別紙第１号様式　　　　　　　　　　　　No.1

博　士　論　文　の　要　旨

専攻名　　システム創成科学専攻

氏　名（本籍）

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学位論文題名

Experimental and Numerical Analysis of Performance of Ground Heat Exchangers for Ground Source Heat Pump

（地中熱利用ヒートポンプに用いる地中熱交換器の性能に関する実験および数値解析）

要旨（２，０００字程度にまとめること。）

Ground source heat pump (GSHP) systems are widely used in residential and commercial building for space heating and cooling as an alternative of conventional air source heat pump (ASHP) systems. GSHP systems provide a higher efficiency than conventional ASHP systems and environmentally friendliness. In GSHP systems, thermal energy transfer between the ground soil and circulating fluid occurs in an underground loop called a ground heat exchanger (GHE), which is laid in horizontal shallow trench or buried in vertical borehole. Though the GSHP systems are energy efficient than ASHP systems; however, initial installation costs are higher due to the additional cost associated with the GHE. The installation cost of GHE can be reduced by intelligently designing of GHE with proper selecting materials and size. Therefore, aiming to understand the physical phenomena occurs between the GHE and ground soil around GHE, studies are necessary.

In present study, the performance analyses of slinky horizontal GHEs have been studied via both experimental measurements and numerical simulation. In addition, optimization of vertical double tube GHE has been carried out by numerical simulation. In experiment, two slinky horizontal GHEs such as reclined (loops are placed parallel to ground surface) and standing (loops are placed perpendicular to ground surface) were installed in Saga University, Japan. All numerical simulations were carried out by using a commercial computational fluid dynamics (CFD) software package ANSYS FLUENT.

The thermal performances of reclined and standing slinky horizontal GHEs were experimentally investigated in different heating modes of continuous and intermittent operations. A copper tube of which outer surface is protected with a thin coating of low density polyethylene (LDPE) was selected as tube material of GHE. The thermal behavior of undisturbed ground and ambient temperature were also measured. To suggest the customary sizing of slinky GHEs for different ground soil temperatures and operating conditions, the overall heat transfer coefficient UA-values were also evaluated. Within the 4-days average heat exchange rate, the standing GHE shows 16.0% higher heat exchange rate than the reclined GHE at a flow rate of 1 L/min. For the mass flow rate 2 L/min, the average heat exchange rate of the standing GHE is 19.1% higher than the reclined GHE. With respect to excavation work, standing slinky GHE is more cost effective than reclined slinky GHE. The trench ground temperature degradation due to heat extraction was stronger in leading loops than trailing loops. This happened because of higher heat load in the leading loops. Hence, the slinky horizontal GHEs can be installed with a gradually sinking loop pitch from the starting loop to the end loop. This will potentially reduce the installation land area or may improve the thermal performance. Furthermore, the effects of different ground temperatures on GHE performance were discussed. For mass flow rate of 1 L/min with inlet water temperature 7 °C, the 4-days average heat extraction rates increased

45.3% and 127.3%, respectively, when the initial average ground temperatures at 1.5 m depth around reclined horizontal GHE increased from 10.4 °C to 11.7 °C and 10.4 °C to 13.7 °C. In the case of intermittent operation, which boosted the thermal performance, a short time interval of intermittent operation is better than a long time interval of intermittent operation. Furthermore, from the viewpoint of power consumption by the circulating pump, the intermittent operation is more efficient than continuous operation.

Aiming to improve the thermal performance of slinky GHE,

Aiming to improve the thermal performance of slinky horizontal GHEs, the uniform distribution of loops were modified by a geometric sequence such that gradually decreasing the loop pitch interval from starting loop to end loop. The performances were investigated numerically in cooling mode. The slinky horizontal GHE loops were distributed by a geometric sequence such that after obtaining the first loop pitch, the preceding next loop pitch is obtained by multiplying the first loop pitch by a constant called the common ratio (pitch reduction factor). A comprehensive experimental investigation was carried out to validate the present numerical model. In numerical study with modified arrangements of loop pitch, slinky loop diameter, number of loop and trench length was fixed as 1 m, 7 and 7 m respectively. The comparative temperature distribution around GHE also being discussed to illustrate the heat exchange improvement mechanisms. The operating water flow rate was 4 L/min and entering water temperature was 27 °C. The computational results indicate that, the modified arrangement of slinky GHE loop is a promising for the performance improvement. Under the present operating conditions and geometric parameters considered, the modified arrangement of slinky GHE loops offers maximum 22.2% higher heat exchange compared to uniform distribution of loops of slinky GHE within 7 day continuous operation. In this study the slinky GHE consists only 7 loops, which is may be suited for load demand of small building. For large building or commercial purpose, the slinky GHE is consisted usually large number of loops. It that situation, the total number of loop can be distributed by sequentially decreasing the loop pitch, or by subdividing the loops in step by step group of loop pitch reduction factor. These types of modified loop arrangement of slinky horizontal GHE minimize the drawback of shallow GHE's unstable thermal performance due to ambient effect.

From previous study, it is seen that, the double tube (coaxial) vertical GHE has higher thermal performance than U-tube and multi-tube GHEs. Therefore, the double tube vertical GHE has adopted to optimize the outer (inlet) tube diameter and inner (outlet) tube diameter in cooling mode. The purpose of this optimization is to reduce the outer and inner tube diameter. A series of two-dimensional axisymmetric numerical simulations were carried out to test the performances considering heat exchange rate and pressure drop. Effect of the different materials on heat transfer and longtime operation were also discussed. The results indicate that, heat transfer rate can be enhanced by reducing the outlet tube diameter for a fixed inlet tube diameter. The double tube vertical GHEs are more effective in laminar flow condition considering balance between heat transfer and pressure drop. The pressure drop is not significantly high in laminar flow condition; it is possible to reduce the inlet and outlet diameter of double tube GHEs if double tube GHEs operates in laminar flow condition. The heat transfer rate decreased only 17% but diameter of the outer tube can be reduced from 130 mm to 40 mm with fixed inner tube diameter of 20 mm. High density polyethylene is usually used in installation of GHE, the present study suggests that in double tube GHE, inlet (outer) tube with high density polyethylene and outlet (inner) tube with polyvinyl chloride is more effective than HDPE tubes use both in inlet and outlet. From the temperature distribution of long time operation, multiple double tube GHE can be installed at 2.0 m apart.

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博　士　論　文　の　要　旨

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The performance of slinky horizontal GHEs was experimentally investigated and numerically analyzed the optimum slinky loop arrangement. In addition, the optimum diameter of inner and outer tube of double tube vertical GHE was determined numerically.

In the experimental performance analysis of two slinky horizontal GHEs such as reclined (loops are placed parallel to ground surface) and standing (loops are placed perpendicular to ground surface), the standing GHE shows the higher heat exchange rate than reclined GHE. Furthermore, the effects of different ground temperatures on GHE performance were discussed. The merit of the intermittent operation of slinky horizontal GHE was also investigated and compared with continuous operation. From the different interval of intermittent operations, it can be suggested that, the short time interval of intermittent operation is better than a long time interval of intermittent operation.

The uniform distributions of loops were modified by a geometric sequence such that gradually decreasing the loop pitch interval from starting loop to end loop. Then the thermal performance improvement of modified slinky loop arrangement was investigated numerically. The results of numerical optimum slinky loop arrangement indicate that, the modified arrangement of slinky GHE loop is a promising for the performance improvement.

In the numerical optimization (to reduce the inner and outer tube diameter) of double tube vertical GHE, a two-dimensional axisymmetric numerical simulation model was developed. The performances were carried out on the basis of heat exchange rate, pressure drop and different materials of GHE. The results indicate that, the double tube vertical GHEs are more effective in laminar flow condition considering balance between heat transfer and pressure drop.