resources are constantly decreasing. Thus, the use and development of emerging energy sources are receiving more attention globally [1]. In China, it is particularly critical due to its large population. Although the total resources are abundant in China, the per capita possession is much lower than the world average levels. Therefore, China has also increased the development and utilization of other resources [2]. Geothermal energy is a kind of abundant and environmental-friendly emerging energy. At present, the utilization of geothermal energy is at

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an early stage. The major research direction is to control and manage the geothermal energy to achieve the purposes of cooling and heating in summer and winter, which is a significant research direction [3]. Compared with traditional energy sources, geothermal energy is prominent in terms of price and cost-performance [4]. At present, there are many problems in the utilization of geothermal energy, such as instability, safety, and low efficiency. These difficulties currently hinder the popularization and utilization of geothermal energy [5]. Therefore, considering the advantages and disadvantages of geothermal energy, this study explores the power consumption and underground temperature control of the constructed ground source heat pump-refrigeration unit-hybrid heating management system of urban heating network and a simple system, so as to avoid the operating obstacles caused by insufficient geothermal energy, which can gradually reduce the dependence of traditional heating methods [6, 7]. Therefore, the actual operating effects of the composite ground source thermal energy management system can be analyzed qualitatively and quantitatively [8].

The dependence on energy is extremely critical in all aspects and industries. Therefore, an efficient and stable energy output system is an essential factor for the development and utilization of all kinds of energy [9]. Geothermal energy is buried underground. In China, due to the vast land area, the storage of geothermal energy is unlimited. Most importantly, geothermal energy is a kind of clean energy, which is cost-effective and inexhaustible. Thus, accelerating the research on the difficulties of deploying geothermal energy is significant. Currently, the field is in the initial stage. Therefore, the research focus of this study is to design and construct a ground source thermal energy management system based on cold and heat auxiliary technology that meets the requirements of normal operation, which is necessary for the further understanding of geothermal energy [10].

This study investigates the energy consumption and temperature control of the ground source thermal energy management system by constructing and simulating a cold-heat source-assisted ground source thermal energy composite management system. Also, this study analyzes the operation control strategy. The constructed ground source heat pump-refrigeration unit-hybrid heating management system of the urban heating network can meet the requirements of minimum power consumption and minimum temperature fluctuations Meanwhile, the control strategy is normally operated. The innovation of this study is that the cold-heat source-assisted composite ground source thermal energy management system is designed for exploration. At present, most of the research directions are a simple operating system. Therefore, this study has significant value for the subsequent research on the ground source thermal energy management system.

Methodology

Composition and applicable conditions of ground source heat pump

The ground source heat pump refers to the extraction of thermal energy contained in the soil by using the stable characteristics of groundwater, soil, and surface water, which consumes less external energy [11]. Therefore, as an energy source for various uses, a major feature of a ground source heat pump is that it can rely on its existence as a space for energy storage and conversion, achieving a comprehensive and integrated operation of heating and cooling. Due to these outstanding characteristics, geothermal energy can be an effective substitute for refrigeration machinery and heating equipment. Meanwhile, the abundant storage and the outstanding pollution-free characteristic of geothermal energy, it will surely become an energy supplier for cooling and heating [12, 13].

The simulation of a simple ground source heat pump system is shown in fig. 1. Generally, a ground source heat pump system is composed of a water source heat pump unit, a geothermal energy collection system, and a terminal machine. The core technology is energy harvesting and heat exchange machinery, which is mainly divided into three modes, *i. e.*, the surface water heat exchange system, the buried tube heat exchange system, and the groundwater heat exchange system.

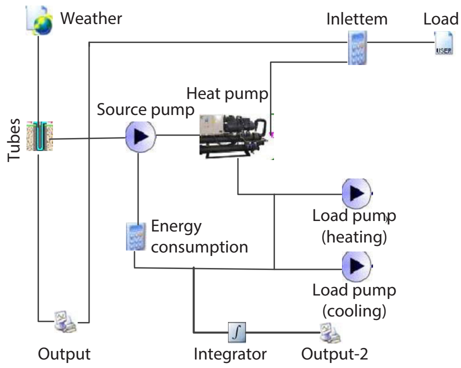

Figure 1. Simulation of a simple ground source heat pump system

Heat transfer model of the buried tube heat exchanger

The schematic diagram of the heat exchanger is shown in fig. 2. Since the underground heat transfer is complicated, the entire heat transfer process of the buried tube heat exchanger affects a long period and a large area, which is also an unstable process. Therefore, the heat transfer model of geothermal heat exchangers has always been the basis and difficulty for the investigation of ground source heat pump systems [14, 15]. In actual engineering, the borehole wall is used as the boundary to divide the heat transfer into two aspects, *i. e.*, the heat transfer outside the borehole (the heat transfer between the borehole wall and the external soil), and the heat transfer inside the hole [16].

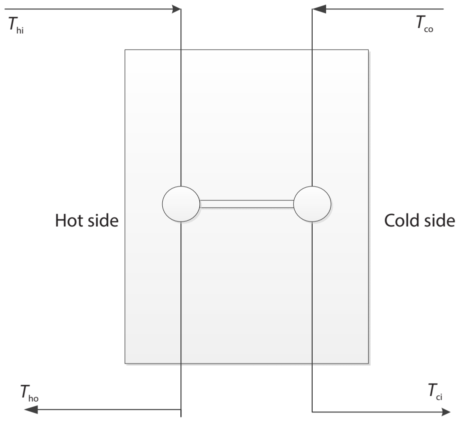

Figure 2. Schematic diagram of the heat exchanger

Heat transfer model inside the borehole

The form and number of holes are shown in fig. 3. Compared with the size of the rock and soil outside the hole, the internal structure and size are relatively smaller, and the heat capacity is also much smaller. The gap is more obvious, thus, generally, the heat transfer process in the borehole will be analyzed and studied as a stable and uniform process.

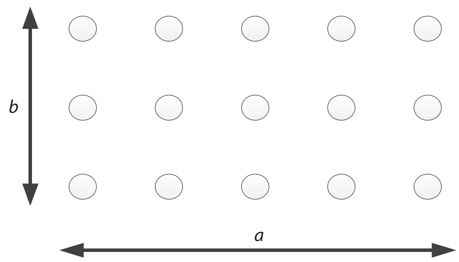

Figure 3. The form and number of holes

This study mainly analyzes the temperature changes of the two branch pipes along with the depth. At the same time, the thermodynamics of convection heat transfer is also analyzed and studied. After analysis, the energy changing process and equation when the *U*-shaped pipe flows freely:

$$\left.\begin{aligned} -Mc = \frac{\mathrm{d}T_{f1}}{\mathrm{d}z} = \frac{T_{f1}-T_{\mathrm{b}}}{R_1^{\Delta}} + \frac{T_{f1}-T_{f2}}{R_{12}^{\Delta}} \\ Mc = \frac{\mathrm{d}T_{f2}}{\mathrm{d}z} = \frac{T_{f2}-T_{\mathrm{b}}}{R_2^{\Delta}} + \frac{T_{f2}-T_{f1}}{R_{12}^{\Delta}} \end{aligned}\right\},\ 0 \le z \le H \tag{1}$$

$$R_1^\Delta = \frac{R_{11}R_{22} - R_{12}^2}{R_{22} - R_{12}}$$
$$R_2^\Delta = \frac{R_{11}R_{22} - R_{12}^2}{R_{11} - R_{12}} \tag{2}$$
$$R_{12}^\Delta = \frac{R_{11}R_{22} - R_{12}^2}{R_{12}}$$

where M is the mass-flow of the fluid in the U-shaped pipe, C – the specific heat of the fluid, and T_b – the wall temperature of the borehole, T_{f1}, T_{f2} – the inlet and outlet temperatures of circulating fluid in different branches, R_{11}, R_{22} – the thermal resistance of the circulating fluid in the bore of the two branches to the borehole wall, R_{12} – the thermal resistance between the two tubes, and z is the flow resistance.

Heat transfer model outside the borehole

The heat transfer outside the borehole is usually studied according to the unsteady-state. In engineering calculations, the finite-length heat source model proposed by Eskilson is usually used. The excess temperature at M:

$$\theta = \frac{Q_1}{4\pi k}\int_0^H \left\{ \frac{erfc\left\{\dfrac{\sqrt{\rho^2 + (z-h)^2}}{2\sqrt{a\tau}}\right\}}{\sqrt{\rho^2 + (z-h)^2}} - \frac{erfc\left\{\dfrac{\sqrt{\rho^2 + (z+h)^2}}{2\sqrt{a\tau}}\right\}}{\sqrt{\rho^2 + (z+h)^2}} \right\} \mathrm{d}h \tag{3}$$

where θ is the heating function at any point in the soil, ρ – the dimensionless radius, z – the dimensionless depth of the soil, $\alpha\tau$ – the dimensionless time, h – the dimensionless depth of the borehole, Q_1 – the exothermic or endothermic heat of the U-shaped buried pipe Strength, and k – the thermal conductivity of the soil. The temperature of the borehole wall is obtained:

$$t_\mathrm{b} = \frac{Q_1}{4\pi k_g}\int_0^H \left\{ \frac{erfc\left\{\dfrac{\sqrt{\rho^2 + (z-h)^2}}{2\sqrt{a\tau}}\right\}}{\sqrt{\rho^2 + (z-h)^2}} - \frac{erfc\left\{\dfrac{\sqrt{\rho^2 + (z+h)^2}}{2\sqrt{a\tau}}\right\}}{\sqrt{\rho^2 + (z+h)^2}} \right\} \mathrm{d}h + t_0 \tag{4}$$

where C_p is the energy efficiency ratio of the refrigeration system, Δt – the temperature difference between the inlet and outlet of the ground source side, and the design flow G on the ground source side:

$$G = \frac{3600 Q_1^{/}}{c_p \rho \Delta t} \tag{5}$$

Operation control strategy of cold and heat source program

The simulation system of ground source heat pump air-conditioning system + chiller + municipal pipe network centralized heating composite system is shown in fig. 4, which is found to have the following advantages:

– the comprehensive operating efficiency of the system is high,
– it solves the problem of unbalanced underground hot and cold system and tight land use for underground pipes in the simple ground source heat pumps, and
– it has lower initial investment and operating costs, which is economical.

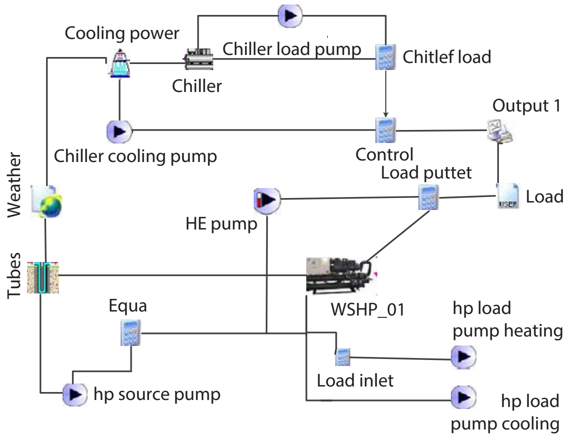

Figure 4. The dynamic simulation of the ground source heat pump+refrigeration unit+plate heat exchanger composite system

The composite system adjustment control strategy based on the cold-heat source-assisted ground source heat pump municipal city pipe network is as follows: The first step is to first simulate the operating state and regularity of the cycle, find the operating regularity and key points, and determine the optimized control operation strategy. In the second step, when using the composite geothermal management system designed in this study to work in summer, if the cooling load required by the load exceeds the rated capacity that the unit can provide, the auxiliary cooling by means of a chiller is required to achieve the purpose of cooling. If the temperature of the water source at the outlet of the heat pump unit of the geothermal system exceeds the set value, the assistance of the cooling tower is required to help the system to dissipate heat and ensure that the temperature is within the control range of the set value. When using the composite geothermal management system designed in this study to work in winter, if the temperature of the water source at the outlet of the heat pump unit of the geothermal system is lower than the set value, the assistance of a plate heat exchanger is needed to help the system to perform with the municipal heating energy and increase the temperature to ensure that the temperature is within the control range of the set value. In such a state, the geothermal system only needs to bear a small part of the heat output. As for the energy that the heat pump unit needs to load, it needs to find the best value through simulation. The third step is to control the imbalance of the buried pipe-line to ensure that it is less than 14%. Under such a simulated operation control strategy, the cold and heat balance of the geothermal system is optimal.

Settings of comprehensive cost calculation equation

The comprehensive cost LCC = initial investment + operating cost; the initial investment = source heat pump cost + refrigeration unit cost + municipal city heat grid board replacement cost; the operating cost = ground source heat pump cost + refrigeration unit cost + municipal city heat grid plate replacement cost. The calculation of initial investment cost:

$$Q_{\text{hp}} = \text{LOADrate}C \times Q_1$$
$$Q_{\text{c}} = \left(1 - \text{LOADrate}C\right) \times Q_1 \tag{6}$$

where Q_1 is the building design cooling load, taken 5061 kw, Q_2 – the building design heating load, taken 3174 kw, LOADrateC – the percentage of the building cooling load undertaken by the heat pump, LOADrateH – the percentage of the building heating load undertaken by the heat pump, $Q_{\rm hp}$ – the rated cooling capacity of the heat pump, and $Q_{\rm c}$ – the rated cooling capacity of the chiller.

The operating cost = cumulative power consumption of the system × electricity cost + + (municipal heating network price + machine room + cooling tower) × area. The cumulative power consumption of the system = ground source heat pump cost + chiller cost + municipal pipe network plate replacement cost:

$$W_{\rm hp} = \int\left[\frac{\left(P_{\rm hp}+P_{\rm sourcepump}\right)\times Con_1 + P_{{\rm loadpump}h}\times Con_{\rm 2h} + P_{{\rm loadpump}c}\times Con_{\rm 2c}}{3600}\right]$$

$$Con_1 = \max\left(\text{hcon},\text{ccon}\right)\times ge\left(\frac{Q_{\rm load}}{Q_{\rm hp}},0.005\right)\times gt\left(\text{hpcop},1\right)$$

$$Con_{\rm 2h} = \text{hcon}\times ge\left(\frac{Q_{\rm load}}{Q_{\rm hp}},0.005\right)\times gt\left(\text{hpcop},1\right) \qquad (7)$$

$$Con_{\rm 2c} = \text{ccon}\times ge\left(\frac{Q_{\rm load}}{Q_{\rm hp}},0.005\right)\times gt\left(\text{hpcop},1\right)$$

where $W_{\rm hp}$ is the cumulative power consumption of the ground source cooling pump, $P_{\rm hp}$ – the power of the heat pump, $P_{\rm sourcepump}$ is the power of the ground source side pump, $P_{\rm loadpumph}$ – the power of the air conditioning side pump (heating), and $P_{{\rm loadpump}c}$ – the air conditioning side pump (cooling) power, Con_1 – the control signal of the heat pump unit and its ground source side circulating water pump, hcon – the heating season signal, ccon – the cooling season signal, $Q_{\rm load}$ – the hourly load of the building, hpcop – the cycle performance coefficient of the heat pump unit, $Con_{\rm 2h}$ – the circulating water pump heating control signal of heat pump air conditioner side, and $Con_{\rm 2c}$ – the circulating water pump cooling control signal of heat pump air conditioning side.

Chiller unit cost:

$$W_{\rm c} = \int\left(\frac{\left(P_{\rm c}+P_{\rm loadpump}\right)\times Con_3 + P_{{\rm coolingpump}h}\times Con_4}{3600} + P_{\rm tower}\times Con_4\right)$$

$$Con_3 = \text{ccon}\times gt\left(Q_{\rm load},\frac{q_{\rm hp}}{3600}\right) \qquad (8)$$

$$Con_4 = \text{ccon}\times gt\left(Q_{\rm load},\frac{q_{\rm load}}{3600}\right)\times gt\left(\text{olt},\text{HPstemCOOL}\right)$$

where $W_{\rm c}$ is the cumulative power consumption of the chiller, $P_{\rm c}$ – the power of the chiller, $P_{\rm loadpump}$ – the power of the air conditioning side pump, $P_{\rm coolpump}$ – the power of the cooling side pump, $P_{\rm tower}$ – the power of the cooling tower, Con_3 – the chiller and its circulating water pump control signal of air conditioning side, $q_{\rm hp}$ – the actual cooling capacity of the heat pump unit, $q_{\rm load}$ – the load temperature, Con_4 – the control signal of the cooling tower and its circulating water pump of cooling circulation side, olt – the outlet water temperature of heat pump source side, and HPstemCOOL – the outlet water temperature of summer heat pump source side.

Municipal pipe network plate replacement cost:

$$W_{\mathrm{HE}} = \int \left[\frac{\left(P_{\mathrm{HE}} + P_{\mathrm{HEpump}}\right) \times Con_{54}}{3600} \right] \qquad (9)$$

$$Con_5 = hcon \times \mathrm{lt}\left(\mathrm{olt}, \mathrm{HPstemHEAT}\right)$$

where W_{HE} is the cumulative power consumption of the replacement part of the municipal pipe network, P_{HE} – the power of the chiller, P_{HEpump} – the power of the air conditioning side pump, Con_{54} – the control signal of circulating water pump of the municipal side and plate heat exchanger, and HPstemHEAT – the winter heat pump water temperature at the source side outlet.

In summary:

$$\mathrm{OPERATIONcosts} = C_7 \times \left(W_{\mathrm{hp}} + W_{\mathrm{c}} + W_{\mathrm{HE}}\right) + \left(C_8 + C_9\right) \times S \qquad (10)$$

where C_7 is 0.7 yuan/kWh for electricity cost, C_8 – 4.5 yuan/m^2 for operating room cost, C_9 – 1.8 yuan/m^2 for operating room cost, S – the area. Monitoring point setting: The principle of differential pressure control is shown in fig. 5. According to the control requirements, the equipment monitoring points of the energy center are set one by one. Taking the ground source heat pump unit as an example, four monitoring points are set, including the manual/automatic state (DD), the running state (DD), the fault state (DD) and the start-stop control (DO). Other pieces of equipment are set up according to their characteristics. In the end, there are 192 energy center monitoring points.

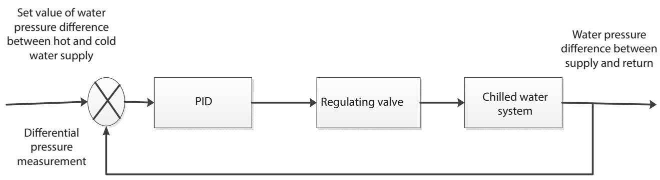

Figure 5. Principle of differential pressure control

System start-stop control: in this study, the construction equipment monitoring system provides operators with three start-stop control methods, *i. e.*, the automatic start-stop control on the workstation, the manual start-stop control on the workstation, and the time control.

Dynamic simulation and performance analysis

This study is based on a renovation project of an energy center in a conference center. The building contains conference, office, guest room, catering and entertainment functions. The total construction area is about 86000 m^2, of which the existing construction area is 70304 m^2, with a total of 22 single units. The proposed construction area is about 14306 m^2, and the original cold and heat sources are planned to be completely transformed. The research method of combining theoretical analysis, numerical simulation, and engineering examples are used, and TRNSYS simulation software is used as a platform to analyze and simulate the operating characteristics of the ground source heat pump + chiller + municipal pipe network centralized heating composite system, thereby finding the most optimized operation control strategy.

Results and discussion

The time-varying curve of the average underground temperature of the composite and simple systems is shown in fig. 6. From the data and trend graphs in the figure, it can be seen that compared with the ground source heat pump-refrigeration unit-hybrid heating management system of the urban heating network, the simple ground source heat energy system

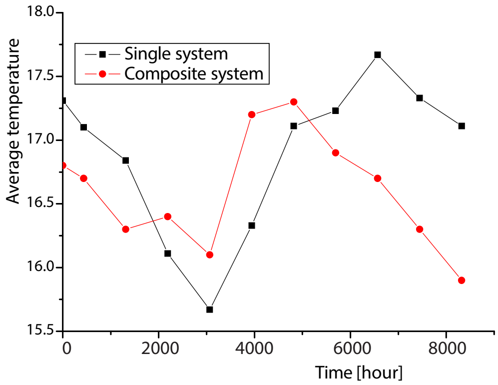

Figure 6. The time-lapse curve of the average underground temperature of composite and simple systems

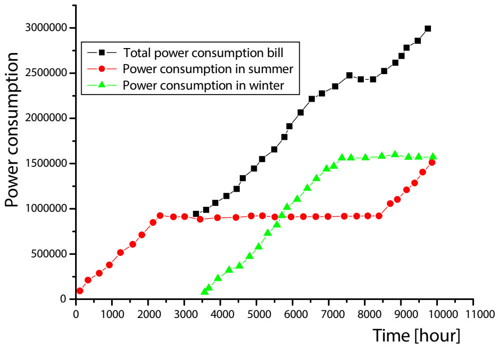

Figure 7. The cumulative annual power consumption of a simple ground source thermal energy system

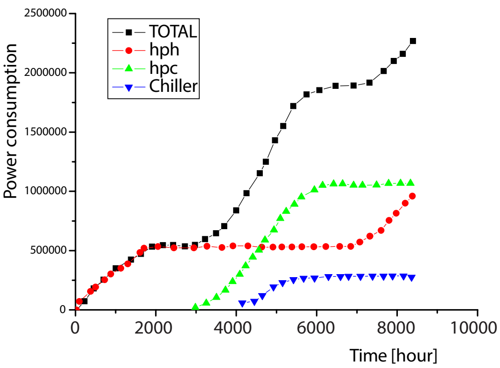

Figure 8. The cumulative annual power consumption of composite ground source thermal energy management system

is more obvious and prominent in the changes of underground temperature. Therefore, it can be seen that the constructed composite ground source heat pump-refrigeration unit-hybrid heating management system of the urban heating network is more stable and prominent in controlling the underground temperature.

The annual cumulative power consumption of a simple ground source thermal energy system is shown in fig. 7. From the data and trend graphs in the figure, it can be seen that within 2000-7000 hours, the power consumption in winter remains stable and does not change with time. After 6000 hours, the power consumption in summer is stable and unchanged. The power consumption of the entire system continues to increase with time, which is greater than the power consumption of the composite ground source thermal energy system over the same period. It can be seen that the ground source heat pump-refrigeration unit-hybrid heating management system of an urban heating network constructed in this study has significant advantages in energy consumption compared to a simple system.

In fig. 8, hph is a ground source heat pump – heating unit – urban heating network system, and hpc – a ground source heat pump – refrigeration unit – urban heat network system. The annual cumulative power consumption of the composite ground-source thermal energy management system is shown in fig. 8. From the data and trend graphs in the figure, it can be seen that the power consumption of the constructed ground source heat pump-refrigeration unit-hybrid heating management system of the urban heating network gradually increases with the increase of time. However, the power of the hph system is stable during 2000-7000 hours, while it remains stable after 6500 hours and does not change as the time changes. The power consumption of the chiller system is stable after 5500 hours. By analyzing the power consumption of the three subsystems, the energy consumption of the composite system constructed in this study can be more fully understood.

Conclusion

This study has investigated the energy consumption and temperature control of the ground source thermal energy management system by constructing and simulating a cold-heat source-assisted ground source thermal energy composite management system. Also, this study has discussed the operation control strategy. The research results show that the constructed ground source heat pump-refrigeration unit-hybrid heating management system of the urban heating network has lower power and energy consumption than a simple system during the same period, which meets the economic requirements and guarantees the system with relatively low energy consumption. For underground temperature control, the constructed system is more stable than a simple system without excessive temperature fluctuations. The operation control strategy of the constructed system is mainly for chiller units, heat pump units, cooling towers, source side, and side circulation water pump modules. This study also has some deficiencies in the research process, which are mainly caused by the fact that the conclusions obtained by the research on the cold-heat source-assisted ground source composite system are more from the experimental and theoretical stages. There will be many factors and problems of the operations under actual application conditions. Since this study is in the experimental stage, many external factors are ignored, and the results may be slightly less convincing. Nevertheless, this study has provided a useful reference for the investigation on the ground source thermal management system qualitatively.

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