The Ground-Coupled Heat Pump Technology in China

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Abstract. The ground-coupled heat pump (GCHP) system utilizes the ground as a heat source/sink of the heat pump, and has been identified as one of the best sustainable energy technologies for space heating and cooling in residential and commercial buildings. Applications of this relatively-new technology in China have grown dramatically in the past decades owing to the urgent demands of energy conservation and environment protection for sustainable development. Government decrees and incentives on the GCHP technology in China are presented in this paper. Research and development on the GCHP technology in China are summarized, including those in the heat transfer modelling of borehole heat exchangers as well as technical developments of energy piles, deep borehole heat exchangers and hybrid GCHP systems.

1. Introduction

China has experienced a rapid urbanization progress for last decades. As a result, the building industry has boomed dramatically. The building boom has created a great demand for heating and air-conditioning. Energy consumption for building operation accounts for 22% of the total energy consumption in China, in which 60% are consumed for heating, air-conditioning and domestic hot water supply in buildings.

Utilizing the ground as a heat source/sink, ground-coupled heat pump (GCHP) systems have been gaining increasing popularity for space conditioning in buildings. The efficiency of GCHP systems is inherently higher than that of air-source heat pumps because the ground maintains a relatively stable temperature throughout the year. Ground-source heat pump (GSHP) systems for HVAC have aroused...
special interests in China also because of the growing concern about the severe air pollution from coal-fired boilers. Coal-fired boilers for heating are prohibited gradually, and heat pumps provide an obvious alternative. The higher energy efficiency of the GSHP systems is also favored in comparison with conventional air-source heat pump systems. Open-loop systems with ground water pumped from wells as heat source/sink were used frequently in northern China in the past decade, but increasingly restrictive environmental regulations covering the use of groundwater and its limited availability have led to interest being focused on closed-loop ground-coupled systems.

A major distinction of the Chinese GCHP applications is the fact that most GCHP projects in China are much larger than those in Europe and North America, with a single project often serving building floor spaces of over 10000 or even 100000 m², which brings in some unique challenges. Another feature of GCHP development in China is that its applications are benefited from the low labor cost. The average installation cost of GCHP projects is 300-400 RMB ($50-65) per m² of floor space for residential and office buildings, much lower than that in North America and Europe.

While experiences from developed countries have been learned for reference in process of developing the GCHP technologies and applications, Chinese researchers and engineers have also made their own contributions to this technology according to specific conditions in China. This paper reviews the preferential policies and regulations of the Chinese government in regard of the application of the GCHP and other renewable energy technologies, and presents the research and development on the GCHP technology in China, mainly achieved by our research group.

2. Government policy and incentives

Great attention has been paid to energy conservation and Green House Gases (GHG) emission reduction in China in recent years. Quite a lot of laws and government decrees have been enacted on this regard. The most important ones include:

- The Renewable Energy Law of the People’s Republic of China, 2005
- The Energy Conservation Law of the People’s Republic of China, 2007
- Mid-and-long-term Development Plan on Renewable Energy, 2007
- Energy Conservation Regulations of Civil Buildings, 2008
- The Action Plan for China’s Energy Strategy (2014-2020), 2014
- The Thirteenth Five-Year Plan for Development and Utilization of Geothermal Energy, 2017

The first national standard on the GSHP technology was promulgated in 2005, and it was revised in 2009. All these laws and decrees have emphasized the importance of energy conservation and GHG emission reduction for global sustainable development, and advocated applications in China of the GSHP technologies as well as other renewable energy sources. As an incentive policy the central government funded 291 GSHP projects, 21 pilot municipalities, and 52 pilot counties of GSHP applications during the 2006-2010 period. Government ministries and local authorities have also joined the efforts in promoting energy conservation technologies in buildings, and issued local regulations to encourage GSHP applications.

Owing to the advocacy and incentives of the government, and also as a result of R&D progress in this area, GCHP applications have grown rapidly in China both for residential and commercial buildings. According to national statistics, up to the end of 2016 over 22000 GSHP projects were completed with a building floor space of more than 487 million m² in China. Nowadays China ranked
the top in the capacity of GSHP installations as well as the utilization volume of the shallow geothermal energy in the world.

3. Heat Transfer Modeling of Borehole Heat Exchangers

Despite all the advantages of the GCHP system, commercial growth of the GCHP technology has been hindered by higher capital cost of the system, of which a significant portion is attributed to the Ground Heat Exchanger (GHE). Heat transfer between a GHE and its surrounding soil/rock is difficult to model for the purpose of sizing the exchanger or simulation of the system. Thus, it is crucial to work out appropriate and validated tools, by which the thermal behaviour of GCHP systems can be assessed and then, optimised in technical and economical aspects.

Our study on the GHE modeling follows the theoretical platform presented by Eskilson [1] and Spitler [2]. The concept of thermal resistances and the principle of superimposition have been used in this approach for GHE analysis. Better understanding of thermal resistances of the single-borehole GHE is crucial, and their analytical solutions are especially preferred to facilitate the simulation and design. A few analytical solutions of the GHE heat transfer have been worked out in our past studies.

3.1 Heat Transfer inside Boreholes

A few models of varying complexity have been established to describe the heat transfer inside the GHE boreholes. Models for practical engineering designs are often oversimplified in dealing with the complicated geometry inside the boreholes. One-dimensional models have been recommended for engineering design, conceiving the U-tube pipes as a single “equivalent” pipe.

Taking the fluid axial convective heat transfer and thermal “short-circuiting” among U-tube legs into account, a quasi-3-D model for boreholes in GHEs has been established, and analytical solutions of the fluid temperature profiles along the borehole depth have been obtained on both single and double U-tube configurations in the borehole [3]. The effective borehole thermal resistance can be determined according to the temperature difference at the inlet and outlet of the tube. A recent study has also been published on the resistance of coaxial tube boreholes [4].

3.2 Heat Conduction outside Boreholes

There have been some classical models for GHE thermal analysis based on analytical one-dimensional (1-D) solutions. A most-widely-used 1-D model for this purpose is Kelven’s line source model. In this model the borehole is replaced by a line heat source with its radial dimension neglected, so that a simple analytical solution may be obtained of the temperature response in the surrounding medium. Another best known 1-D model, referred as the cylindrical heat source model, was also suggested as an alternative approach to sizing ground heat exchangers. Even though the radial dimension of the borehole is taken into consideration in this model, the heat capacity of the cylinder (all the materials inside the borehole in this case) is ignored, so the geometrical domain of the model can be regarded as an infinite medium with a cylindrical cavity in it. Significant simplifications are made in both the classical models, which result in substantial deviations of the temperature response from the actual situation especially in the initial period of the heating pulse. Therefore, neither of these two models is suitable for short time-step analysis in the case of borehole GHEs. Modified from the classical models and referred to as the “solid” cylindrical source model, a new concept is proposed, partly in view of its application in the pile GHE [5]. In this model it is supposed that the cylindrical source is no longer a
cavity, but filled with the medium identical to that out of the cylinder. So the whole infinite domain is composed of a homogeneous medium. A heat source shaped in an infinite cylindrical surface of a radius $r_0$ is supposed to be buried in the medium. The heating rate per length of the cylindrical source, $q_l$, is constant since a starting instant, $\tau = 0$. The analytical solution of the 1-D transient temperature response is derived as

$$\theta(r, \tau) = -\frac{q_l}{4\pi^2k} \int_0^\pi E_1\left(\frac{r^2}{4a^2} - \frac{r_0^2}{4a^2} \cos\varphi\right) d\varphi' \tag{1}$$

Calculations indicate that there is significant difference among these three models especially at the initial stage of the response. The new model presents a more appropriate result than the classical models do to describe the heat conduction in both the borehole and pile GHEs owing to its more realistic assumption.

For heat conduction outside boreholes both the classical 1-D models of the Kelvin’s line source theory and the cylindrical source model neglect the axial heat flow; therefore they are inadequate for the long-term analysis of GCHP systems. Considering the influences of the finite length of the borehole and the ground surface as a boundary, an analytical solution to the finite line source has been developed [6] and used in GHE design software. Furthermore, the 3-D conduction around an inclined finite line source has also been studied by the Green’s function method, and an analytical solution derived [7].

3.3 Groundwater Infiltration

Groundwater filtration may exert significant impact on performance of GHEs. All of the GHE design tools available at present, however, are based simply on principles of heat conduction, and do not consider the implications of groundwater flow in carrying away heat. Diao et al. [8] have solved the combined heat transfer of conduction and advection in the vertical GHEs by an analytical approach, and an explicit expression of the temperature response has been derived describing correlation among various factors which impact on this process. It takes the following expression.

$$\theta(x, y, \tau) = \frac{q_l}{4\pi k} \exp\left(\frac{Ux}{2a}\right) \int_0^\infty \exp\left[-\frac{1}{\eta} - \frac{U^2r^2}{16a^2} \right] d\eta \tag{2}$$

The obtained temperature response to a single line-source heating with water advection considered can be used to compute the response of a GHE with multiple boreholes by superimposition of all temperature rises caused by individual boreholes. Figure 1 demonstrates such isotherms of an 18-borehole GHE with groundwater advection in a direction oblique to the borehole matrix. The methodology has also been used to analyze the temperature responses of a buried coil with the groundwater filtration taken into account [9]. It has been shown that simulations with such analytical solutions take much less computing time and assure more reliable precision than numerical solutions do.
3.4 GHE Design and Simulation Software

A software package in Chinese interface named GeoStar has been developed and spread for the design and simulation of the GHEs by our research group [10] on basis of the theoretical studies of GHE modelling. This software package is able to size GHEs to meet the user-specified minimum and maximum entering fluid temperatures to a heat pump for a given set of design conditions, such as building load, ground thermal properties, borehole configuration, and heat pump operating characteristics. In addition, the modelling procedure uses spatial superposition for multiple boreholes and sequential temporal superposition to determine the arbitrary heating or cooling loads of the systems. The software is suitable for simulation of the performance and energy consumption of given GCHP systems as well.

4. Technical Development of GCHP Systems

4.1. Pile GHE

Foundation piles of buildings are used as part of the ground heat exchangers in recent years in order to reduce the cost of borehole field and to save the land it requires. The schematic diagrams of a pile GHE with spiral coil are illustrated in Figure 2.
Piles are much thicker in diameter but shorter in depth than the boreholes. Few analytical models on the pile GHE have been seen in literature, and models for the boreholes are often used for reference to give a rule-of-thumb estimation in pile GHE applications. Modified from the classical models, a new model, referred to as the “solid” cylindrical source model, is proposed, which takes the pile GHE characteristics into proper consideration. Man et al. [5] derived the analytical solution of the new model by means of regarding the cylindrical heat source as a collection of numerous line sources. Improved models have been also presented in considering the spiral pipe in the energy pile as a number of rings or a helical line source, analytical solutions have been obtained with groundwater filtration taking into account [9].

4.2. Deep Borehole Heat Exchangers

The concept of Deep Borehole Heat Exchanger (DBHE) has aroused growing interests from both academic and engineering arenas in China recently. The DBHEs are usually drilled down to depths of 1000-2000m at present. Rather than the single or double U-tube configurations commonly used in shallow GCHPs, coaxial tubes are used for DBHEs on construction considerations. The DBHEs may go down much deeper below the ground surface; and temperature at the borehole bottom may reach 50-80°C. Therefore, they constitute a desirable alternative to the traditional shallow BHEs in GCHP systems with advantages of much less land demand and higher efficiency of the heat pumps. The DBHE may also be employed for the purpose of seasonal heat storage owing to its favorable features of flexibility, higher temperature available and enormous storage capacity in limited land plots. A borehole with a coaxial tube is schematically shown in Figure 3.

![Figure 3](image-url) A diagram of a deep borehole with coaxial tubes

The processes of shallow and deep BHEs have a few fundamental distinctions. A uniform initial temperature in the ground is usually assumed in heat transfer models for the shallow boreholes in view of the limited depth of shallow BHEs and limited temperature difference in the longitudinal direction. It is unreasonable, however, to ignore the geothermal gradient in DBHEs, which constitutes a key factor of their performance. Numerical simulation seems more appropriate means for thermal analysis of DBHE where the geothermal gradient in subsurface may be considered adequately. Based on the FDM, a numerical scheme developed specifically for coaxial DBHEs is proven to be computationally-efficient, and may provide a useful tool for DBHE design and optimization [11]. Results of the simulation have shown that the configurations of the circulation directions make difference in the
DBHE performance in view of the influence of geothermal gradient. Nominal DBHE capacities are evaluated according to their key parameters such as borehole depth, subsurface conductivity and geothermal heat flux. Obtained by this software, a simulation result of responses of a DBHE in 10 years is plotted in Figure 4. A pilot DBHE project is being constructed with technical assistance of this study. Real operation data will be collected to further verify the models.

4.3. Hybrid GCHP systems

Because the GCHP system uses the ground soil/rock as the heat source and sink of the heat pump, adequate attention should be paid to long-term impact of the annual imbalance in heating and cooling loads of the system on the subsurface environment. When the GCHP systems are used in the cooling-dominated buildings in warm climates, more heat will be rejected to the ground than that extracted from the ground on an annual basis. The heat build-up within the ground will make the ground temperature rise, which can consequently deteriorate the system performance over time. Similarly, when the GCHP systems are applied to heating-dominated buildings in cold climate, cold build-up would occur.

The hybrid GCHP system can be employed to make the annual heat injection and extraction in the GHE more balanced. Cooling towers are usually employed as the heat rejecter in cooling-dominated applications of the hybrid GCHP [12]. GCHP systems with hot water supply are also designed and studied as an effective hybrid system to reduce the heat injected into the ground [13]. As for the heating-dominated applications of the GCHP systems in cold climate, hybrid systems with solar thermal collectors are also studied, incorporating the concept of seasonal thermal energy storage, and some pilot projects of such hybrid Solar-GCHP system have been constructed in China.

5. Concluding Remarks

The ground source heat pump industry has grown dramatically in China for last decades following its rapid economic development as a whole. The advocacy and preferential policies of the Chinese government have promoted the GSHP applications greatly. Chinese scholars and engineers have worked hard to adapt this sustainable technology to local geological, meteorological and social situations in China. It is crucial to develop computationally effective methods for sizing and
simulating the GHEs especially for their large scale applications. Various kinds of hybrid ground source heat pump systems are of great significance to construct effective and economical GCHP applications in view of the vast territory and diversiform climate in China. Innovations on the GCHP systems have been explored such as the energy piles and deep borehole heat exchangers. Besides, as drilling and installation of borehole heat exchangers constitute the greatest portion of the first cost of GCHP systems, better drilling and ground loop installation techniques will continue to be pursued in order to ensure quicker and less expensive construction of the GHEs. It is certain that the Chinese GCHP industry will keep its momentum of rapid growth; and the research and development on GCHP technology is expected to provide supports for the industry and contribute to the sustainable development in China.

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