Energy 104 (2016) 229–236

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Performance of ground-source heat exchangers using short residential foundation piles

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A R T I C L E I N F O

Article history:
Received 16 July 2015
Received in revised form
26 February 2016
Accepted 29 March 2016

Keywords:
Ground heat
Heat exchanger
Thermal resistance
U-tube
Double-tube

A B S T R A C T

Experiments on the performance of ground-source heat exchangers using short residential foundation piles were performed in Saga, Japan. U-tube, double-tube, and multitube heat exchangers were installed in the ground to depths of 20 m. Water was used as the working fluid. Temperatures were measured on pipe walls, pile walls, and in the ground. From the measured data, thermal resistances of pipes, grout, and soil were calculated. We also investigated the effect of the ground surface temperature on heat transfer rate. Total thermal resistances of the double-tube, multitube, and U-tube exchangers were 0.231 (m K)/W, 0.295 (m K)/W, and 0.356 (m K)/W, respectively. Of these total resistances, soil, grout, and pipe thermal resistances accounted for 89%, 0%, and 11%, respectively, for the double-tube heat exchanger; 50%, 27%, and 23%, respectively, for the multitube heat exchanger; and 62%, 21%, and 17%, respectively, for the U-tube heat exchanger. Heat transfer rates of the tested heat exchangers could be predicted within 8.6% by using a measured value for the surface temperature coefficient. For atmospheric temperatures around 30 °C, the effect of the surface ground temperature on heat transfer rates was approximately 10%–15%.

1. Introduction

The annual consumption of geothermal energy, which is often used for air conditioning, agriculture, snow melting, etc., is 423,830 TJ [1]. Some of this geothermal energy is acquired from heat exchangers installed underground. Many ground heat exchangers are installed at depths of approximately 100 m or more; however, such installations involve high initial costs of construction, especially in Japan because of soft ground conditions. These initial costs could be reduced by using short residential foundation piles at depths of only about 20 m. However, the characteristics of a short residential foundation pile ground heat exchanger are poorly understood. Those characteristics depend on the total thermal resistance and ground temperature; below about 5 m, the ground forms an isothermal layer in which the temperature is almost constant throughout the year. However, near the surface, the ground temperature changes with the season of the year and the hour of the day. These changes affect the performance of ground heat exchangers, especially short heat exchangers. To clarify the characteristics of short ground heat exchangers that use residential foundation piles, studies are needed regarding thermal resistances and the effects of temperature changes near the ground surface.

Thermal resistances have been investigated by many researchers. The total thermal resistance of a ground heat exchanger comprises fluid convection, conduction through pipe walls, the conduction of the grout, and the conduction of the soil. Thermal response tests have been performed to determine the equivalent thermal conductivity of soil [2–9]. The thermal resistance of boreholes (grout and pipes) can be estimated by assuming values for the volumetric heat capacity of soils. Many researchers have studied fluid convective resistance and pipe conduction resistance by conventional heat exchanger research [10]. The conduction resistance of borehole grout for U-tube type ground heat exchangers has been investigated by analytical methods and numerical simulation [11–15]. The conduction resistance of soil has been estimated using the line-source theory and cylindrical-source theory [16–18]. Jun et al. calculated each thermal resistance and compared the calculated total resistance with that obtained from experimental results [14]. Han et al. evaluated the performance of a residential ground source heat pump system using thermal resistances analyzed by measured data [19]. Liu et al. evaluated the

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http://dx.doi.org/10.1016/j.energy.2016.03.133
0360-5442/

heat transfer enhancements of ground heat exchangers by thermal resistances calculated analytically [20]. Ruiz-Calvo et al. calculated a short-term temperature change using thermal resistances [21].

In this study, thermal resistances and the effects of the ground near the surface were investigated experimentally. By measuring temperatures of soil and pipe walls and measuring heat transfer rates, the thermal resistances of pipe, grout, and soil can be determined directly. Because of the difficulty in measuring wall and ground temperatures, there are few reports of thermal resistance data calculated from measured wall and soil temperatures. Thermal resistances were investigated after 23–24 h of heat exchanger operations. The heat transfer phenomenon on ground heat exchanger is not steady state. However temperature change after $(a\ t/r^2) > 5$ is sufficiently small [22]. In our case $(t\ a/r^2)$ is 6.91 for 23 h. Then heat transfer rates were sufficiently close to steady state. The experiments were performed in Saga, a warm southern region of Japan, from September 29, 2008, to February 22, 2012. The working conditions were assumed to be for cooling.

2. Experimental apparatus

As shown in Fig. 1, three types of ground heat exchangers were investigated: a single U-tube, double tube, and multitube [23]. All three heat exchangers were installed in piles that were 20 m deep with a 130 mm inner diameter and a 140 mm outer diameter. The depths of all heat exchangers were the same as the pile, 20 m. The U-tube was made of cross-linked polyethylene pipe with a 32 mm outer diameter and a 25 mm inner diameter; it was installed in a steel pile, as shown in Fig. 1(a). The distance between the two tubes was approximately 40 mm. The tubes were fixed at the bottom, and the space between the tubes and the steel pipe was filled with silica sand and water. Temperatures at pipe and pile walls were measured by thermocouples placed vertically every 2.5 m. Ground temperatures 1.5 m from the center of the heat exchanger were measured by thermocouples placed vertically every 2.5 m to a depth of 10 m deep, then every 5 m from 10 to 25 m.

The double-tube heat exchanger used a polyvinyl chloride pipe with a 48 mm outer diameter and a 40 mm inner diameter as the inner tube, as shown in Fig. 1(b). The outer tube was a stainless steel pile. Temperatures at pipe and pile walls were measured by thermocouples placed vertically every 2.0 m. Ground temperatures 1.5 m from the center of the heat exchanger were measured by thermocouples placed vertically every 2.0 m to a depth of 12 m, every 4.0 m from 12 to 20 m, and at 25 m.

As shown in Fig. 1(c), the multitube heat exchanger was composed of five tubes. One tube, with an inner diameter of 16 mm and an outer diameter of 20 mm, was installed in the center of a steel pile. The other four tubes were set around the center tube. The tubes were made of polyvinyl chloride and were 20 mm in inner diameter and 25 mm in outer diameter. The four outer tubes were used as inlets, and the central tube was used as the outlet. Distances between the center tube and the surrounding tubes were approximately 20 mm, and each of the five tubes was fixed at the bottom. Temperatures at pipe and pile walls were measured by thermocouples placed vertically every 2.0 m. A small steel pipe, with an inner diameter of 22 mm and an outer diameter of 27 mm, was welded outside the steel pipe to insert the thermocouples. Ground temperatures 1.0 m from the center of the heat exchanger were measured by thermocouples placed vertically every 2.0 m to a depth of 22 m. The ground surface temperature was measured only at the multitube exchanger. A ground surface thermocouple was set a few centimeters below the surface to avoid the effect of sunlight.

For all three heat exchangers, water was used as the working fluid. For each heat exchanger, temperature-controlled water was supplied from a thermostatic bath. Temperatures of the water were measured at the inlets and outlets of the heat exchangers after passing through the mixing chambers. Flow rates of the water were measured upstream of each heat exchanger inlet. All temperature measurements were recorded by a data logger at one-minute intervals. The inlet water temperature was kept constant in the thermal bath. The constant-temperature water flowed through the boreholes for 24 h. Data from the last hour of flow, i.e., 23 to 24, were used to determine thermal resistances. After each 24-h run, an interval of at least one week was imposed to allow the ground to recover its thermal condition.

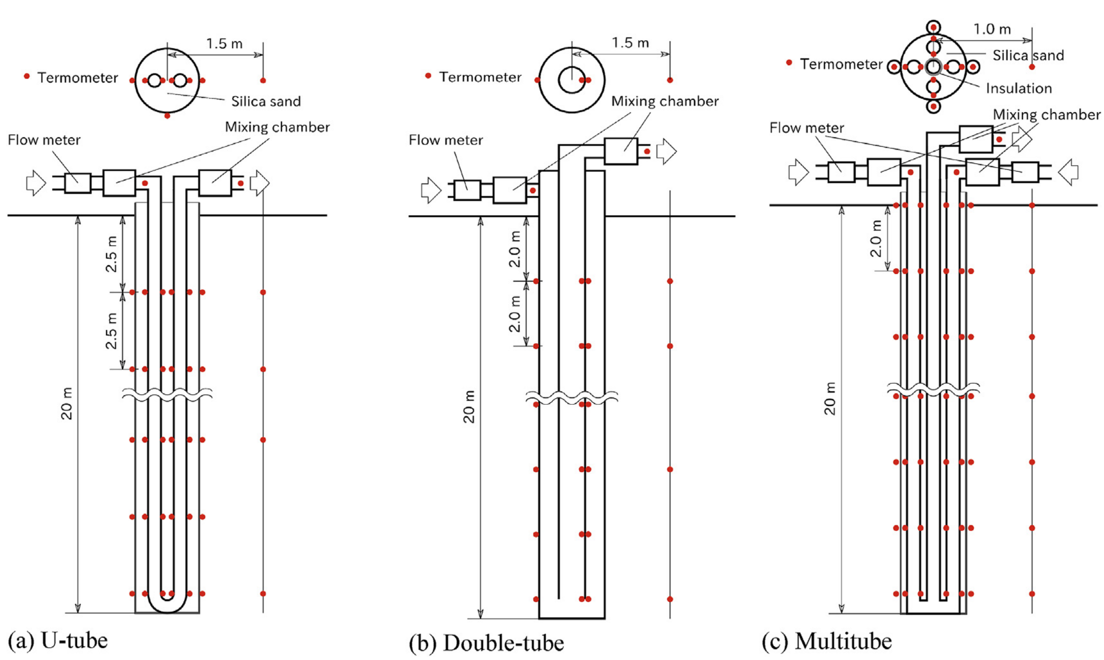

Fig. 1. Schematic diagrams of ground heat exchangers used in this work.