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Numerical simulation and sensitivity study of double-layer Slinky-coil horizontal ground heat exchangers

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ABSTRACT

In ground-source heat pump (GSHP) systems, the application of Slinky-coil horizontal ground heat exchangers (HGHEs) greatly reduces the initial costs for the system since the HGHEs can be constructed using common excavation machines. Though HGHEs have been commonly used in the United States and Canada, where abundant land space is available for installing HGHEs, the reduction of the land area requirement is important for the wider application of the system to other regions of the world. For this purpose, the introduction of a double-layer Slinky-coil HGHE is considered an effective choice if the heat exchange rates are much more than those for single-layer HGHEs.

In this study, long-term cooling and heating tests, using single-layer and double-layer Slinky-coil HGHEs as the heat source, were conducted in Fukuoka, Japan to compare their heat exchange capacities. The tests showed that the heat exchange capacity of HGHEs per unit land area is remarkably enhanced by the introduction of double-layer HGHEs. Numerical simulation models were then developed for the HGHEs on the basis of the procedures of Fujii et al. (2012) after modifications of surface boundary conditions. The models could successfully reproduce the temperature behaviors of the heat medium (heat carrier fluid) and ground temperatures in the cooling and heating tests, demonstrating the reliability of the numerical model for double-layer Slinky-coil HGHEs.

Using the model, sensitivity studies were performed to optimize the design of the double-layer HGHEs. The results of the sensitivity study on installation depth showed that the optimum depth of the upper layer was 1.5 m in case that the depth of the lower layer was fixed at 2.0 m. The preferable direction of heat-medium circulation was then investigated and it was concluded that circulation from the upper layer to the lower layer is the most suitable direction. Finally, the influence of the reflectance of the land surface was investigated by changing the albedo of the land surface as 0.1, 0.3 and 0.6. The numerical simulations showed that lower albedo is preferable in heating operations, while higher albedo is favorable in cooling operations.

1. Introduction

Slinky-coil horizontal ground heat exchangers (HGHEs) are known to be a cost-effective choice to reduce the initial cost of ground-source heat pump (GSHP) systems since HGHEs do not require drilling machines to construct. However, there are far fewer applications of Slinky-coil HGHEs than applications of vertical GHEs owing to the large land area required to bury the heat-exchange pipes. Therefore, to promote the use of HGHEs in locations with limited space, the heat exchange rate per unit land area should be improved according to an optimum design of the HGHEs.

The application of double-layer Slinky-coil HGHEs is considered one of the most promising ways to enhance the heat exchange rate per unit area. Hence, the effectiveness of the double-layer HGHEs needs to be proved though field tests or numerical simulations. Several investigations have been carried out to develop analytical and numerical models of single-layer straight HGHEs (Mei, 1986; Piechowski, 1998; Esen et al., 2007; Koyun et al., 2009; Pulat et al., 2009; Demir et al., 2009; Philippe et al., 2010; Bottarelli and Di Federico, 2010; Bennaza et al., 2011; Fontaine et al., 2011). In contrast, the research on Slinky-coil HGHEs has been limited. Fujii et al.

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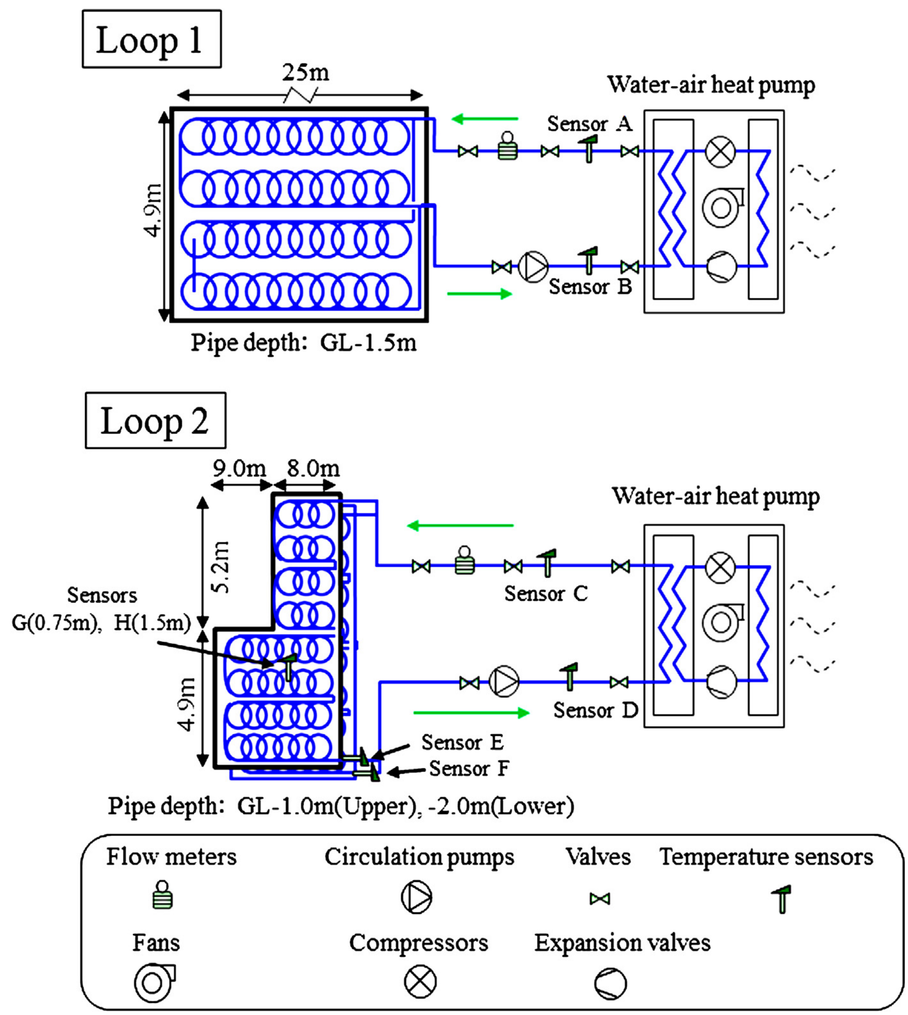

Fig. 1. Schematics of the field test facility.

(2010) presented the results of thermal response tests and long-term cooling and heating tests on two sets of Slinky-coil HGHEs with different loop angles and compared their heat-exchange capabilities. Wu et al. (2010) developed a 3D numerical model to simulate the performance of Slinky-coil HGHEs and conducted sensitivity studies on coil diameters and pitches. Congedo et al. (2012) developed 3D numerical models for straight, Slinky and spiral HGHEs and compared their performances. Using fine meshes to model the Slinky-coils, however, the numerical models by Wu et al. (2010) or by Congedo et al. (2012) could handle only small-scale models and were not applicable for the modeling of field-scale HGHEs. Fujii et al. (2012) then developed a full-field numerical simulation model of single-layer Slinky-coil HGHEs applying a simplified shape of Slinky-coils using numerical software, FEFLOW, and validated the model using the results of short-term and long-term heat-exchange tests. Li et al. (2012) developed an analytical model of Slinky-coil HGHEs using the moving line source theory and validated the model using laboratory experiments. Through the above researches, the optimum designs of the single-layer Slinky-coils have been rigorously studied. However, there has been no experimental or analytical research on double-layer Slinky-coil HGHEs.

In this study, numerical simulation models of single-layer and double-layer Slinky-coil HGHEs are constructed after modifications of the numerical model developed by Fujii et al. (2012). The models are validated using the results of long-term cooling and heating tests of single-layer and double-layer Slinky-coil HGHEs, which were carried out from December 2010 to February 2011 in Fukuoka, Japan. Using the developed numerical model, sensitivity studies are performed to optimize the design of the double-layer Slinky-coil HGHEs. In the analysis, a fixed heat load is given to the heat medium assuming the operation of heat pumps, and the temperatures of the heat medium are calculated to evaluate the energy efficiency of the heat pump. First, the optimum depth of the upper layer is investigated using a fixed depth of the lower layer of 2.0 m. The preferable direction of heat-medium circulation, upper to lower, lower to upper or in parallel, is then determined from the simulation results. Finally, the effect of reflectance (albedo) at the land surface is investigated by changing the albedo as 0.1, 0.3 and 0.6, assuming various types of land uses.

2. Field tests of Slinky-coil ground heat exchangers

From September 2010 to February 2011, long-term cooling and heating tests on single-layer and double-layer Slinky-coil HGHEs were carried out in Itoshima City, Fukuoka, Japan. The local annual temperatures used were the 10-year averages (2000–2009) for the annual average temperature (16.5 °C) and for the monthly average temperatures in February (7.1 °C) and August (27.5 °C). The field site is located on a hill on which several greenhouses have been built to grow orchids and other plants. The type of soil is sandy clay, which is widespread in the shallow ground. The groundwater level was measured in a 30-m-deep observation well as being approximately