A PILOT PROJECT OF THE CLOSED-LOOP GROUND SOURCE HEAT PUMP SYSTEM IN CHINA

M. Z. Yu, Lecturer, GSHP Research Center, Shandong Institute of Architecture and Engineering, 47 Heping Road, Jinan, P. R. China, 250014
N. R. Diao, Doctoral Candidate, Department of Engineering Mechanics, Tsinghua University, Beijing, 100084, P. R. China
D. C. Su, Senior Engineer, GSHP Research Center, Shandong Institute of Architecture and Engineering, 47 Heping Road, Jinan, P. R. China, 250014
Y. J. Ge, General Manager, Yantai Ebara Air Conditioning Equipment Co. Ltd., 720 Yongda Road, Yantai, China, 265500
P. C. Wang, Senior Engineer, Yantai Ebara Air Conditioning Equipment Co. Ltd., 720 Yongda Road, Yantai, China, 265500
Z. H. Fang, Professor, GSHP Research Center, Shandong Institute of Architecture and Engineering, 47 Heping Road, Jinan, P. R. China, 250014

Abstract: A recently completed pilot project in Jinan, China, is summarized using a ground coupled heat pump (GCHP) system for heating and air-conditioning a lecture hall and offices. In this paper the heat transfer models are discussed for the vertical ground heat exchanger, and a model of the line source with finite length is presented, which predicts the ground heat exchanger performance more adequately for longer durations. The design procedure is recommended for the vertical ground heat exchangers. An apparatus is devised for in-situ measurement of the ground thermal properties. The advantages and problems of applying GCHP in China are also explored based on the experience of this project.

1. INTRODUCTION

With China's growing economy and social development over the past several decades it has become a common practice now to heat and air-condition its commercial and institutional buildings as well as its residential ones. At the same time, awareness of the need to conserve energy and protect the environment has increased significantly. This concern over environmental protection has led to the banning of small and medium sized coal-burning boilers in most Chinese cities. Thus, heat pumps have become a favorable choice for heating. Another incentive for the application of heat pumps in heating, ventilating and air-conditioning (HVAC) is that electric power supply in most areas of China has turned from shortage to abundance. Consequently, ground-source heat pump (GSHP) systems for HVAC have been the source of more interest. Their higher energy efficiency is favored in comparison with conventional systems. Open-loop systems with ground water pumped from a well as heat source/sink have been frequently used in China in recent years, but increasingly restrictive environmental regulations governing use of ground water and along with its limited availability have led to a shift of interest towards the use of closed-loop ground-coupled systems. Ground-coupled heat pumps (GCHPs) are an attractive alternative for groundwater heat pumps (GWHPs), and have attracted increasing attention. This technology satisfies requirements for both heating and cooling of buildings with the same units. Efficiency of GCHP systems is inherently higher than that of air source heat pumps because the ground temperature is higher than the average air temperature in winter, when heating is required, and lower in summer, when cooling is required. The environment-friendly technology eliminates the need for small coal-burning boilers, which allows for improved air quality besides being able to conserve the precious groundwater resources. The GCHP collector loop can be installed horizontally or vertically although vertical borehole systems are preferred over horizontal trench systems in most cases. The advantages of vertical GCHPs are that they require a smaller plot of ground, are in contact with soil that varies little in temperature, and, then, require the smallest amount of pipe and pumping energy, and can yield the most efficient GCHP system performance.

On the basis of learning from successful applications of GCHPs in North America and Europe, a pilot GCHP project for HVAC system was put into operation on campus of Shandong Institute of Architecture and Engineering in Jinan in May 2001. This project is intended to be used in research and teaching and the gathering of valuable experience and data which will assist in development of even more efficient systems.

2. PROJECT SUMMARY

The pilot GCHP project locates in Jinan, the capital city of East China's Shandong Province, at about 37 degrees of north latitude. It was originally planned for the lecture hall and later expanded to cover a reading room and some library offices. A 480-seat lecture hall occupies the upper floor of a two-story building that is attached to the main library building. The air-conditioning system was initially designed for the lecture hall. In consideration of infrequent occupancy of the lecture hall the HVAC system was extended to serve the first floor reading room and some offices within the library, and has enabled the system to be used to its full capacity. The scene of the library and lecture hall complex is shown in Figure 1. The floor spaces and heating/cooling loads of the zones served by the system are listed in Table 1.

Table 1 The HVAC zones and their loads

	Lecture Hall	Reading Room	Offices
Building Space, m^2	500	500	1800
Cooling Load, kW	110	80	120
Heating Load, kW	80	50	Separate system

The project features a much larger cooling load in summer than its heating load in winter as shown in Table 1. In view of the considerable cost of the ground loop heat exchanger a hybrid system has been employed. This means that the ground heat exchanger undertakes the heating load in winter as well as a part of the cooling load in summer while the remaining cooling load is shouldered by a cooling tower. Occupying a plot of about 240 square meters, the ground heat exchanger is buried beneath the lawn in front of the library. The ground heat exchanger system consists of 25 vertical U-tubes 60 meters deep for a total of 1500 meters of vertical boreholes. The U-tubes are constructed of nominal 1-inch (SDR 11) high-density polyethylene pipe connected to headers up to 4 inches. Two water-to-water heat pumps have been used with cooling capacities of 130 and 200 kW respectively. In winter the two heat pumps can operate singly in connection with the ground heat exchanger; in summer the heat pumps work with the ground loop and the cooling tower separately.

Fig. 1 The project exterior

The interior HVAC system is composed of different layouts. A central air-handling unit is used for the lecture hall; fan-coils for the offices; and a radiant floor heating/cooling system has been constructed for the reading room. The hot water of around 45℃ from the heat pumps suits the radiant floor heating well and is directly introduced into the coils under the floor. This is one of the advantages of applying heat pumps in the floor heating systems. The design of such a multi-component and multi-function system is not only economical, but also provides for further research opportunities.

Monitoring and measuring devices have also been installed for the project. The temperature, flow rates, heating/cooling rates and power consumptions are recorded automatically so that the performances of the heat pumps and the ground heat exchanger can be assessed over a long period of time, and valuable data will be accumulated for further studies.

3. GROUND HEAT EXCHANGER DESIGN

Proper design and installation of the ground heat exchanger is the key for success of GCHP application in HVAC systems. The system design took the following steps:

1) Calculation of the required heating and cooling loads of the building, and selecting the type and capacities of the heat pumps according to characteristics of the HVAC system to be employed.
2) Design and selection of the ground heat exchanger. The vertical U-tube configuration of the ground heat exchanger is, in most cases, the only choice in China due to its limited land and large population, and so was for this project. A computer program GEOSTAR was employed,

which was developed by the Institute's GSHP Research Center to size and simulate the ground heat exchangers. The ground property was measured in the field. It resulted in a total heat exchanger length of 3000 meters. In each 62-meter deep borehole settled a single U-tube, and 25 boreholes in two rows formed a borehole matrix. The U-tubes were connected in parallel through a reverse return. The space between the rows is 5 meters with 4-meter spans between the boreholes. This was a compromise between the plot area available at the site and the long-term performance of the heat exchanger. The site plan is shown in Figure 2. The horizontal supply and return headers were buried in the center of the borehole rows and 2 meters beneath the surface.

3) Selecting of the pipe. High-density polyethylene (PE 3408 in US category) pipes were used for the ground loops. The pipe diameter was determined by the flow rate requirement of the heat pumps and the pipe connection type. The water/antifreeze solution velocity in the pipes should be high enough to maintain a turbulent flow and low enough to keep the flow resistance and, then, the pump power as low as possible. In this project PE pipe of outer and inner diameters 32/26 mm was adopted, which resulted in a flow velocity of 0.6 m/s in the U-tubes. The pipes and fittings were joined by heat fusion.
4) Selecting of the circulating fluid. The designed inlet/outlet fluid temperatures of the heat pump evaporator are 5/0 ℃ in heating mode, although lower temperature may also be allowed. So, an aqueous ethylene glycol solution was chosen as the ground loop circulating fluid in consideration of its minor toxicity, flammability and corrosiveness.

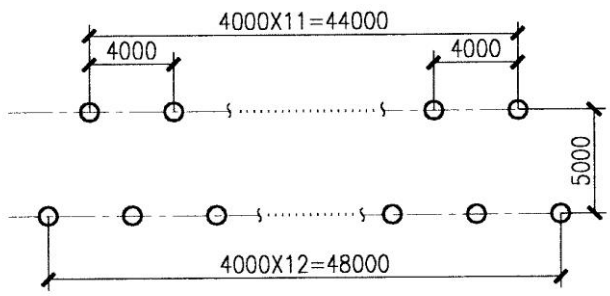

Fig. 2 The site plan of boreholes

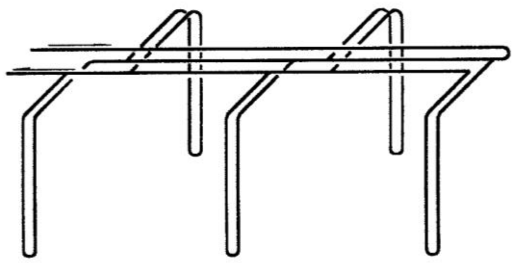

Fig. 3 Parallel connection of U-tubes

4. HEAT TRANSFER MODELS FOR THE GROUND HEAT EXCHANGER

Due to their varied locations the vertical U-tube heat exchangers encounter diversified geological structures, including the compositions, moisture content and groundwater movement. All these factors affect the performance of the ground heat exchangers. It is desirable to obtain a detailed insight into the ground conditions before commencement of design. For engineering practices, however, it is almost impossible to obtain all the information needed for detailed simulation and analysis. All the design algorithms available at present are based on simplified models, which assume a homogeneous ground medium. Therefore, the best way to estimate the ground physical properties is in-situ measurement with some special device.

Sizing the ground loop is based on the heat transfer analysis of a single borehole. The heat transfer of a borehole group can be determined by superposition of the temperature excesses from individual borehole inputs. Discontinuous and variable operation of the GCHP system can also be discussed by superposition of a series of step heating (Fang et al. 2002). Dissipating from the fluid in the pipe to far-off ground at constant temperature, the heat flux overcomes four thermal resistances, i.e. the convective resistance inside the pipe, the conductive resistance of the pipe wall and borehole backfilling, and the ground resistance outside the borehole. The former three resistances may usually be treated as steady-state ones in consideration of the negligible heat capacities compared with the long duration and minor temperature changes involved. The last one, i.e. the resistance from the borehole wall to far-off ground, has to be analyzed with transient models. For a ground collector to remain adequate it is important to consider the long-term energy balance in the ground. The energy balance can be maintained if the ground collector is used in a balanced heating and cooling condition with the ground acting as inter-seasonal storage. The most common model for the last term of the thermal resistance is based on a line source in an infinite medium (Bose et al. 1985), which features a simple function to present the temperature changes in days and months. But this model fails to predict adequately borehole performance in years. Two-dimensional cylindrical models (ASHRAE 1995) may result in more reasonable estimates for long duration operations while requiring time-consuming numerical computation.

A two-dimensional model of the line source with finite length presented by the authors (Zeng et al. 2002) is more appropriate for longer times and also in the form of an explicit function. A diagram of the finite line source geometry is shown in Figure 4. Assumptions are taken in this model as follows.

1) The ground is regarded as a homogeneous semi-infinite medium, and its thermal properties do not change with temperature;
2) The medium has a uniform initial temperature, t_0;
3) The boundary of the medium, i.e. the ground surface, keeps a constant temperature same as its initial one throughout the period concerned;
4) The radial dimension of the borehole is neglected so that it may be approximated as a line-source stretching from the boundary to a certain depth, H;
5) As a basic case of study, the heating rate per length of the source, q_l, is constant since a starting instant, $\tau = 0$.

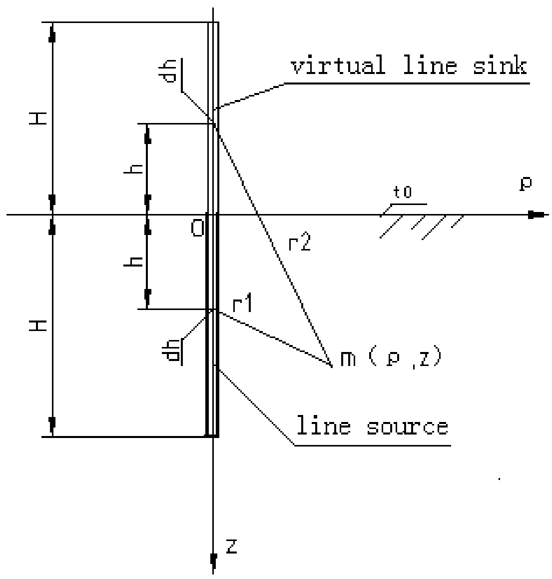

Fig. 3 The geometry of a finite line source system

The temperature excess in the medium at any time τ, $\theta = t - t_0$, is derived as

$$\theta = \frac{q_l}{4k\pi}\int_0^H \left\{ \frac{erfc\left(\frac{\sqrt{\rho^2+(z-h)^2}}{2\sqrt{a\tau}}\right)}{\sqrt{\rho^2+(z-h)^2}} - \frac{erfc\left(\frac{\sqrt{\rho^2+(z+h)^2}}{2\sqrt{a\tau}}\right)}{\sqrt{\rho^2+(z+h)^2}} \right\} dh$$

where *a* and *k* are thermal diffusivity and conductivity of the medium, respectively.

This model has been adopted in the software GEOSTAR developed by the GSHP Research Center for simulating and sizing the vertical ground loop. Then, the ground heat exchanger performance in its lifetime can be studied on the design stage. This feature is especially significant for those cases with imbalanced heating and cooling loads. More of our study on the heat transfer modeling can be found elsewhere (Liu et al. 2001).

5. THERMAL PROPERTY MEASUREMENT

Thermal properties of the deep ground are important data for design of ground heat exchangers in GCHP systems. To determine the thermal properties of deep ground soil/rock, an in-situ apparatus has been devised for the project as well as for future researches. The schematic diagram of the device is shown in Figure 5. The apparatus comprises an electrical heater, a circulating pump, a flow meter, two thermometers, an A/D transformer and a data logger. The test was carried out with the U-tubes installed at the site. The inlet and the outlet of the water loop in the apparatus were connected to one of the U-tubes in the ground heat exchanger after the U-tube had been installed and the borehole backfilled. A heat input from a resistance heater was imposed on the U-tube, and the temperature increase with time was recorded of the circulating water in the loop. The heating power of 46 W/m was used in the test. One of the monitored temperature variations in the circulating water is presented in Figure 6. A parameter estimation algorithm was used to determine the mean thermal properties of the ground (Yu and Fang 2002). As can be seen in Figure 7, in which the estimated mean thermal conductivity of the ground is plotted against test durations, the measured results change little within the range of 1.530 ~ 1.538 W/m℃, provided the test duration is longer than 50 hours. The irregularity in the results obtained from shorter test durations may be accounted for by the inaccurate model used for parameter estimation, in which heat capacity of the backfilling, pipes and circulating water was neglected. We recommend, therefore, that the test duration be 60 hours or longer for similar situations so as to ensure reliable estimations. A more accurate transient model is also being considered making allowance for contributions of these

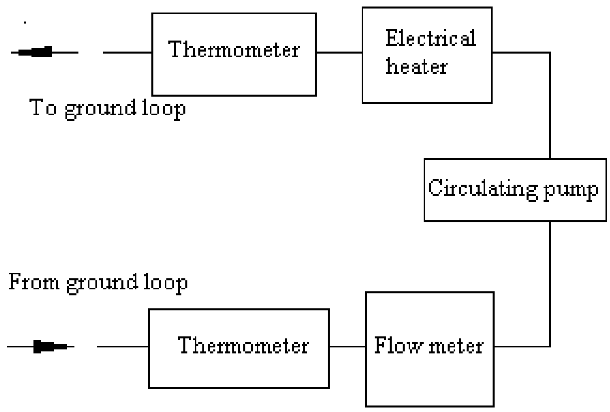

Fig. 5 Diagram of the in-situ measurement apparatus

heat capacities inside the borehole.

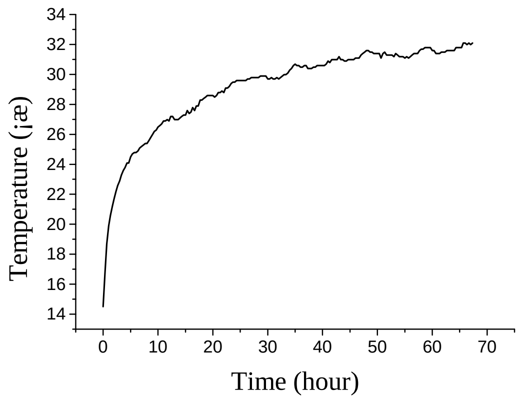

Fig. 6 Temperature response of the circulating water

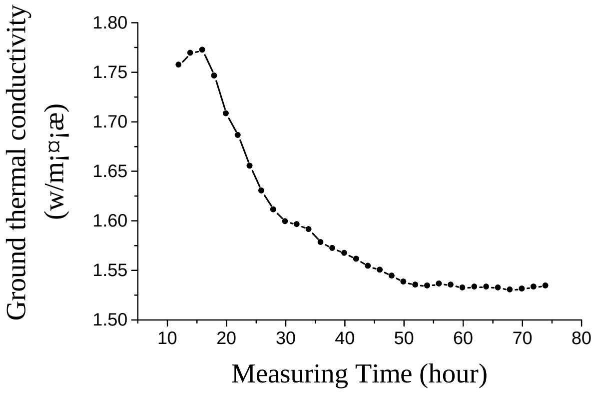

Fig. 7 Estimated conductivity vs. the test duration

6. HEAT PUMP

The project has been completed with the support and patronage from Yantai Ebara Air Conditioning Equipment Co., Ltd. A packaged water-to-water chiller (Model RHSCR060M) manufactured by this joint venture enterprise in China is used as the main heat pump. The unit comprises a semi-hermetic screw compressor and stainless steel plate heat exchangers. Its nominal refrigerating capacity is 200 kilowatts under condition of cooling water temperatures 30/35 ℃, and nominal heating capacity is 220 kilowatts when using circulating water of 15.5/7 ℃ for the evaporator. The machine features high-efficiency, compactness and computerized control. The control includes convenient automatic operation and management, PID regulation of water temperature and intellective malfunction prevention. The screw compressor can provide continuous capacity modulation, from 100% capacity down to 30% or less. This feature is especially desirable for HVAC applications where loads vary dramatically from time to time and part-load operation is a more common situation. So, the screw compressor provides stable operation

Fig. 7 Ebara screw heat pump on the site

over the whole working range, and reduces power consumption to the largest extent at the same time. The energy efficiency ratio (EER) of 4.5 for cooling and coefficients of performance (COP) of 3.3 for heating have been achieved in the past operation of this application.

7. SYSTEM PERFORMANCE

The GCHP system has been in operation since May 2001, and worked in both cooling and heating modes. The system is currently operating within its expectations. The lecture hall temperature can be maintained below 25℃ at its full occupancy in July as required. The normal entering/leaving fluid temperature of the heat pump condenser was 28/33℃ in summer, which agrees with the design and is better than cooling tower performance. The normal entering/leaving fluid temperature of the heat pump evaporator in winter is 6.5/2℃ after a 30-day operation. The radiant floor heating of the reading room, in particular, provides a comfortable indoor environment with an appropriate temperature profile and little air movement. The measured heat pump COP for heating and EER for cooling are 3.3 and 4.5, respectively, excluding the power used by the circulating pumps. Because of the limited running hours so far and the intermittent building occupancy sufficient data have not been recorded yet for long-term economic analysis of the system.

8. PROBLEMS AND PROSPECTS

The project is an attempt to introduce the GCHP technology into China. The system has been proven a success, and has received quite a lot of visitors since its completion. We realize, however, that there is still much to do in order to make GCHP application popular in China. There are a couple of Chinese institutions, mainly universities, are doing research on theoretical aspects of GCHPs, but few real projects have been reported yet. It may be accounted for by the fact that GCHP systems are typically higher in capital cost in comparison with conventional and groundwater heat pump systems due to construction cost of the ground loops. Besides, the engineering aspects, including equipment and materials availability as well as the processes of drilling and installing ground loops, seem also to pose significant challenges at present. In the project we used drilling rigs usually for geological surveys to install the ground loop. The completion of a single borehole took approximately three days. Such a long process would be unacceptable for most potential applications. Suitable water source heat pumps have not been developed in China, which are designed specifically for the lower entering liquid temperature encountered in closed ground loop applications. Limited availability of appropriate equipment and qualified installation personnel has greatly hindered acceptance of the new technology. Besides, further studies on economics of using the GCHP system through both analyses and demonstrations, especially under the conditions in China, are also vital to promote this new HVAC approach.

Among the different ground source heat pump configurations the GCHP is the latest development. It has grown into a mature and successful industry owing to its energy-efficient and environment-friendly features. Chinese HVAC researchers and engineers have put considerable efforts into this technology and learned a lot from the application experience of developed countries. With China’s integration into the world economy and people’s increasing awareness of environment protection more GCHP projects will undoubtedly appear in China for both residential and commercial applications.

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