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Numerical simulation for the optimum design of ground source heat pump system using building foundation as horizontal heat exchanger

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A R T I C L E I N F O

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A B S T R A C T

Ground source heat pump system takes advantage of the stable ground temperature to achieve energy savings and to reduce CO_2 emission. However, the system has several barriers for the wider application such as high installation costs, incompletion of design standard and lack of recognition as heating and cooling system. In order to solve the problems, the energy-foundation system was developed by several researches which use building foundation as a heat exchanger. Although many construction companies have more interest in various types of energy-foundations, there are few researches on the design method. In this study, in order to establish the optimum design tool of an energy-foundation system integrated with the horizontal heat exchanger, the prediction method of ground heat exchange rate was developed with numerical simulation model. The developed model was coupled with ground heat transfer model, ground surface heat model and ground heat exchanger model. Furthermore, case studies on prediction of heat exchange rate (HER) have been conducted at different conditions of design and installation with variables such as pipe spacing, installation depth, pipe diameter, circulation water temperature, flow rate, and operation condition. The HER for each case study has been calculated based on the long-term simulation.

1. Introduction

Recently, the interest in the efficient use of energy and the technology of renewable energy has increased according to growing environmental pollution crisis and resource depletion. Ground source heat pump (GSHP) systems are becoming more attractive since they can achieve higher system performance than the conventional air-source heat pump system. These systems utilize the stable annual underground soil temperature as a heat sink for cooling or as a heat source for heating. Generally, GSHP system can be divided into two types, open type and closed type according to the configuration of ground heat exchanger. The closed type is further divided into horizontal and vertical system. In Korea, since 2004, public buildings of up to 3000 m^2 floor space must invest a minimum of 5% of total construction cost on the renewable energy equipment such as solar, geothermal, wind power energy, biomass and others. As a result of this regulation, the renewable systems including GSHP systems became more common, the market of the systems grew dramatically and the market growth of GSHP system among the renewable energy systems was the most remarkable in the last decade [1]. Especially, the vertically closed type and the standing column well type have been mainly applied due to relatively high thermal conductivity, simple design and sufficient experience [2]. However, these types of systems need to be located at the depth of more than 100 m for the installation of ground heat exchanger and require additional initial cost and construction period than the conventional systems for the application in real buildings. In order to minimize the initial cost, several researches suggested systems which utilize the building structures as ground heat exchanger. However, the prediction of the system performance was significantly complicated to design the system by conventional design tools. Several researches have been conducted to estimate the system performance by experimental analysis and simulation method. Morino and Oka [3] developed a heat exchange system with a steel pile and conducted experimental analysis by circulating water in the pile. They found that the system achieved the heat exchange with the soil of 210 MJ/day as a heat sink, and 113–150 MJ/day as a heat source during a short-term experiment. Pahud et al. [4] developed PILSIM, a simple simulation tool for the performance of an energy pile in the framework of the Zurich airport project. They approximately predicted the system performance of an energy pile by the modifying Hellstrom's DST (duct ground heat storage) model.

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Lee and Lam [5] developed a simplified model for a single cylindrical energy pile and analyzed the system performance on the various conditions. Difference between the comparison results for heat source from simplified method and finite line source model was 0.11 °C. Gao et al. [6] conducted numerical and experimental analysis for vertical energy piles and it was found that the W-shaped heat exchanger was the most efficient system. Zhang et al. [7] developed a solid cylindrical simulation model for heat transfer around foundation pile ground heat exchangers with groundwater flow. It was found that the groundwater flow can improve heat exchange performance and the heat transfer quantity per meter pile can become 4 or 5 times higher than in the case of pure conduction.

In Korea, Park et al. [8] also evaluated the performance of energy pile with PHC (pre-stressed high-strength concrete) by numerical simulation and field simulation. According to the simulation results, the energy pile with 3U heat exchanger was expected to provide about 15% higher heat exchange rate to that with W heat exchanger in the intermediate operation, but there was negligible difference for continuous operation. In Japan, Yasuhiro et al. [9] studied the field performance of an 'energy-pile' system for space heating and the seasonal primary energy reduction rate of the system compared with a typical air conditioning system was 23.2%. Moreover, Jalaluddin et al. [10] evaluated the heat exchange rate of several heat exchangers in a steel energy foundation according to the change of the operation condition by experimental study and the heat exchange rate was 49.6 W/m for double-tube, 34.8 W/m for multi-tube, and 30.4 W/m for the U-tube in continuous operation. Nam et al. [11] developed the prediction method for heat exchange rate of GSHP system including the energy pile which can evaluate the system performance in various design conditions. It was found that the heat exchange rate of an energy pile with a cast-in-concrete pile reached 227.7 W/m in the condition of 16 pipes.

Although the previous researches have been conducted for the application to buildings, the standardization for system design and construction method has not been established yet. Furthermore, there are few researches on the horizontal system with mat foundation, because the prediction for heat exchange rate (HER) is difficult and it depends on various conditions of installation and construction such as the shape of foundation and pipe, the pattern of building loads, and geological condition of the site. Experimental approach for the performance evaluation of the horizontal GSHP system was conducted by Naili et al. [12] and it was found that the heat exchange rate was about 26 W/m with a mass flow rate of 0.12 kg/s during cooling season in Tunisia.

Recently, Choi [13] conducted experimental approach for the system design of 'energy-slab' which uses the building foundation as horizontal heat exchanger and he found that HER of the system was 13.3 W/m in heating and 15.53 W/m in cooling. However, the proper prediction method of the system performance still remains as the main obstacle to the use of energy-slab system.

The GSHP system for horizontal heat exchanger offers great benefits in view of cost-efficiency especially when it is applied to a large site. In recent years, many high-rise residential buildings have been constructed in Korea, and they mostly have underground parking lots, as large as the total site area. Even though the horizontal GSHP system cannot achieve as high heat exchange rate as vertical GSHP system, it is still available and cost-efficient particularly in the large site area. Therefore, in order to properly design the system using building foundation as heat exchanger, it is necessary to develop a prediction method for HER. In this study, in order to predict the performance of the system using building foundation as horizontal heat exchanger, the coupled simulation with a ground heat transfer model, a heat exchanger circulation model and ground surface heat balance model has been developed. Furthermore, case studies on predication of HER have been conducted for different conditions of design and installation with variables such as pipe spacing, installation depth, pipe diameter, circulation water temperature, flow rate, and operation condition.

2. System summary

Generally, the building foundations, especially the mat foundation, are installed at a depth of −3 to −10 m under the ground. Although temperature of this zone is influenced by the heat flux of ground surface, its annual fluctuation is relatively stable. This system utilizes building foundation as heat sink or heat source of GSHP system by installing horizontal heat exchanger pipes in concrete foundation. It is possible to reduce initial investment costs and to apply it into the building structure such as the underground parking lot. In this research, Fig. 1 shows the horizontal heat exchanger of the energy-foundation system. If the ground heat exchangers are installed at deeper level, higher HER would be achieved but installation cost can increase. Pipe spacing and pipe diameter also are important design factors in this system. In this study, for the optimum design of these horizontal heat exchangers, heat exchange rate between underground and circulation water in the piping has been calculated by the numerical simulation. Fig. 2 presents system configuration of GSHP system with the energy-foundation. This heat source system consists of heat pump, circulation pump and horizontal heat exchanger, which can be combined with various secondary systems.

3. Simulation overview

3.1. Prediction model of ground heat exchange rate

The heat exchange rate of GSHP system depends on the design, installation and operation condition of heat exchanger. In order to consider these conditions and optimize the system, it is necessary to develop the simulation tool which can be applied to various conditions of shape and thermal properties. In this study, the simulation method was developed coupled with the ground heat transfer model, the horizontal heat exchanger model and the surface heat balance model.

The heat transfer in the soil was calculated by FEFLOW which was based on finite element method and is widely used in fields of groundwater, material and heat transfer analysis. In this model, heat and material transfer in soil was calculated for three phases of gas, liquid and solid, respectively. Eqs. (1)–(3) present the governing equations of mass conservation, momentum conservation and energy conservation.

$$\frac{\partial}{\partial t}(\varepsilon_\alpha \rho^\alpha) + \frac{\partial}{\partial x_i}(\varepsilon_\alpha \rho^\alpha v_i^\alpha) = \varepsilon_\alpha \rho^\alpha Q_\rho^\alpha \tag{1}$$

$$v_i^\alpha + \frac{k_{ij}^\alpha}{\varepsilon_\alpha \mu^\alpha}\left(\frac{\partial p^\alpha}{\partial x_j} - \rho^\alpha g_j\right) = 0 \tag{2}$$

$$\frac{\partial}{\partial t}(\varepsilon_\alpha \rho^\alpha E^\alpha) + \frac{\partial}{\partial x_i}(\varepsilon_\alpha \rho^\alpha v_i^\alpha E^\alpha) + \frac{\partial}{\partial x_i}(j_{iT}^\alpha) = \varepsilon_\alpha \rho^\alpha Q_T^\alpha \tag{3}$$

Heat flux (Q) from the ground surface to underground is given by the following heat balance Eq. (4). Fig. 3(a) shows the schematic of the heat transfer on the ground surface. The surface heat flux was calculated by total radiation (R_{sol}), atmospheric radiation (R_{sky}), long-wave radiation from the ground surface (R_{surf}), sensible heat flux (H_{suf}), and latent heat flux (L_{suf}). Each detailed equation is shown in Eqs. (5)–(9).