THE MODELING AND ENERGY EFFICIENCY ANALYSIS OF THERMAL ENERGY MANAGEMENT OPERATION OF GROUND SOURCE HEAT PUMP AIR CONDITIONING SYSTEM

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To improve the energy-saving effect of the ground source heat pump air conditioning system, an example is investigated, and the annual loads of the building are simulated and analyzed. The thermal energy management operation modeling is conducted. The hydraulic analysis is performed for different modes in each section. Given the same flow and tube type, a larger pipe diameter indicates a smaller hydraulic loss. Compared with the parallel 5-well loop and the parallel 10-well loop, the hydraulic loss of the series 2-well loop is the highest. When the sub-catch is connected to 5 loops, as the number of series wells increases, the tube length gets longer, the flow rate allocated by the loop gets less, and the load increases. Besides, the energy efficiency ratio of the ground source side decreases as the heat rejection load increases. Therefore, by adjusting the pipe diameter, the pipe type, and the depth of the well, the hydraulic loss can be reduced. The energy-saving effect of the loop in the parallel mode is better. Given the limited number of the managed wells, the parallel circuit can be adjusted to the same program. The connection allows the collector to distribute the flow evenly. The energy efficiency ratio of the ground source can be improved by changing the diameter of the horizontal trunk pipe. It is hoped that the hydraulic optimization design of the ground source heat pump air conditioning system can provide a theoretical basis for the application and promotion of the ground source heat pumps.

Key words*: ground source heat pump air conditioning system; thermal management; efficacy analysis; hydraulic optimization; load simulation*

1. Introduction

With the rapid development of the economy and the continuous improvement of the living standards per capita, the energy demand is increasing. According to the survey, in some first- and second-tier cities, the energy consumed by summer cooling and winter heating is as high as 40-50% of the total energy consumption of buildings [1]. The large-scale use of non-renewable resources such as coal has caused great environmental problems, and at the same time, it has harmed people's health to a certain extent. Therefore, building pollution control and energy conservation have become a major issue in the development of the national economy. In recent years, to improve the atmospheric environment, China has vigorously promoted the use of clean energy sources such as ground heat energy, wind energy, water energy and solar energy. Ground heat energy is the natural heat extracted from the earth's crust. It is a non-polluting and harmless renewable clean energy. At present, the development and utilization of ground heat energy have become an important energy source for coping with climate change, promoting energy diversification and achieving sustainable development, which is a worldwide development trend. The ground source heat pump technology is to use the ground heat energy absorbed by groundwater to form low-temperature low-level heat energy. By adopting a heat pump principle, a technology of transferring low-level heat energy to high-level heat energy is realized through a small amount of electric energy output [2]. As a green air conditioning application technology, the application of ground source heat pump has developed rapidly and is highly valued for its efficient energy saving. Theoretically, up to 4.9 kW of heat can be supplied with 1 kW of electricity [3]. The ground source heat pump air conditioning system exchanges heat with the soil, and the soil temperature is relatively constant throughout the year; so, the cooling and heating effects are not affected by the external environment. In addition, no defrosting is required during heating in winter, and the outdoor unit will not blow out the cold air. Thus, it is the most advanced, energy-saving, and most popular air-conditioning system. Zhong et al. conducted a three-year field test on a water source heat pump air conditioner in a modern office building and proposed plans and recommendations to improve the system operation management and the energy-saving effects [4]. Ruiz-Calvo et al. applied the variable speed ground source heat pump to the displacement ventilation system, which reduced the initial and operating costs and improved the economic feasibility of the system [5]. Cang et al. conducted a variable water temperature adjustment for the shallow buried ground source heat pump system with low energy utilization efficiency during summer cooling. The results showed that the energy-saving effect of the variable water temperature regulation system was better than that of the fixed water temperature system during summer cooling [6]. Luo et al. proposed an efficient operation control system for a hybrid ground source heat pump based on extreme value search, which achieved the approximate optimal efficiency without object model [7].

In general, the ground source heat pump air conditioning system is a relatively energy-saving and efficient air conditioning system. However, at present, it still has many limitations in actual operation. This study takes a ground source heat pump air conditioning system as an example to analyze the air conditioning load characteristics of the ground source heat pump air conditioning system and proposes relevant hydraulic optimization measures based on actual conditions. It is proposed to use long-term energy efficiency as the optimization target for the ground source heat pump, providing a reference basis for the energy-saving transformation.

2. Methods

2.1. Basic facts of a certain ground source heat pump air conditioning system

The building has four floors with a total land area of approximately 3,000 m^2, of which the air-conditioned area has an area of approximately 2,500 m^2. The main technical parameters are as follows: the heat load is 320 kW, the cooling load is 483 kW, the heating load index in the heating season is 112 W/m^2, and the cooling load index in the cooling season is 146 W/m^2.

Taking a ground source heat pump air conditioning system as an example, the system uses a ground source heat pump of cold and heat source, which has two pumps, a pumping well, and a recirculation well. The system has auxiliary heating when the unit is started, and no electric heating is used after normal operation. There are 3 units in the machine room, one is for the preparation and standby of domestic hot water, and the other two are for cooling and heating. The air conditioning area uses a fan coil and a fresh air system. During the operation of the ground source heat pump air conditioning system, the following problems mainly exist: The operating frequency is unreasonable. During the winter test period, the operating frequency of the two pumps remains unchanged; the applicability is poor, the average daily usage of groundwater reaches 800 tons, and the demand is large, which seriously affects the local geology. The thermal load varies. It has an adverse effect on the underground heat balance and reduces the heating and cooling effects of the system.

2.2. Load simulation of the building and the comparative analysis

At present, there are two types of commonly used simulation software, i.e., energy simulation software and simulation software. The energy simulation software mainly simulates the dynamic load changes of buildings and ground source heat pump air conditioning systems by establishing mathematical models. Under different weather conditions, the annual dynamic load of the building is predicted, and the cooling load and heat load of the whole year are calculated to simulate the energy consumption. In this study, the DeST energy simulation software is used to simulate the energy consumption of the building, set the main room parameters of the building, calculate the cooling load and heat load of the whole year, and compare and analyze the design and simulation parameters of the air conditioning system.

2.3. Optimization of ground source pipe network for ground source heat pump air conditioning system

2.3.1 Modeling of thermal energy management operation of ground source heat pump air conditioning system

The pipeline system hydraulic modeling software Pipe Flow Expert has the advantages of intuitive and user-friendly interface, simple modeling, comprehensive database, reliable calculation results, and graphical results. It can design and analyze complex pipeline networks, including the entire pipeline network, the flow distribution, and the pressure loss, especially where tube flow and pressure need to be balanced. The simulation software simulates the operation and control process of the system. Therefore, this study uses the Pipe Flow Expert software for modeling. The U-shaped tube is linearized for modeling without affecting the hydraulic characteristics. The single U-shaped tube should be straightened into a straight tube connected to the horizontal connecting tube, and the double U-shaped tube is simplified to a single U-shaped tube. The simplified nodes and pipelines are entered, and the parameters are modified according to the Computer-Aided Design (CAD) diagram, including the length, pipe diameter, and node elevation. Then, the corresponding pipe section resistance coefficients are added at the pipeline location. After the input is completed, a complete buried pipe network model is connected. The terminal pressure is input, and system analysis is performed. Information such as flow rate, volume, and hydraulic loss of the pipe section is obtained. Also, the problems that occur during the calculation are modified and adjusted. Data analysis is performed on the pipe network system, and the required result data are obtained by adjusting the input parameters.

2.3.2 Hydraulic optimization of single-hole buried tube wells

The depth of the buried pipe heat exchanger should be more than 20 m, and the construction cost and installation difficulty will increase exponentially with the increase of depth. Therefore, the influence of parameters such as buried depth, flow velocity, and pipe diameter on the head loss of single-soil buried well is analyzed to get the optimal layout of a single well. The U-tube resistance consists of two parts, i.e., the local resistance and resistance along the path. The local resistance can be calculated as the equivalent pipe length to calculate the heat loss, and the resistance along the path is calculated by the Colebrook's formula, as shown in Eq. (1).

$$\frac{1}{\sqrt{\lambda}}=-21g\left(\frac{k}{3.7d}+\frac{2.51}{\mathrm{R_e}\sqrt{\lambda}}\right) \tag{1}$$

Where d is the inner diameter of the pipe, k is the absolute roughness of the inner wall of the pipe, $\mathrm{R_e}$ indicates the Reynolds number in the pipe, λ indicates the resistance coefficient along the path.

2.3.3 Hydraulic optimization of a single buried pipe loop

To reduce the material costs, the same number of pipe diameters should be selected in each loop to connect the same buried pipe. The length of the vertically buried pipe adopts parallel pipelines, and each loop header is connected to a single loop. The water collector is buried in the underground pipe trench. In this study, the hydraulic losses under the three different loop modes of parallel 5-wells, parallel 10-wells, and series 2-wells are compared to analyze the optimal connection method.

2.3.4 Hydraulic optimization of buried pipes in each section

Since the buried area of the buried pipe is irregular in shape and is greatly affected by the construction, the final formed tube group area and the actual design may deviate. In this study, the X-section is selected for hydraulic optimization research. The section is divided into three sub-sections, i.e., X_1, X_2, and X_3. The three sub-sections are connected by the same program. The sub-sectional loops are connected by the same program, which is in the series relationship. The load is 10.4 kW, and there are 55 pile-buried tube wells in the X-section. A total of 102 single U-shaped tube and 11.2 kW loads are deployed. The load on the X_1 sub-section is 2.92 kW, the load on the X_2 sub-section is 3.77 kW, and the load on the X_3 sub-section is 4.51 kW. Each sub-section is provided with a set of water separators, and the underground heat exchanger is connected to the manifold by a horizontal main pipe. The X_1 sub-section is taken as an example. The X_1 distinguishes five parallel loops on the sump and calculates the hydraulic loss of the pile-buried pipe joint loop in the X_1 section.

2.3.5 Overall hydraulic optimization of ground source side pipe network

In the ground source heat pump air conditioning system, the hydraulic imbalance is prone to occur. Therefore, this study optimizes the design of the ground source side pipe network to improve the stability of the air conditioning system. The energy delivered by the buried pipe side is the energy delivered by the system. The power consumption is mainly used for the ground source side circulating water pump, and this part of the energy consumption is counted as the shaft power of the water pump. The power consumption of the ground source side water pump is as shown in Eq. (2).

$$N_c = \frac{\rho_\omega gGH}{3600\times1000\eta_\xi} \tag{2}$$

Where G is the water flow, H is the lift, and η_ξ indicates the efficiency.

The coefficient of performance of the ground source side delivery system is defined, as shown in Eq. (3):

$$COP_d = \frac{Q_d}{N_d} \tag{3}$$

Where Q_d is the heat transferred, and N_d is the pump power consumption and the input power of the heat pump unit.

Through the pipe design software Pipe Flow modeling, after theoretical calculations, most buried pipe wells can meet the design requirements. However, some sections need to be internally adjusted. The number of buried pipe wells connected in each section is different, which results in different distances of the equivalent pipe long-distance collectors. In this case, the sections should be re-sectioned as much as possible, or the number of pipe wells in each section should be equal to the identical connection. In some sections, there are too many or too few buried pipes, and the number of buried pipes is less than that of the buried pipes. In this case, the horizontal dry pipe diameter can be changed to adjust the flow capacity in the section. Being locally connected to the program may result in different lengths of the horizontal trunk of the manifold. The same horizontal trunk diameter may cause the flow of the remote manifold to be smaller than the flow of the proximal manifold. In this case, a balancing valve can be provided to balance the flow difference. The flow rate inside the pipe is changed, the change of hydraulic loss at different flow rates of the most unfavorable loop of the pipe network and is analyzed to adjust and optimize the energy-saving effects according to the results.

3. Results and discussion

3.1. Results of load simulation of the building and the comparative analysis

The construction load simulation results are shown in Fig. 1 and Fig. 2. It can be seen that the maximum heating load throughout the year is 134.9 kW, which appears on January 15th. Meanwhile, the maximum annual cooling load is 377.2 kW, which appears on July 28th. The cooling load begins to show a gradual upward trend from June and a gradual downward trend after reaching a peak in July.

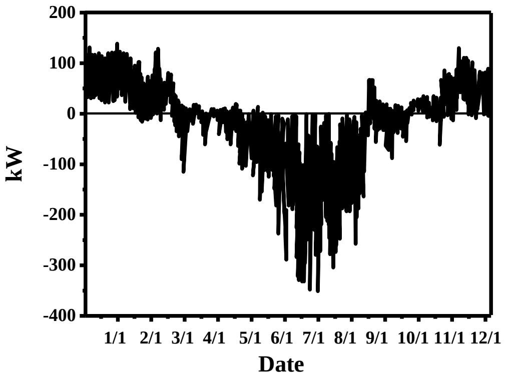

Figure 1 Hourly cooling load and heating load throughout the year

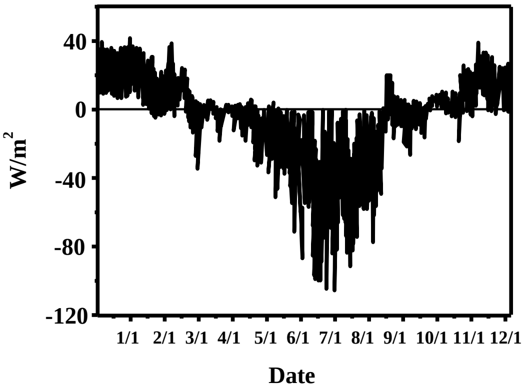

Figure 2 Hourly load of per unit section throughout the year

The design parameters and simulation results of the ground source heat pump air conditioning system are shown in Tab. 1. It can be seen that the design parameters of the cooling load index and the heating load index are not much different from the simulation results. Meanwhile, the design of the maximum cooling load and the maximum heating load in winter are designed. The difference between the parameters and the simulation results is large, and the design parameters are much larger than the simulation results. The reason for the analysis may be caused by inaccuracies or errors in the design calculation.

Table 1 Comparison of design parameters and simulation parameters of ground source heat pump air conditioning system

Comparative analysis	The cooling load index (W/m^2)	The heating load index (W/m^2)	Maximum cooling load in summer (kW)	Maximum heating load in winter (kW)
Design parameters	150.0	105.0	450.0	300.0
Simulation results	125.6	76.4	377.2	134.9

3.2. Hydraulic analysis results of single-mouth buried pipe wells

The hydraulic analysis results of a single-mouth buried pipe well are shown in Fig. 3. Given the same flow rate and pipe type, a larger pipe diameter indicates a smaller head loss. The hydraulic loss lines of the double U-shaped pipe De25 and the single U-shaped pipe De32 almost coincide. It shows that the single U-shaped tube has a similar head loss compared to the double U-shaped tube of its smaller model. Therefore, the purpose of reducing the hydraulic loss can be achieved by adjusting the pipe type, pipe diameter, and well depth. The most suitable and effective method is to adjust the pipe diameter, the pipe type, and the well depth, and increase the engineering cost.

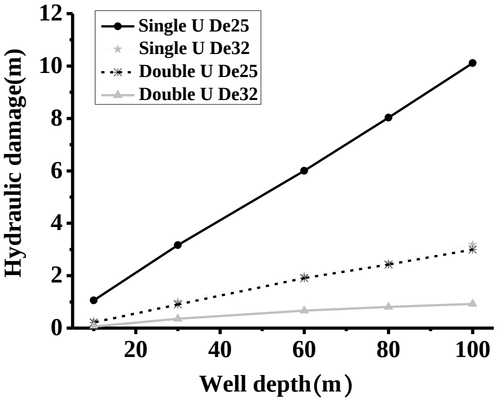

Figure 3 Hydraulic analysis results of single-mouth buried pipe wells

3.3. Hydraulic analysis results of a single buried pipe loop

The hydraulic analysis results of a single buried pipe loop are shown in Fig. 4. It can be seen that the hydraulic power of the two wells is connected in series under the loop modes of the parallel 5-well loop, parallel 10-well loop, and series 2-well loop. The hydraulic loss of series 2-well loop is the highest, while the hydraulic losses of the parallel 5-well loop and the parallel 10-well loop are relatively small, which are also similar. Therefore, the energy-saving effect of the loop in parallel mode is better.

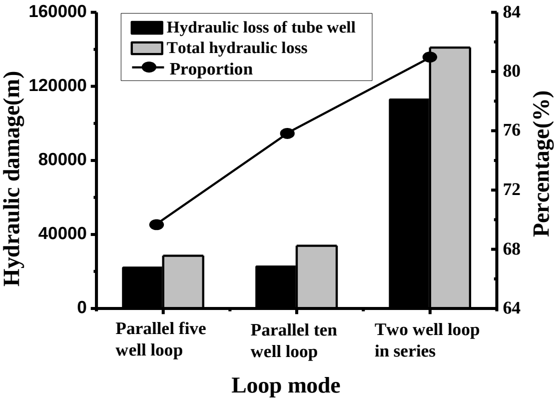

Figure 4 Hydraulic analysis results of a single buried pipe loop

3.4. Hydraulic analysis results of buried pipes in each section

The hydraulic analysis results of the buried pipes in each section are shown in Table 2. It can be seen that when five loops are connected between the sub-catchers, the more the number of series wells is, the longer the pipe length is, the less the flow rate allocated by the loop is, and the load is greater. Therefore, given the limited number of the managed wells, the parallel circuit can be adjusted to the same program, thereby the connection allows the collector to distribute the flow evenly.

Table 2 Hydraulic analysis results of buried pipes in the X_1 section

Loop	Number of series wells	Pipe length (m)	Flow rate (m^3/s)	Load (W)	Total resistance (Pa)
A	2	161	0.0003	6265	29142

B	4	185	0.0004	7952	55341
C	8	229	0.0005	9624	91245

3.5. Overall hydraulic analysis results of ground source side pipe network

The flow rate in the pipe is changed, and the changes in the hydraulic loss at different flow rates of the most unfavorable loop of the pipe network are analyzed, as shown in Fig. 5. Where H1 represents the total unfavorable loop total hydraulic loss, H2 represents the loop hydraulic loss connecting the vertical buried pipe, H3 represents the horizontal main pipe hydraulic loss from the machine room to the secondary manifold, and H4 represents the hydraulic loss between the secondary sub-collector and the third-stage sub-catcher. It can be seen that the hydraulic loss from the secondary manifold to the tertiary separator is relatively small compared to other loops. Therefore, the horizontal trunk connected from the machine room to each secondary section is the section with the most potential of being optimized.

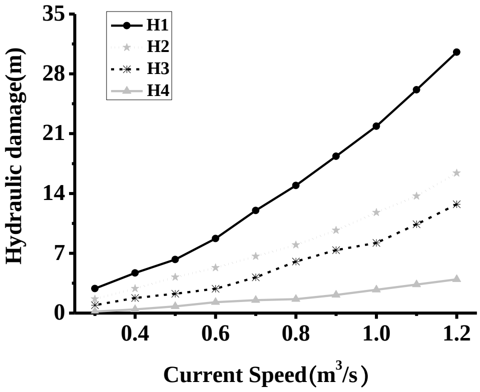

Figure 5 Changes in the hydraulic loss at different flow rates of the most unfavorable loop of the pipe network

Therefore, this study adjusts the horizontal trunk pipe diameter of some remote sections. Under the premise of ensuring the flow rate, the pipe diameter is appropriately increased, and the total hydraulic loss and flow change of the pipe network before and after adjustment are analyzed. Based on the adjustment of the front and rear variable frequency pump heads with load changes, the energy efficiency ratio of the ground source side conveying system is statistically calculated. In addition, it is necessary to adjust the number of grounding buried pipes of each loop string, as well as the number of loops connected to the secondary section water separator; therefore, the number of the two is as close as possible to achieve hydraulic balance. As shown in Tab. 3, it can be seen that the unbalanced flow rate imbalance ratio and the loop flow imbalance rate of the different programs are relatively high, while the local unbalanced flow rate unbalance rate and the loop flow imbalance rate are relatively low. Therefore, in the ground source heat pump air conditioning system of the buried pipe, the outdoor buried pipe is more complicated, and the area is divided. The sections can achieve the purpose of reducing the flow imbalance rate by using the local same program.

Table 3 Comparison of traffic imbalance rates between different programs and local programs

Secondary section	The imbalance ratio of trunk flow (%)	The imbalance ratio of loop flow (%)
Different program	5.06	10.56

Local same program	0.41	0.82

The changes in the energy efficiency ratio of ground source side transportation under different combination schemes are analyzed. The heat rejection load is set to 230 kW, and the heat removal capacities of the six secondary sections (A, B, C, D, E, F) are set to 105 kW, 105 kW, 160 kW, 100 kW, 120 kW, and 160 kW respectively. The piles (A, B, D, E) and boreholes (C, F) are combined. The system resistance and transport efficiency ratio under various combinations are analyzed.

The energy efficiency of the ground source side transmission before and after the horizontal main pipe diameter adjustment is shown in Fig. 6. It can be seen that as the heat removal load increases, the energy efficiency ratio of the ground source side is gradually reduced, and the pipe diameter of the horizontal main pipe can be changed to a certain extent, thereby improving the energy efficiency ratio of the ground source side. The system resistance and transport energy efficiency ratio results of different combinations are shown in Fig. 7. It can be seen that the system resistance of the combination of C section or F section is relatively small, the optimal combination scheme is A, C, and the system resistance is 6.198 m. The transport energy efficiency ratio is 4.66.

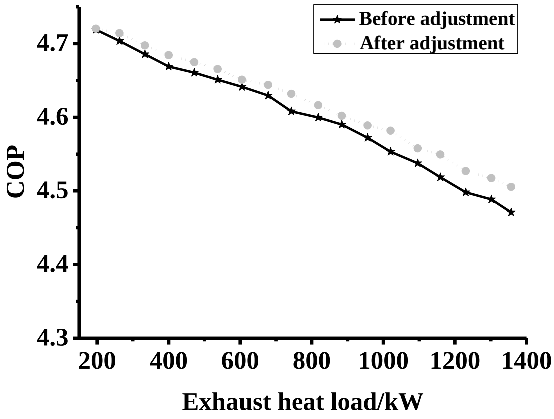

Figure 6 Energy efficiency ratio of source-side transportation before and after horizontal trunk pipe diameter adjustment

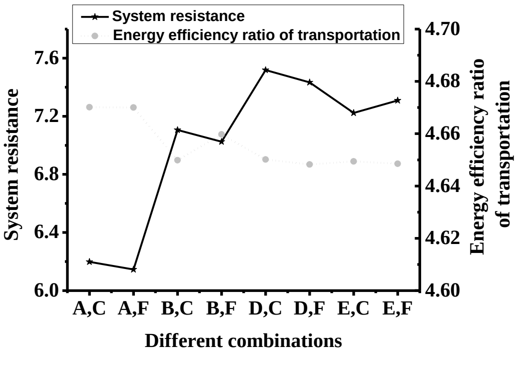

Figure 7 System resistance and transport energy efficiency ratio of different combinations

4. Conclusion

The hydraulic analysis is performed on single-mouth buried pipe wells, single buried pipe loops, and buried pipes in each section, which is then optimized. Given the same flow and tube type, a larger pipe diameter indicates smaller water head loss. Compared with the parallel 5-well loop and the parallel 10-well loop, the hydraulic loss of the series 2-well loop is the highest. When the sub-catch is connected to 5 loops, as the number of series wells increases, the tube length gets longer, the flow rate allocated by the loop gets less, and the load increases. Besides, the energy efficiency ratio of the ground source side decreases as the heat rejection load increases. Therefore, by adjusting the pipe diameter, the pipe type, and the depth of the well, the hydraulic loss can be reduced. The energy-saving effect of the loop in the parallel mode is better. Given the limited number of the managed wells, the parallel circuit can be adjusted to the same program. The connection allows the collector to distribute the flow evenly. The energy efficiency ratio of the ground source can be improved by changing the diameter of the horizontal trunk pipe. It is hoped that the hydraulic optimization design of the ground source heat pump air conditioning system can provide a theoretical basis for the application and promotion of the ground source heat pumps. Due to the subjective and objective limitations, deficiencies can be found in the research process. For example, in the hydraulic analysis, several optimization methods have been obtained, but the best method has not been explored. Therefore, in the process of future research, the optimal solution will be explored further to make the obtained results more valuable.

5. Acknowledgement

Science and technology project of State Grid Corporation of China(B3440818K005).

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