Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

# Economic Analysis of Semi-Open Loon Ground Source Heat Pump Systems in Different Parts of Japan

Saeid Mohammadzadeh Bina, Hikari Fujii, Shunsuke Tsuya, Younes Noorollahi, Hadi Farabi

Graduate School of Engineering and Resource Science, Akita University, Akita, Japan

S.bina@mine.akita-u.ac.jp

**Keywords:** GSHP**,** Heat pump, FEFLOW, Semi-open loop, Japan

## ABSTRACT

Ground Source Heat Pump (GSHP) systems have received enormous attention of energy decision makers for residential heating and cooling applications. Although, the obstacles such as high drilling cost especially in countries like Japan acts as barriers to the development of these systems. Therefore, the optimum design of a GSHP system with the possible lowest Ground Heat Exchanger (GHE) length plays the vital and important role in the early stage of these systems utilization. The shallower length of the GHEs, which is influenced by regions geological condition and also varies based on different heating and cooling loads can make these systems much more competitive comparing to the conventional systems.

This study compares the well length of a system at two different parts of the country with totally different geological and weather conditions. The main goal of this paper is to investigate the effect of heating and cooling loads distribution and to carry out the economic analysis for these regions. In this research, a new type of GSHP system namely "Semi-open loop GSHP", which is developed by the authors in their previous studies is simulated for Tokyo and Akita Cities in central and northern Japan, respectively. This system is installed in Akita University campus and its model in FEFLOW software is validated based on conducted thermal response tests (TRTs). Afterwards, the economic analysis was done for a specific heating and cooling load and based on Akita's weather. This process was repeated similarly for Tokyo City importing the new time series of heating and cooling load as well as changing the average ground temperature (as one of boundary conditions) according to Tokyo's recorded data.

## 1. INTRODUCTION

Currently, the electric split air conditioner systems and fossil fuel based small domestic boiler packages are the dominant methods for providing space heating and hot water supply, respectively [1]. It is worth mentioning that in the northern part of Japan, in Tohoku area which experiences very cold and long winters, the small portable kerosene heaters are still being used to supply heat for single rooms. The lower price of kerosene (80 Yen/Lit) compared to high electricity costs (20 to 30 ¥/kWh based on consumption, which imposes high electricity bills upon Japanese families), is the main reason of this heaters' popularity. On the other hand, due to inefficient heat distribution over the space and also the release of unpleasant smells as well as harmful gases (as they do not have an exhaust), this system presents a very low comfort level compared to other systems such as central hot water heating system.

There has been a rapid growth in ground source heat pump system (GSHP) for building heating and cooling. For example, around 500,000 systems were installed in the USA [2]. GSHP technology is the low enthalpy heat from absorbed solar energy in the shallow depth which exists in the ground surface and subsurface. Despite conventional heating, ventilation and air conditioning (HVAC) systems, GSHPs have lower maintenance cost, longer life time, ignorable visual impacts on the building, and lower CO2 emissions. In addition, several studies confirm that there is a potential for GSHP systems almost anywhere all around the world. However, the higher drilling cost especially in some countries like Japan increases its initial costs [3, 4].

GSHP system consists of heat pump unit system, ground wells, and borehole heat exchangers that carries heat medium as thermal heat source/sink. This system is classified either based on its borehole type (vertical and horizontal) or its circulation system (closed or open loop system) [5]. In the veridical systems, the borehole heat exchangers (tubes) are installed into drilled vertical wells that are known as borehole heat exchangers (BHEs). In this system, the U-tubes are installed into well with depths around 30 m to 200 m and the space between the U-tube and borehole casing is generally filled with grout [6].

Rapid growth in GSHP systems and its popularity in the worldwide caused more detailed studies and suggestion of novel systems to increase its performance. For instance, since, in the presence of a groundwater flow, the heat is also transported by convection, some research efforts have included the effects of the presence of a groundwater flow in GHE modeling [7]. In this regard, the semi-open loop GSHP system was introduced by Farabi Asl et al. [8]. This system comprises two ungrouted vertical GHEs and groundwater is pumped from one GHE and injected to the other using a water pump. The main reason of the water pumping and injection is to create an artificial groundwater flow around the GHEs and to increase the heat advection between the GHEs and the surrounding environment.

On the other hand, it has been shown that the design of GSHP system and its important parameters such as borehole length are directly related to the balance of heat load and distribution of cooling and heating loads. However, the effect of weather and climate conditions such as temperature and solar radiation on the system performance has not been examined, especially in Japanese cities. The literature shows the lack of studies done on GSHP performance in various cities with different climates. Therefore, this study examines the effect of thermal load distribution on a GSHP system which is installed in Akita University campus. This system is a semi-open loop GSHP system with two boreholes designed to provide heating and cooling for an office in the university.

This research consists of two scenarios entitled "Scenario #1" and "Scenario #2" for the conditions of without and with groundwater flow, respectively. The heating and cooling load is calculated based on hourly ambient temperature in Tokyo and for a hypothesis room. Afterward, the results of this study will be compared with the authoer previous study, which was applied for Akita City. The main aim of this study is to observe the effect of heat load and its distribuation on GHE length as well as system's cost.

## 2. SEMI-OPEN LOOP GSHP SYSTEM

The semi-open loop GSHP system in our study (Fig. 1) comprises two vertical un-grouted GHEs (GHE1 and GHE2) with 5 m distance at the Akita University campus, Akita City, Japan. In geology point of view, the formation of the upper part (from surface to 60 m) is an alluvial deposit of the Quaternary System, comprising mainly silt, sand and gravel. The lower part comprises siltstone of the Tertiary System. Below 15 m, a clear geothermal gradient of 0.04 °C/m was observed. Both double U-tubes are installed in both GHEs into a steel casing from the surface to −60 m. In order to have the groundwater flow effect across the GHEs, the casing is slotted between −10 m and −60 m. The GHE connecting pipes are placed on 10 cm higher than ground surface. In order to prevent the thermal interaction between ambient and working fluid inside the piping, insulation with 3 cm of thickness covers the pipes. The water pumping and injection pipe with a control unit placed on the ground surface which connects two wells to each other and pumps between the two GHEs. The bottoms of the water pumping and injection pipes in GHE2 and GHE1 are located at a depth of 50 m. The heat pump unit has a heating and cooling capacity of 10 kW.

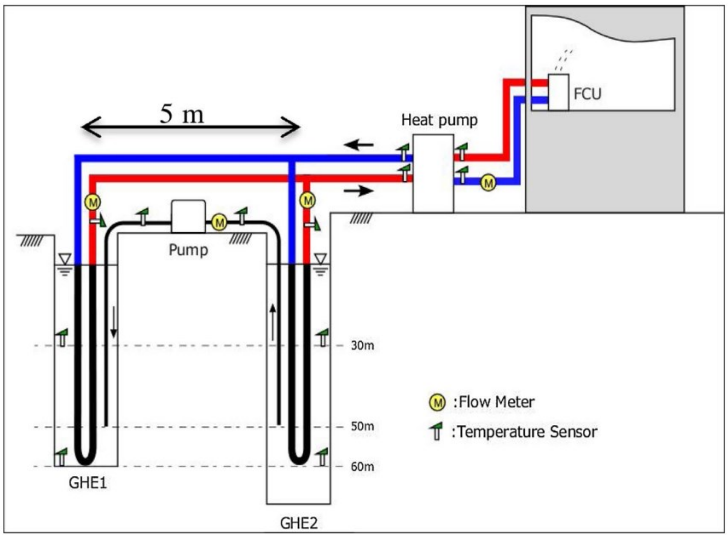


**Figure 1: Schematic of the semi-open loop system.**

## 3. NUMERICAL MODELING

The numerical model was developed using FEFLOW 7 and based on the actual model which is installed in the field study. In order to increase the accuracy of the model, the meshing around the GHEs' nodes were refined in the software. The undisturbed water table at the test site was measured as −5 m. The pumping and injection depth was placed at 50 m for both GHE 2 and GHE 1. The "Borehole heat exchanger" boundary condition representative of both GHEs in the semi-open loop GSHP system, were set in the numerical model with 5 m distance same as the field test condition. The high density PE pipe with thermal conductivity of 0.45 W/m/K was used for U-tube pipes. The working fluid inside the U-tube is the mixture of water with 20% vol. ethylene glycol.

The GHE specifications and the thermal properties of the working fluid such as volumetric heat capacity, thermal conductivity, dynamic viscosity, density were set based on the standards which were also used in the authors previous study [8].

The initial ground temperature was determined based on weather data for Tokyo City. Constant temperature at the bottom and peripheral boundaries were set as the boundary conditions. Similarly, constant hydraulic head of −5.0 m and −5.2 m were considered at the eastern and western boundary, respectively. This boundary condition causes a hydraulic head difference between the eastern and western lateral boundaries, generating a natural groundwater flow from the eastern to the western boundaries.

## 4. ECONOMIC ANALYSIS

As it was mentioned above, the semi-open loop GSHP system has an additional water pump compared with conventional GSHP systems. This water pump implies an additional initial cost as well as extra power consumption to the whole system. The aim of this step is to answer the question that: is it worth adding an additional water pump to a normal GSHP system?

A sample building, with characteristics similar to the field test conditions, was considered to calculate the hourly heating and cooling loads during a reference year and according to Tokyo City's metrological data. The validated numerical FEFLOW model was used to calculate the minimum necessary GHE length to meet the heating and cooling demand of the building, for different scenarios including different natural groundwater conditions and also water pumping and injection rates. Finally, the total saving due to water pumping and injection was calculated using a cash flow diagram while considering GHE length reduction and water pump installation and power consumption costs.

### 4.1 Heating and cooling loads

In order to calculate the heating and cooling loads for the conventional buildings an especial method which is published by the Japan Energy Saving Standard, published by the Japanese Ministry of Land, Infrastructure, Transport and Tourism [9] was used. In this method Japan is classified into eight regions of energy conservation standards (Fig. 2) and the heating and cooling load can be calculated using the following equations.

$$Q_{heating} = \frac{U \times A_e \times (T_i - T_0)}{A_f} - \frac{I \times \eta}{A_f} \tag{1}$$

$$Q_{cooling} = \frac{U \times A_e \times (T_0 - T_i)}{A_f} - \frac{I \times \eta}{A_f} \tag{2}$$

In these equations:

$Q_{heating}$ and $Q_{cooling}$: Heating and cooling loads (W/m$^2$)
$A_e$: Building envelope area (m$^2$)
$A_f$: Building floor area (m$^2$)
$T_i$: Room temperature (°C)
To: Ambient temperature (°C)
I: Solar radiation (W/m$^2$)
U: Overall heat transfer coefficient (W/m$^2$ /K)
η: Average solar heat acquisition rate (W/W/m$^2$)

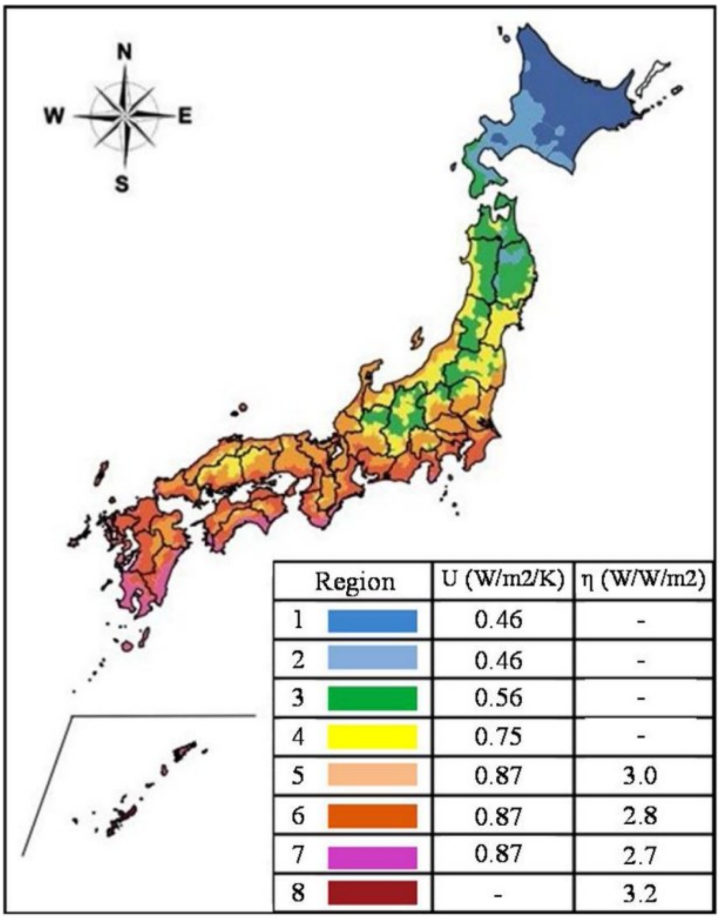


**Figure 2: Region classification in the energy conservation standard.**

As it is shown in Fig. 2 the values of U and η vary by region within the country. As Tokyo City is located in Region 5, therefore, the value of U and η are 0.87 W/m$^2$/K and 3.0 W/m$^2$, respectively. The values of Ae and Af for our case study are calculated around 300 m$^2$ and 120 m$^2$, respectively. The desire room temperatures set points for heating and cooling were set as 22 °C and 24 °C, respectively, according to ASHRAE Standard 55 (2013), [10]. The annual average ambient temperatures (To) for Tokyo City from 2000–2017 as well as ambient temperature in 2016 (as reference year) is shown in Fig. 3. This year is selected as reference year in calculations because the data of 2016 overlaps the average temperature data during these 18 years. The figure shows that Tokyo City has a short mild winter and the long hot summer. The heating and cooling period were set as December-March (4 months) and Jun–September (4 months), respectively. The daily time schedule is 8:00 to 20:00, due to the working hours of the conditioned rooms during the field tests. The heating and cooling loads were calculated on an hourly basis and are shown in Fig. 4.

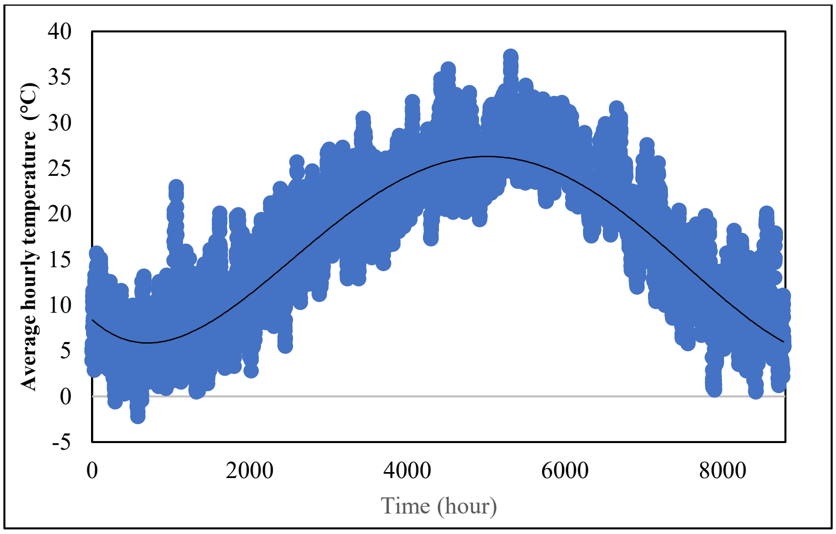


**Figure 3: Average ambient temperature from 2000 to 2017 (points) and hourly ambient temperature in 2016 (line) for Tokyo City.**

### 4.2 Calculation of GHE heat transfer rate

In order to calculate the minimum GHE length in the GSHP system, the heat transfer rate between the GHE and the ground must be calculated. The relationships between the heating or cooling load (QROOM), transfer rate (QGHE) and heat pump power consumption (W) for heating and cooling conditions are shown in following equations.

$$Q_{GHE} = Q_{ROOM} - W_{HP} \tag{3}$$

$$Q_{GHE} = Q_{ROOM} + W_{HP} \tag{4}$$

In the above equations, COP is the ratio of QROOM to WHP. In our calculation, we assumed that the heating and cooling COPs are 3.5 and 5.5, respectively. Therefore, based on these definitions, QGHE was calculated on an hourly basis and was shown in Fig. 5. This value is the input parameter to the validated numerical model to calculate the minimum necessary GHE length to meet the heating and cooling demand of the building. It is necessary to note that in Fig. 5, heating loads have negative values and cooling loads have positive values.

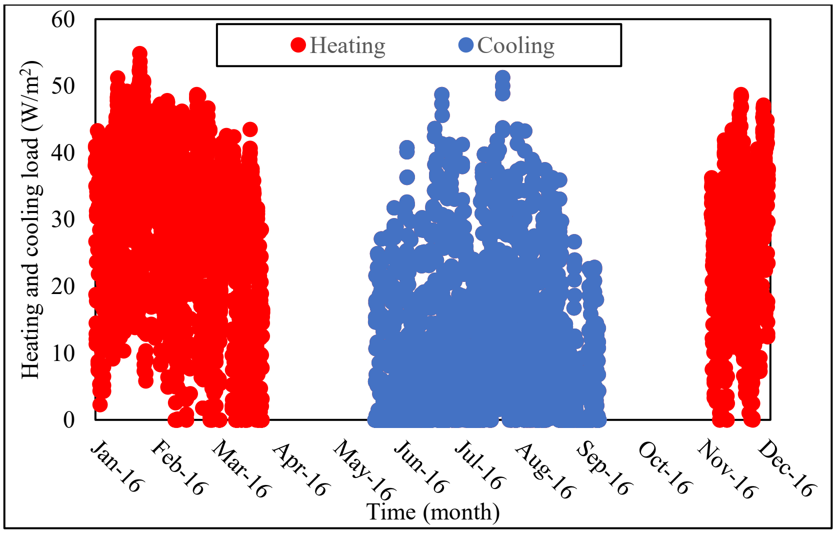


**Figure 4: Calculated hourly heating and cooling loads.**

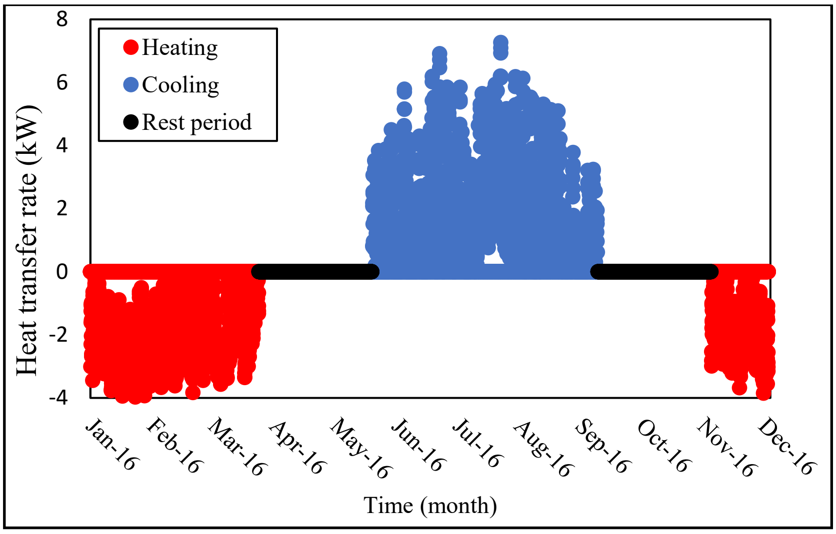


**Figure 5: Calculated hourly GHE heat transfer rate.**

This data was also used as input data to size the required lengths of GHEs. This method sizes the GHEs to meet the assumed heat load previously discussed within our pre-specified minimum and maximum heat pump inlet temperature (0 °C and 35 °C for heating and cooling, respectively). Fig. 6 shows the simulation results for finding the optimum GHE length under the heat pump unit operation condition. As can be seen in this figure, the designed system length satisfied the assumed heat load except for two harsh conditions, which are ignored as data fluctuation errors.

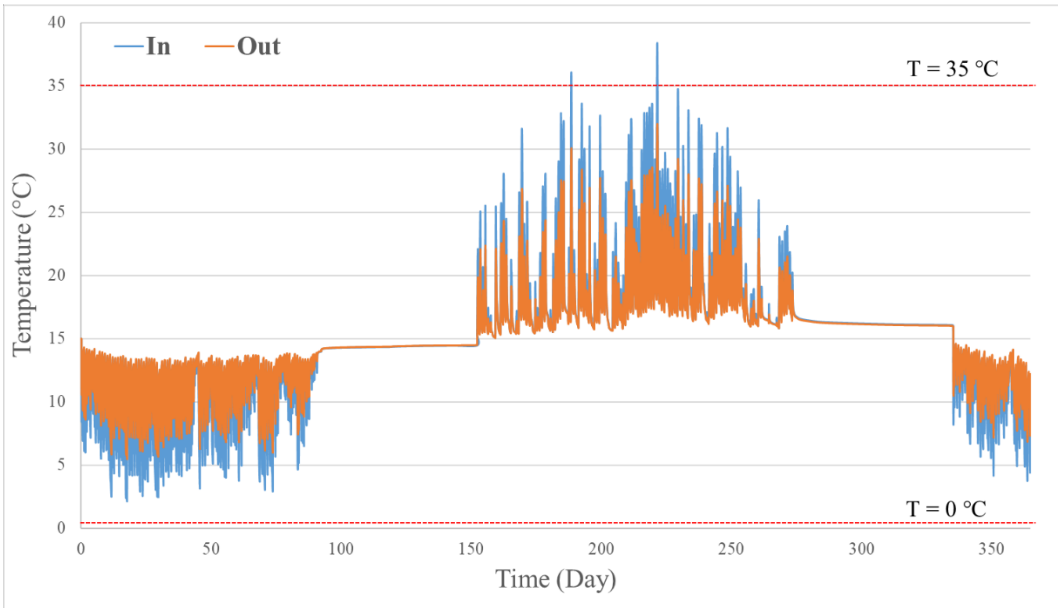


**Figure 6: GHE inlet and outlet temperature in FEFLOW simulation**

### 4.3 Semi-open loop cost saving calculation

In the field tests and also in the numerical model specification, the working fluid inside the GHE is a mixture of water and ethylene glycol (20% volume, freezing point: −7.9 °C). Considering the safety factor to prevent freezing during the cold season and also GSHP unit's operation, the minimum and maximum working fluid temperature during the winter and summer seasons were set as −0.5 °C and 35 °C, respectively. In order to consider the effect of natural groundwater flow and also the water pumping and injection rates, two different scenarios were analyzed and the minimum GHE length in each scenario was calculated both for the base case (without water pumping and injection) and for semi-open loop operation. After setting the minimum GHE length for base case operation, the GHE length for semi-open loop operation was set to ensure equal heat pump power consumption for the base case and semi-open loop operation.

**Table 1: GHE lengths and drilling cost savings for different scenarios.**

| | No groundwater (Scenario #1) | Slow groundwater (Scenario #2) |
|---|---|---|
| Water pumping/injection rate (L/min) | 5 | 5 |
| Total length in base case (m) | 195 | 175 |
| Total length in semi-open loop (m) | 45 | 40 |
| Drilling cost saving (Yen) | 2,250,000 | 2,025,000 |

In Scenario 1, the “No groundwater flow” condition was considered. Under the base case conditions, there is no water pumping and injection inside the GHE wells. Under the semi-open loop conditions, the groundwater is pumped from GHE 2 to GHE 1 at a rate of 5 L/min for Scenarios 1 and 2, respectively. The pumping and injection node in the numerical model was placed 10 m higher than the bottom of the GHE to avoid sucking up sediment. In order to evaluate the effect of natural groundwater flow on the minimum necessary GHE length, “Slow groundwater flow” conditions were also considered in Scenario 2. In this scenario, the hydraulic head gradient between the eastern and western lateral boundaries was set as 0.001 (0.1 times the value in the experiments). Semi-open loop operation was modeled and analyzed with 5 L/min of water pumping and injection between the GHEs. The drilling cost in Japan was set as 15000 Yen/m. The two scenarios and the results of the calculations are shown in Table 1.

The additional components and their costs in the semi-open loop system are shown in Table 2. In order to prevent possible damage to the water pump under outside conditions and also to guarantee the longterm operation of water pump, a “water pump casing” item was added to the system cost. The price of the housing material and installation is estimated to be 10,000 Yen. The price of the water pumping and injection pipe is 500 Yen/m and the length of this tube is different for different scenarios.

**Table 2: Additional Component for pumping and injection.**

| Items | Cost |
|---|---|
| Water pump | 60,000 Yen |
| Water pumping pipe | 500 Yen/m |
| Water pumping installation | 20,000 Yen |
| Water pump casing | 10,000 Yen |

Table 3 shows the water pumping and injection pipe length and cost and the total cost of additional components in the semi-open loop system, for different scenarios.

**Table 3: Capital cost of water pumping and injection for different scenarios.**

| | Scenario #1 | Scenario #2 |
|---|---|---|
| Water pumping and injection pipe length (m) | 30 | 25 |
| Water pumping and injection pipe cost (Yen) | 15,000 | 12,500 |
| Total cost of additional components (Yen) | 105,000 | 102,500 |

During semi-open loop operation, the water pump is working when the heat pump unit is on. According to the heating and cooling schedule, the total water pump working period is 2880 h/year. Taking the electricity price in Japan to be 20 Yen/kWh, the water pump power consumption cost for one year was calculated. Table 4. Shows the present values of the water pump power consumption costs for different scenarios.

**Table 4: Water pumping and injection costs for the first year and the present value.**

| | Scenario #1 | Scenario #2 |
|---|---|---|
| Power consumption per day (W) | 20 | 20 |
| Power consumption for the first year (kWh) | 50.08 | 50.08 |
| Water pumping and injection cost for the first year (Yen) | 1,101 | 1,101 |
| Present value of Water pump power consumption cost for 20 years of operation (Yen) | 17,350 | 17,350 |

In order to calculate the present value of the water pump power consumption cost for 20 years of operation, it is necessary to consider the “annual inflation rate” and “interest rate” factors in the economic analysis. According to the World Bank online data in December 2016, the average annual inflation and interest rates in Japan were 0.19% and 2.57%, respectively [11]. The water pump power consumption cost over 20 years of operation (P) can be calculated using the concept of net present value based on the following parameters:

- Average of inflation rate in Japan =0.19%
- Project life time = 20 years
- Average interest rate in Japan = 2.57%

The calculations showed that the present value of the water pump power consumption cost for 20 years of operation is 15.75 times as much as the water pump power consumption cost in the first year of operation. Table 5 shows the present values of the water pump power consumption costs for different scenarios. Water pumping and injection has positive and negative effects on the GSHP system costs.

In order to calculate the percentage of semi-open loop savings against the total cost of the GSHP system in the base case, it is necessary to calculate the total system cost of the GSHP system in the base case for different scenarios. Here are the GSHP system capital costs for base case operation:

- Drilling cost: 15,000 Yen/m
- Heat pump unit cost: 800,000 Yen
- Distribution system cost: 200,000 Yen
- Piping and labor cost for installation: 500,000 Yen

The heat pump unit power consumption during heating and cooling operation is calculated using Eq. (5).

$$W_{heating/cooling} = \frac{Q_{heating/cooling}}{COP_{heating/cooling}} \quad (5)$$

In this equation, $Q_{heating}$ or $Q_{cooling}$ are the calculated yearly room heating or cooling loads, respectively. $W_{heating}$ and $W_{cooling}$ are the yearly heat pump power consumptions for heating and cooling operations, respectively. Table 6 shows the present values of the heat pump unit consumption costs for different scenarios.

**Table 5: Heat pump power consumption.**

| | |
|---|---|
| $Q_{heating}$ (kW) | 3105 |
| $Q_{cooling}$ (kW) | 2809 |
| $W_{cooling}$ (kWh) | 887 |
| $W_{heating}$ (kWh) | 510 |
| Total power consumption of GHE (kWh) | 27,963 |
| Present values of total power consumption (kWh) | 440,413 |

Table 6 shows the calculated parameters and final savings of a semi-open loop GSHP system for different scenarios. In this table, the "saving" factor is the saving due to the water pumping and injection.

**Table 6: Total cost and final saving (Yen).**

| | Scenario 1 | Scenario 2 |
|---|---|---|
| Drilling cost | 2,925,000 | 2,625,000 |
| Heat pump unit cost | 800,000 | 800,000 |
| Distribution system cost | 200,000 | 200,000 |
| Piping and labor cost | 500,000 | 500,000 |
| Power consumption cost | 440,000 | 440,000 |
| Total cost (conventional system) | 4,865,000 | 4,565,000 |
| Final saving | 2,127,625 | 1,905,150 |
| Saving percent (%) | 44 | 42 |

## 5. CONCLUSION

The maximum saving percentage for Scenario 1 is 44%. The results of the economic analysis demonstrated the remarkable effect of water pumping and injection on GHSP system cost reduction. The economic analysis showed that water pumping and injection could save 42-44% in GSHP system costs that comparing to the previous study these numbers are increased. Even though the cooling load is very higher than Akita City, but this system consumes 54% lower than installed system in Akita (due to higher cooling COP). Therefore, the distribution of heating and cooling seasons and loads are very important factors in system power consumption. Changing load and case study showed very considerable difference of GHE length in scenario #1 (without groundwater), while in presence of groundwater (base case and semi-open loop) the lengths were almost same as the system for Akita. Therefore, it can be concluded that, as this system was so over designed for Tokyo's weather and also our assumed room load was too small, the effect of scenario with groundwater was not big enough to be shown in this study. Even though the average and total load in Tokyo were lower than Akita, but because of some harsh hot days, we had to choose longer GHE lengths (it is necessary to mention that outlying point which were not realistic were deleted). Thus, the distribution and pick points of heat loads are very important factors in obtaining GHE length for the scenarios. In all scenarios, influence of pumping was much more important than presence of groundwater flow. As it can be seen, in scenario #1, the length was shortened around 26% (from 195 m to 45 m), while this number was about 23% (from 175m to 40m). Therefore, pumping (semi-open loop system) has huge and considerable effect on the long length systems.

## REFERENCES

Baldvinsson, I. and T. Nakata, A comparative exergy and exergoeconomic analysis of a residential heat supply system paradigm of Japan and local source based district heating system using SPECO (specific exergy cost) method. Energy, 2014. 74: p. 537-554.

CHIASSON, A.D., ADVANCES IN MODELING OF GROUND-SOURCE REAT PUMP SYSTEMS. 1999.

Lund, J.W., Direct-use of geothermal energy in the USA. Applied Energy, 2003. 74(1): p. 33-42.

Majorowicz, J.A., et al., Topography and the subsurface temperature regime in the western canadian sedimentary basin: implications for low-enthalpy geothermal energy recovery. Geothermics, 1985. 14(2): p. 175-187.

Daemi, N. and M.M. Krol, Impact of building thermal load on the developed thermal plumes of a multi-borehole GSHP system in different canadian climates. Renewable Energy, 2019. 134: p. 550-557.

Li, M. and A.C.K. Lai, Review of analytical models for heat transfer by vertical ground heat exchangers (GHEs): A perspective of time and space scales. Applied Energy, 2015. 151: p. 178-191.

Fujii, H., et al., Optimizing the design of large-scale ground-coupled heat pump systems using groundwater and heat transport modeling. Geothermics, 2005. 34(3): p. 347-364.

Farabi-Asl, H., H. Fujii, and H. Kosukegawa, Cooling tests, numerical modeling and economic analysis of semi-open loop ground source heat pump system. Geothermics, 2018. 71: p. 34-45.

Japanese Ministry of Land, I., Transport and Tourism Japan Energy Saving Standard. 2014.

American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE), Standard 55-2013, Thermal Environmental Conditions for Human Occupancy. 2013.

The World Bank online data center December 2016.