Available online at www.sciencedirect.com

ScienceDirect

Applied Thermal Engineering 28 (2008) 2295–2304

APPLIED THERMAL ENGINEERING

www.elsevier.com/locate/apthermeng

Thermal performance and ground temperature of vertical pile-foundation heat exchangers: A case study

Jun Gao, Xu Zhang *, Jun Liu, Kui Shan Li, Jie Yang

Institute of HVAC&GAS Engineering, College of Mechanical Engineering, Tongji University, Shanghai 200092, China

Received 21 August 2007; accepted 9 January 2008
Available online 26 January 2008

Abstract

To assess the geothermal energy for a district heating and cooling system in Shanghai, China, a case study of ground heat exchangers for a ground-coupled heat pump (GCHP) system is presented in this study. Several types of vertical pile-foundation heat exchangers selected are intercompared to determine the most efficient one. Based on a series of performance tests, experimental data of single pile-foundation heat exchanger are presented. Heat transfer performance is also evaluated by numerical method, which couples heat convection and conduction through water in pipeline, concrete pile and soil. It is further used to investigate five-year changes in the ground temperatures. Numerical results under two imbalance ratios between cooling and heating load are analyzed to evaluate the potential of geothermal energy in the present application. The present study is aimed to provide guidelines for better design of large-scale GCHP in a district heating and cooling system in Shanghai.

Keywords: Geothermal energy; Ground-coupled heat pump; Ground temperature; Pile-foundation heat exchanger; Thermal imbalance ratio

1. Introduction

Low-cost energy resources are more and more popular for energy-efficiency buildings. Sustainable geothermal energy technologies for heating and air-conditioning in buildings have been very attractive since significant development of ground-source or ground-coupled heat pump (GSHP/GCHP) system was achieved in these years [1–6]. Bloomquist [2] indicated that the development of geothermal district heating has been one of the fastest growing segments of the geothermal space heating industry and now accounts for over 75% of all space heating provided from geothermal resources world wide. Ozgener et al. [6] presented some case studies to investigate the thermodynamic aspects in terms of energy and exergy and performance improvement opportunities of three geothermal district heating systems installed in Turkey. Their results are very beneficial to the development of GSHP/GCHP system for much improvement of the system design and project implementation can be achieved through the energetic and exergetic assessment. Recently, numerical methods in the GSHP/GCHP system, combined with the experiment in situ, have been widely applied and significantly developed [5,7–11]. Esen et al. [11] experimentally studied a GCHP system with horizontal ground heat exchangers installed in a test room and its performance coefficient COP_{sys} based on the measured data. Further, a numerical model for heat transfer in the ground was also developed to determine the temperature distribution in the vicinity of the pipe and good agreement with the experimental results were obtained. As for the experiments for ground heat exchangers, much research [12–15] was found to focus on the thermal response and performance test based on the constant heat rejection rate. This kind of test was aimed to obtain such thermal parameters as the conductivity of whole heat exchanger system including backfills, soil, and the heat exchangers in situ. Therefore, long time of experiment was necessary for the experiment system to achieve a steady-state heat transfer, i.e., the condition of constant

* Corresponding author. Tel.: +86 21 65984243; fax: +86 21 65983605.
E-mail address: zhangxu-hvac@mail.tongji.edu.cn (X. Zhang).

1359-4311/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.applthermaleng.2008.01.013

heat flux. In the cases when thermal performance of different types of ground heat exchangers are to be compared, Li et al. [9] suggested a test method with constant inlet temperature and varied heat flux using a large water tank of constant temperature. In such kind of experiment, test time was much reduced, but the thermal conductivity could not be correctly derived. Therefore, it is usually used to assess the thermal performance. As for the research method of ground temperatures, in the cases when long-period ground temperatures and the potential of geothermal energy in operation require to be investigated, numerical methods appear to be good alternatives to the experiments on the premise of being well verified and validated. Many recent studies have focused on the performance of different ground heat exchangers and the system. Recently, utilization of the pile foundations of buildings as ground heat exchangers have attracted much attention for it reduces the cost [16–19]. It is often regarded as an energy pile or heat exchanger pile system in the literature and several types can be found in practical applications. Large amount of research on the ground heat exchangers and the heat pump systems can be found. However, there are few practical examples concerning the evaluation of pile-foundation heat exchangers and the underground field performance, especially for the large-scale applications.

In this present work, a case study is presented to assess the geothermal energy for a district heating and cooling system in Shanghai, China. First, the experimental setup and numerical method are introduced three-dimensional numerical simulations, coupling heat convection and conduction through water in pipeline, concrete pile and soil, are performed to determine the most efficient type of pile-foundation heat exchangers. Experimental data are used to validate the numerical results. Second, numerical method is further applied to investigate five-year variations of the ground temperatures. The potential of geothermal energy and the operating performance of ground heat exchanger selected are analyzed using the modified energy output based on the practical ground temperatures in operation. Results of the present study are to be used by a practical application to a district heating and cooling system in Shanghai, China, based on which river water will be used as a supplementary source for an eventual GCHP system.

2. Selection on ground heat exchangers

2.1. Project introduction and pile-foundation heat exchangers

An energy resource scheme for the district heating and cooling system and a report of engineering geological survey for the GCHP system were completed in 2006, based on which a group of 5500 pile foundations in a land parcel of 100 m × 1000 m, cast-in situ and made from concrete, was used as energy piles. These energy piles will be operated in a GCHP system and are designed to take about 30% thermal load of the district heating and cooling system. The potential of geothermal energy are to be discussed and supplementary source is to be provided by river water, which has been adequately calculated and tested last year. According to the climate data of Shanghai, space cooling season is designed from May to September and space heating season from December to next February.

Depth of frozen earth in Shanghai is about 8 cm and soil temperature under 5 m depth stays almost constant. The pile-foundation heat exchangers, length 25 m, are then vertically laid at the depth of 5 m. Cast-in situ concrete bearing piles are used and heat exchange is performed by taking advantage of the inner portion of piles. Outer meter of the piles is 600 mm. The thermal medium is water, which flows in the high-density polyethylene (HDPE) pipes cased in the piles. Four types of underground heat exchangers investigated and their sizes are shown in Fig. 1. In consideration of cost reduction of in situ experiment and avoiding the large pressure loss and water flow rate, only the U and W types are applied. The water pipe arrangement is, however, limited by the structure design and construction work. It is necessary for the long pipeline to be firmly attached to the steel frame (see Fig. 2). Properties of concrete, HDPE and soil are listed in Table 1.

2.2. Experimental data

Performance experiment of four types of ground heat exchangers have been conducted in situ. The view of the pile-foundation heat exchangers and experimental system are shown in Figs. 2 and 3, respectively. Water was supplied into the PE pipes and its temperature was stabilized at about 35 °C by a water tank of constant temperature and two electric heaters (see Fig. 3). Real supply temperature and return temperature were measured by platinum resistance thermometers with A-class PT100 sensor, whose precision is 0.15 °C and the errors during experiment are less than 1.0%. Volumetric flow rate was measured by a turbine flowmeter LWGY-10, whose precision is 0.005 m^3/h and the errors during experiment are less than 0.5%. To observe the heat transfer performance of the four types of ground heat exchangers, dynamic measurements were carried out and results were obtained when all parameters came to be stable.

Table 2 provides the stable results of water temperature and the performance of the four ground heat exchangers investigated. Water supply temperature is approximately 35 °C and the flow rate is controlled at three levels: 0.342 m^3/h, and its double, tripe. Energy output from the ground heat exchanger is calculated by the flow rate and temperature difference, and the heat transfer coefficient is derived by the energy output and the average temperature difference between water and soil. Soil temperature under 5 m depth stays almost constant and it is 18.2 °C according to the measurements.

Experimental data provide the maximum value of energy output, and some percentages will be adopted as the design load. The results in Table 2 will be discussed in the latter numerical study. The most efficient type of