# ANALYSIS OF A GROUND SOURCE HEAT PUMP SYSTEM OPERATION UTILIZING STEEL FOUNDATION PILES AS GROUND HEAT EXCHANGERS

*Takao Katsura, Fujiwara Environmental Science Institute Ltd, Sapporo, Japan*
*Katsunori Nagano, Professor, Hokkaido University, Sapporo, Japan*
*Shogo Hori, M.C. Student, Hokkaido University, Sapporo, Japan*
*Sayaka Kindaichi, Assistant Professor, University of Tokyo, Tokyo, Japan*
*Yasushi Nakamura, Nippon Steel Engineering, Tokyo, Japan*

**Abstract:** A ground source heat pump (GSHP) system has been installed into a new building in Soen Campus of Sapporo City University. The GSHP system uses steel foundation piles as the ground heat exchangers. The construction works were carried out based on the design by using a design tool for GSHP systems that the authors have developed. The system has operated and the authors has analysed the system since April 2006.
The result showed that steel foundation piles used as ground heat exchangers injected heat of around 250 W/m to the ground at the maximum during the cooling period. Also, it is expected the GSHP system in this building can operate with high efficiency for long term due to the ground water flow. The GSHP system can operate with average COP of more than 4.5 and reduce $CO_2$ emission of 40% compared to a gas boiler system.

**Key Words:** ***Ground Source Heat Pump System, Steel Foundation Pile, Analysis of System Operation***

## 1 INTRODUCTION

Using foundation piles of the buildings as ground heat exchangers has great possibility of cost reduction in installation of ground source heat pump (GSHP) systems. The first idea was presented in early 1960s in Japan. Recently, this method has been called as “Energy Pile System” and it has become popular gradually in European countries.
A GSHP system installed to a new building in Soen campus of Sapporo City University is the first system adopting steel foundation piles as ground heat exchangers, which is applied for non-residential building. Additionally, the authors designed the GSHP system by using a design tool for GSHP systems and analysed the two years’ operation.
Here, the authors introduce outlines of the GSHP system, proceeding of the design, result of the daily operation, result of seasonal operation, and result of comparison between operating performance in the first year and the second year.

## 2 OUTLINES OF BUILDING AND GROUND SOURCE HEAT PUMP SYSTEM

### 2.1 New building and steel foundation piles

Figure 1 and Figure 2 show an appearance and location of Soen campus of Sapporo City University. Sapporo is the capital city of Hokkaido, which is northernmost island in Japan. The campus is located about 2 km west of Sapporo’s central railway station. South part of Sapporo city is surrounded by mountains and the city is in alluvial fan area. Thus, it is expected that the ground water flow is generated under the ground.

Figure 3 shows a top view of the new building and arrangement of steel foundation piles. The new building consists of two parts. One part is a high-rise building with four stories which has a floor area of 2,800 $m^2$. The other is a low-rise building with two stories of 2,000 $m^2$ floor area. Only high-rise building is provided with steel foundation piles. As many as 51 piles were buried into the ground under the base plates at - 4.0 m depth from the ground level. Diameter of the steel piles ranges from 600 mmϕ to 800 mmϕ. As shown in Figure 4, a layer of hard gravel and pebble appears under the depth of 10 m in this area. Consequently length of the piles was determined at 6.2 m on average. Needed head space of 1.0 m for the footing and bottom space of 0.5 m were deducted. The average effective length of ground heat exchangers would be 4.7 m and total effective length were estimated 240 m. Double U-tubes were inserted to steel piles and steel piles are used as indirect ground heat exchangers.
In respect to soil properties, the effective thermal conductivity $\lambda_s$ and ground water velocity at the site were determined by the thermal response test. From the result, $\lambda_s$ was estimated 2.1 W/m/K and the ground water velocity was estimated 40 m/year. In addition, the ground temperature was 12.1 $^{o}$C obtained from a measurement in observation well at the site.

### 2.2 Ground source heat pump system design

Panel heaters used as heating system in this building require hot water temperature of approximately 80 $^{o}$C in order to satisfy the maximum heating demand. Additionally, it is predicted that heat extracted from the ground via the steel foundation piles would not be enough to cover the total heating demand. Thus, the authors designed that the GSHP system operates for heating supply air (SA) of ventilation. Furthermore, scale of the ground heat exchangers that can satisfy the following conditions was determined by using a design tool.

1. Rated heating output from a heat pump unit is 50 kW.
2. Minimum temperature of heating medium in primary side is larger than – 2 $^{o}$C
3. Ground temperature is kept stable for long term

The result showed that the steel foundation piles and three-borehole ground heat exchangers with single U-tube of 75 m long can fulfil these conditions. Then three-borehole ground heat exchangers were added based on this design.

### 2.3 Ground source heat pump system operation

Figure 5 illustrates diagram and specification of the GSHP system actually installed. The GSHP unit has a compressor of 20-horse power and the rated heating output is 50 kW. Heat is extracted from the ground via the steel foundation piles and borehole ground heat exchangers. Afterward hot water of 30~40 $^{o}$C is generated by using the GSHP unit in order to raise the SA temperature. A gas boiler system is installed to support the GSHP system. The operating conditions in the first and second year differ from each other. The detail is indicated in Figure 5. In the second year, only the GSHP was operated unless the outlet temperature T-7 decreases so much because the ground temperature in the first year did not decrease as much as the authors predicted.
With regard to cooling period, it is suggested that to inject the exhaust heat to the ground contribute to recover ground temperature. Thus, direct cooling system without a refrigerator was adopted in the first year. In the second year, we installed a four-direction valve into the heat pump unit and used the heat pump unit as a refrigerator. This means the GSHP system has been mainly used as the cooling system with a refrigerator since the second year’s cooling period.

Figure 1: Appearance of Soen campus of Sapporo City University

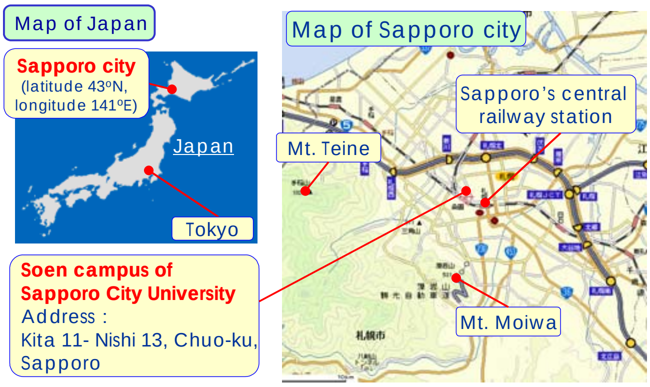



Figure 2: Location of Soen campus of Sapporo City University

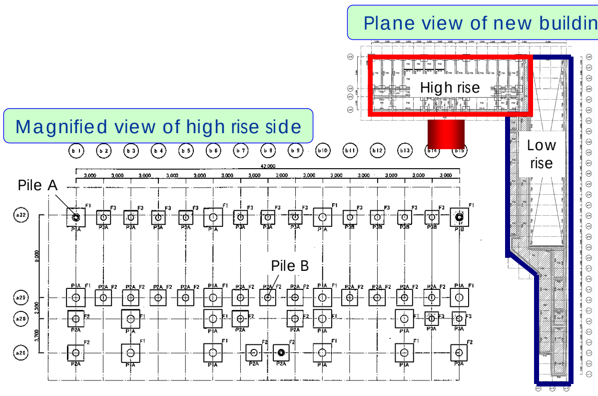



Figure 3: Top view of new building and arrangement of steel foundation piles

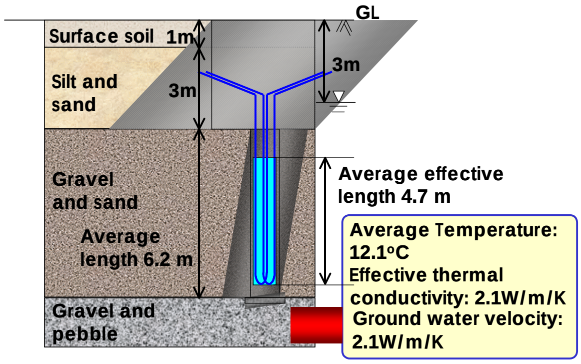
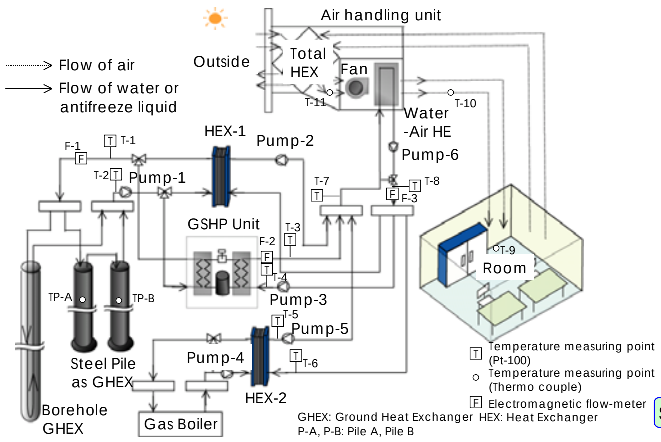
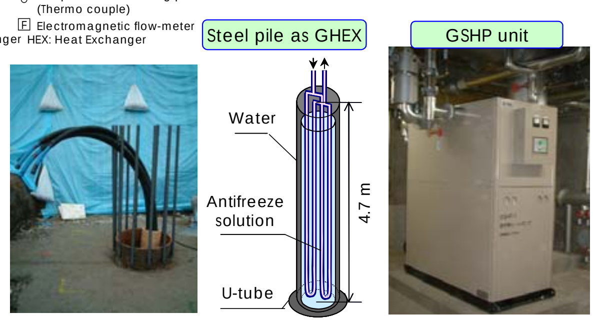



Figure 4: Geological condition and detail of underground construction




- GSHP unit
  - Compressor : 20 horse-power
  - COP(0 - 35 ºC) : 4.0Output : 50 kW
- Gas Boiler Output : 349 kW
- Air-handling unit Number : 5 unit
- Pump-1 Flow rate: 200 L/min
  - Electric power consumption: 3.7 kW
- Pump-2 Flow rate: 485 L/min
  - Electric power consumption: 1.5 kW
- Pump-3 Flow rate: 145 L/min
  - Electric power consumption: 0.75 kW
- Pump-4 Flow rate: 170 L/min
  - Electric power consumption: 1.5 kW x 2
- Pump-5 Flow rate: 340 L/min
  - Electric power consumption: 1.5 kW x 2
- Pump-6 Flow rate: 487 L/min
  - Electric power consumption: 0.4 kW x 3, 1.5 kW x 2
- Steel pile as GHE (with double U-tube)
  - Average length : 4.7 m
  - Number : 51 piles
- Borehole GHE (with single U-tube)
  - Length : 75 mNumber : 3




Operating condition of Gas Boiler First year : Heating output of GSHP system > 50 kW
Second year : Outlet temperature to air handling unit < 33 ºC

Figure 5: Diagram and specification of GSHP system

## 3 DAILY PERFORMANCE OF GROUND HEAT PUMP SYSTEM

### 3.1 Cooling operation

As the representative result of the direct cooling system operation, Figure 6 and Figure 7 show variations of temperatures and flow rates of each part indicated in Figure 5 on Aug. 9th 2006. The system is mainly operated from 7:00 to 17:00. The temperatures T-7 and T-8 in Figure 6 are smaller than ambient air temperature. Thus it is suggested that this system absorbs heat in the supplied ambient air and the temperatures T-1, T-2, T-7, and T-8 increase by the exhaust heat.
Shown in Figure 8 are variations of cooling output from the air-handling units and heat injected to the ground via the ground heat exchangers. The cooling output is around 30 kW, but the injected heat is up to 40 kW. This is due to heat generation from the circulation pumps.
Next, Figure 9 and Figure 10 demonstrate variations of temperatures and flow rates of each part on Aug. 8th 2007. Additionally, drawn in Figure 11 is dairy variations of cooling output from the GSHP and air-handling unit, injected heat, and electric power consumption of the compressor. These are results of the representative day of the cooling system with a refrigerator. The temperatures T-1 and T-2 rise during the GSHP system operation and the increments are lager than those of the direct cooling system in Figure 6. Also, increase of the temperatures TP-A and TP-B is observed more clearly. The reason is that the injected heat shown in Figure 11 is larger than that of the direct cooling system in Figure 8. By operating the heat pump unit as a refrigerator, the temperature T-3 is maintained around 15 $^{o}$C and it is smaller than the temperature T-2 in Figure 6, which is the cold-water temperature supplied by the direct cooling system. However, the temperature T-7 after 9:00 is around 20 $^{o}$C and this is higher than the general outlet temperature to the secondary side during cooling operation. This is caused by excessive cooling capacity of the air-handling unit compared to cooling output from the heat pump unit. The room temperature T-9 is kept lower than 27 $^{o}$C all through the day although outside ambient air temperature becomes larger than 30 $^{o}$C.
As shown in Figure 11, the injected heat in operation is kept at around 80 kW. The ratio between injected heat via steel foundation piles and borehole is predicted approximately 3:1 from a simulation result. Thus, injected heat via steel foundation piles is estimated to be 60 kW. Additionally, injected heat per length via steel foundation piles is evaluated approximately 250 W/m. The value is larger than the one via borehole ground heat exchangers. The reasons are that free convection of water happened in the piles and that heat capacity of water reduces the temperature decrement. The ground water flow generated in this site suppresses temperature change of the ground around the ground heat exchangers and it also yields increase of the heat injection.
Furthermore, the results of the cooling operation with and without the heat pump unit as refrigerator are summarized and compared to each other. Figure 12 indicates average cooling output, average heat injected to the ground via steel foundation piles and boreholes during operation of each system. Average temperature variation of the thermal medium in the ground heat exchanger from the initial temperature is also drawn in Figure 12. Since the cooling capacity of the air-handling unit is excessively larger than the cooling output of both systems, the cooling output with the heat pump unit becomes larger by the heat pump operation. This increases the injected heat and temperature variation of the thermal medium. The injected heat and temperature variation with the heat pump unit is approximately twice compared with those without the heat pump unit. Additionally, the heat injected via boreholes is around 40 W/m. This result indicates that the cooling capacity of the direct cooling system can cover the heat demand for SC in the residential house in Sapporo, which is generally estimated 3~4 kW, if the borehole length is 100 m.

### 3.2 Heating operation

Figure 13 show variations of temperatures and flow rates of each part on Jan. 17th 2008. In the lower part of Figure 13, it shows that the temperatures in primary side become lower during the operation. However, the system safety operates since the minimum temperature of T-1 is larger than 0 $^{o}$C. The temperatures T-3 during operation are 30~35 $^{o}$C and they are smaller than those of the 1st year's operation in the previous report. The reason is that the condition of operating the gas boiler was changed as shown in Figure 5.

Shown in Figure 14 are variations of heating output from the GSHP unit, extracted heat from the ground, and electric power consumption of the compressor on Jan. 17th 2008. The heating output of the GSHP system is around 60 kW for 9 am ~ 1 pm, around 50 kW for 1 pm ~ 6 pm, around 30 kW for 6 pm ~ 10 pm, respectively. The extracted heat is kept at around 45 kW when the heating output is around 60 kW.

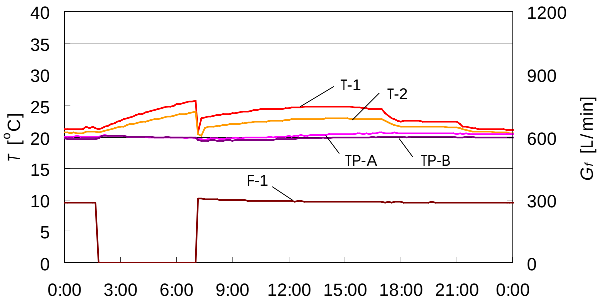



**Figure 6: Variations of temperatures and flow rates of each part on Aug. 9th 2006 (In primary side)**

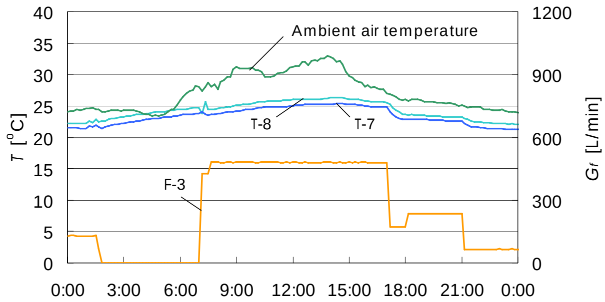



**Figure 7: Variations of temperatures and flow rates of each part on Aug. 9th 2006 (In secondary side)**

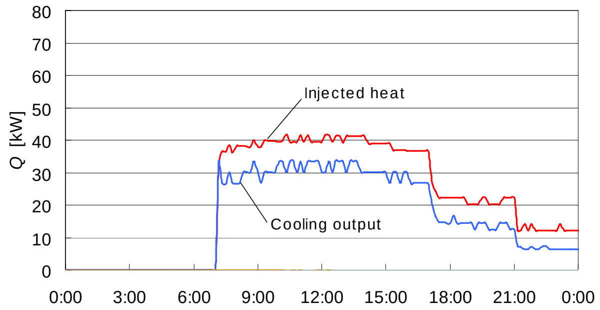



**Figure 8: Variations of cooling output and injected heat Aug. 9th 2006**

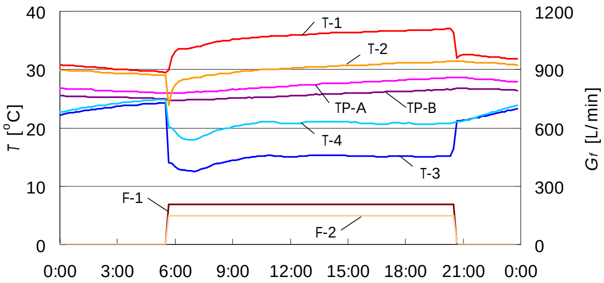



**Figure 9: Variations of temperatures and flow rates of each part on Aug. 8th 2007 (In primary side)**

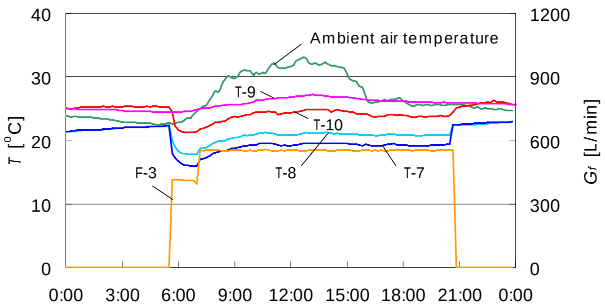



**Figure 10: Variations of temperatures and flow rates of each part on Aug. 8th 2007 (In secondary side)**

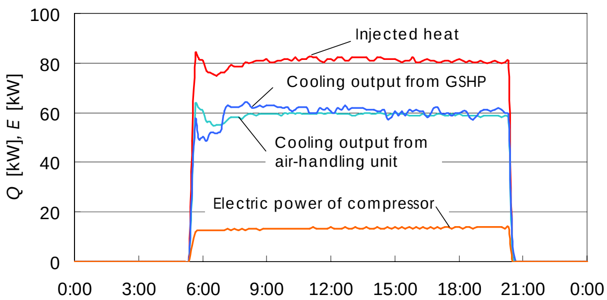



**Figure 11: Variations of cooling output, injected heat, and electric power on Aug. 9th 2006**

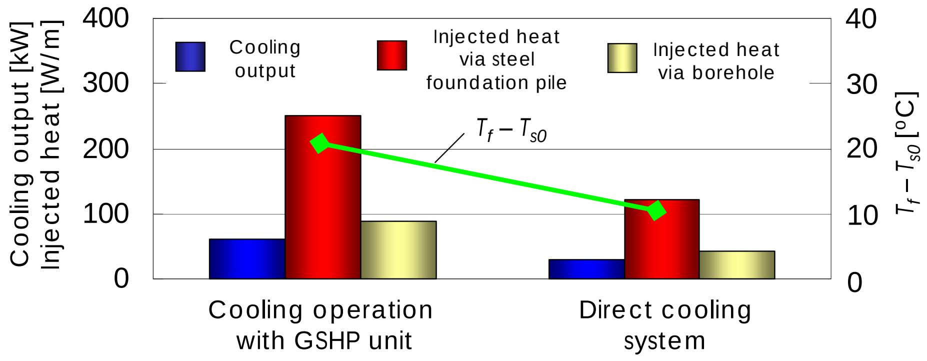



**Figure 12: Comparison of cooling operation with and without heat pump unit**

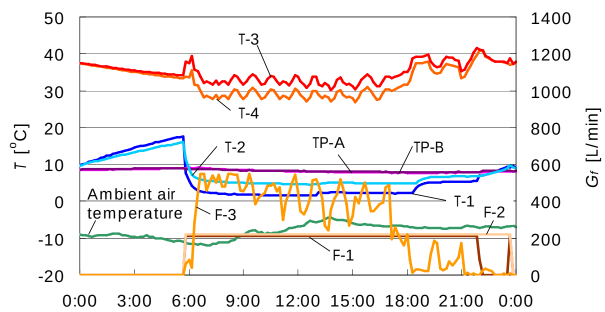



**Figure 13: Variations of temperatures and flow rates of each part on Jan. 17th 2008**

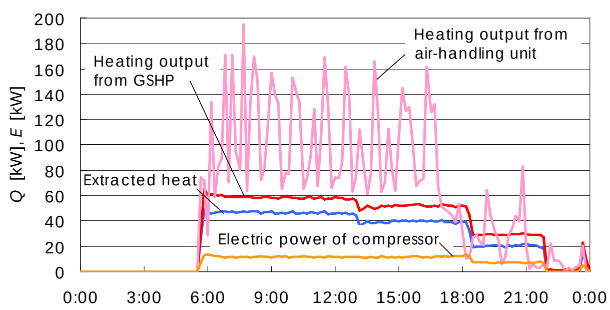



**Figure 14: Variations of heating output, extracted heat, electric power on Jan. 17th 2008**

# 4 ANALYSIS OF GROUND SOURCE HEAT PUMP SYSTEM

## 4.1 Seasonal Performance

### 4.1.1 Cooling operation

Figure 15 indicates seasonal energy balances of the GSHP system during cooling period in the first and second year. This includes total amount of the heat injected to the ground, cooling output, and electric power consumption of the compressor and circulation pumps. Average COP and system COP are also shown in Figure 15. The injected heat in the second year is approximately 54,000 kWh and 2.6 times compared to the one in the first year. The value of system COP (SCOP) including electric power of the circulation pumps in the second year is larger than that in the first year. This is due to improving operation of the circulation pumps.

### 4.1.2 Heating operation

As the result of heating operation, seasonal energy balances of the GSHP system in the first and second year are shown in Figure 16. Both of the periods to evaluate the GSHP system are set from Oct 12th to Jan 31st for the comparison. Total amounts of heat extracted from the ground and heating output of the GSHP system in the second year are lager than those in the first year. This is caused by change of the operating condition of the GSHP system and increase of total heating output because of lower ambient air temperature in the second year drawn in Figure 17. The value of COP in the second year is little better. The lower temperature T-3 in the second year, which is outlet temperature in the secondary side of the heat pump unit, brings it. With regard to SCOP, the second year is better then the first year. The reason is similar to that during cooling period.

## 4.2 Temperature variation in steel foundation pile

Since the injected heat during cooling period in the second year is larger than that in the first year, temperature in the steel foundation pile (= (TP-A + TP-B) / 2) from June to September in the second year becomes lager as shown in Figure 17. However, the temperature after November in the second year is nearly equal to the one in the first year. This is because the ground water flow removes the heat injected during cooling period in this short term. The ground water advection also yields the temperature recovery from April to May 2007. As the result, it is expected the GSHP system in this building can operate with high efficiency for long term like the first year even if the heat extraction or injection is not excessive larger than the other side.

## 4.3 Performance and installation effect

By using the result of the second year's heating operation (Oct. 12th, 2007 ~ Jan. 31st, 2007), $CO_2$ emission and running cost generated by the GSHP system operation are estimated. Conversion factors in Table 1 are used for this estimation. Then, the GSHP system is compared with conventional systems, which are a gas boiler and oil boiler system. Here, efficiency of these boiler systems is set at 0.85. Figure 18 shows comparisons of annual $CO_2$ emissions and annual running costs of the GSHP system with conventional systems. $CO_2$ emission of the GSHP system is 8.8 tons and it is indicated that the GSHP system can reduce 40 % of $CO_2$ emission compared to the gas boiler system. The GSHP system's running cost is less than half of the gas boiler system and oil boiler system.

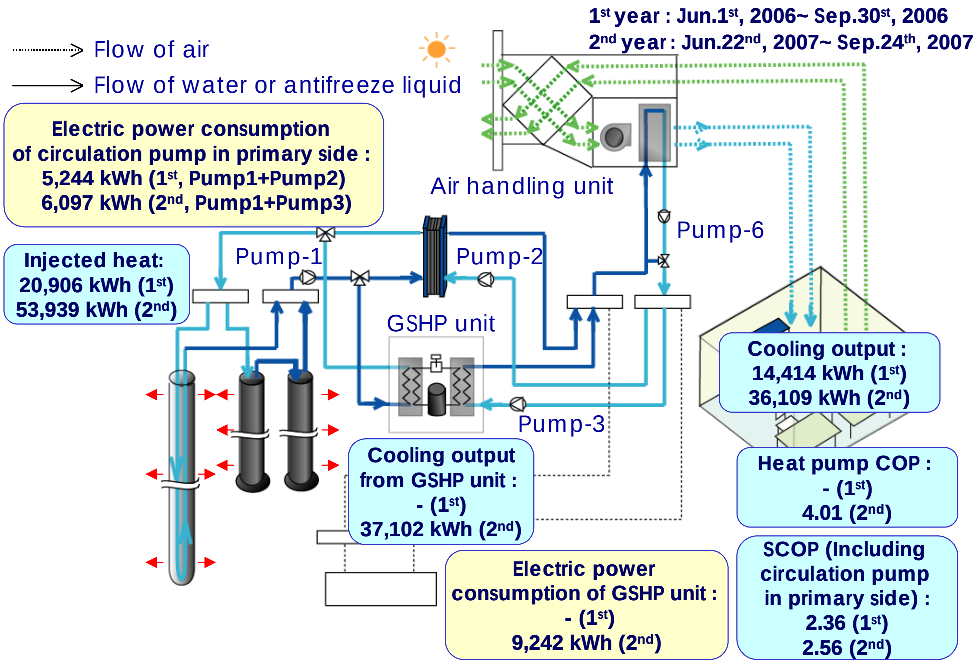



**Figure 15: Seasonal energy balance of GSHP system (During cooling period)**

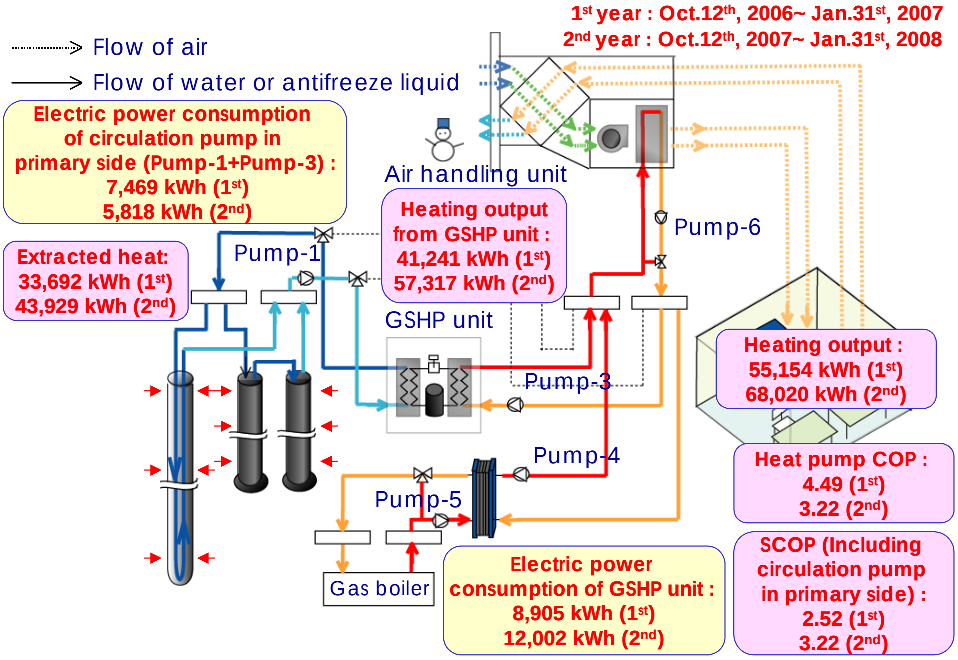



**Figure 16: Seasonal energy balance of GSHP system (During heating period)**

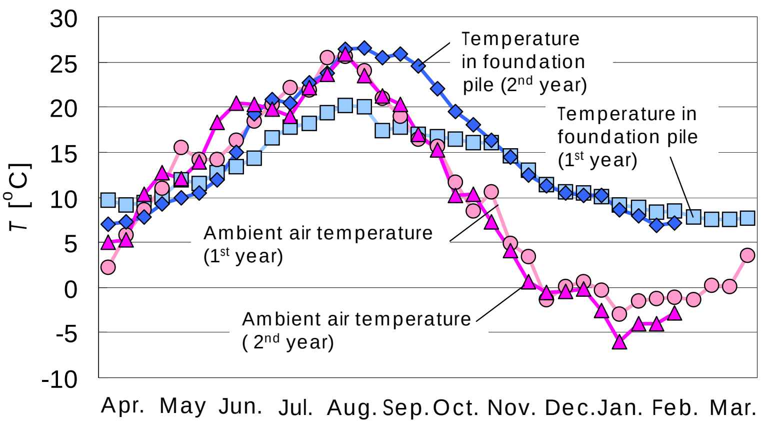



**Figure 17: Variations of ambient air temperatures and temperatures in steel foundation pile in annual**

**Table 1: Conversion factors for estimation of $CO_2$ emission and running cost**

| | Primary energy consumption [MJ] | $CO_2$ emission [kg-$CO_2$] | Charge: Basis rate [JPN/month] | Charge: Unit cost [JPN] |
|---|---|---|---|---|
| Erectric power (Heat pump) [/kWh] | 9.42 | 0.48 | For three months : 1060<br>Others : 270 | 7.67 |
| Erectric power (others) [/kWh] | | | 1,700 | 11.24 |
| Gas [/m³] | 41.1 | 2.1 | Flat rate :2500 Unit rate :1100 | 90.21 |
| Oil [/L] | 36.7 | 2.5 | 0 | 100 |

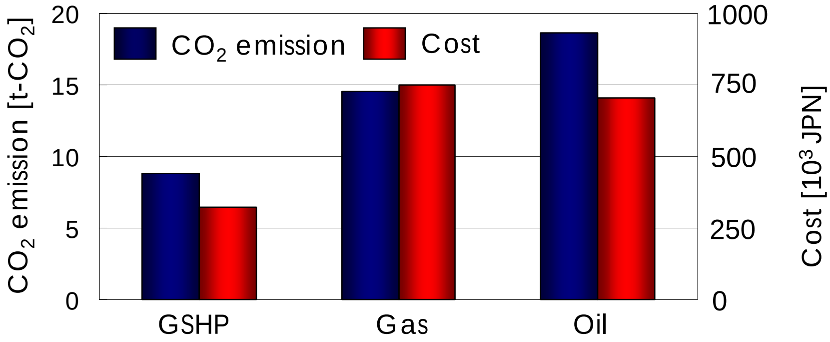



**Figure 18: Comparison of annual $CO_2$ emissions and running costs**

## 5 CONCLUSIONS

1) The authors introduced outlines of the GSHP system with steel foundation piles. Also, proceeding of the design by using a design tool was described.
2) The GSHP system operation for two years was analysed. As the results, the followings were obtained.

   1. The maximum cooling outputs with and without a heat pump unit as a refrigerator were around 60 kW and 30 kW, respectively.
   2. The rate of heat injected via steel foundation piles during cooling operation with a heat pump unit was estimated approximately 250 W/m at the maximum.
   3. In the heating operation, the minimum temperature of thermal medium was higher than 0 $^{o}$C. This result indicated that the GSHP system in the second year operated safety as well as in the first year.
   4. It is expected the GSHP system in this building can operate with high efficiency for long term due to the ground water flow even if the heat extraction or injection is not excessive larger than the other side.
   5. The GSHP system reduces 40 % of $CO_2$ emission compared to the gas boiler system throughout the heating period. Additionally, the running cost is less than half of the gas boiler system and oil boiler system.

## 6 REFERENCES

Katsura T, K. Nagano, S. Takeda, T. Ibamoto, S. Narita, Y. Nakamura, N. Homma 2006 “Development of a Design and Performance Prediction Tool for the Ground Source Heat Pump System,“ Proceedings of 10th Energy Conservation Thermal Energy Storage Conference Ecostock’2006, New Jersey

Katsura T, K. Nagano, S. Takeda, T. Ibamoto, S.Narita, Y. Nakamura, S. Nakamura, Y. Tanaka 2006 “A Geothermal Heat Pump System Using Steel Foundation Piles as Ground Heat Exchangers,” Proceedings of Renewable Energy 2006, P-G-8, Chiba

Katsura T, K. Nagano, S. Takeda, T. Ibamoto, S.Narita, Y. Nakamura 2007 “Development of a Design and Performance Prediction Tool for the Ground Source Heat Pump System and Underground Thermal Energy System, ” Proceedings of CISBAT 2007, Lausanne

Katsura T, K. Nagano, S. Takeda, S. Hori, T. Ibamoto, Y. Nakamura, T. Kotani, M. Sekiyama, A. Saito 2007 “Design and actual measurement of a ground source heat pump system using steel foundation piles as ground heat exchangers, " Proceedings of CISBAT 2007, Lausanne

Katsura T, K. Nagano, S. Takeda 2008 "Method of Calculation of the Ground Temperature for Multiple Ground Heat Exchangers," Applied Thermal Engineering, Applied Thermal Engineering 28

Nagano K, T. Katsura, S. Takeda, E. Saeki, Y. Nakamura, A. Okamoto, S. Narita 2005 "Thermal Characteristics of Steel Foundation Piles as Ground Heat Exchangers," Proceedings of 8th IEA Heat Pump Conference 2005, P6-12, Las Vegas

Nagano K, T. Katsura, S. Takeda 2006 "Development of a Design and Performance Prediction Tool for the Ground Source Heat Pump System," Applied Thermal Engineering, Volume 26, Issues 14-15, pp.1578-1592

Takashi T 1962 "A Study of Underground Thermal Energy Usage as the Heat Source of Heat Pumps," Transactions of the Japanese Association of Refrigeration, No.37, pp.1-17, (in Japanese)

## 7 ACKNOWLEDGEMENT

The authors are grateful to Former Guest Prof. T. Ibamoto and Former Guest Assoc. Prof. S.Narita in the laboratory of ground thermal energy system of corporate donated chair in Hokkaido University, Nippon Steel Corporation, Hokkaido Electric Power Co., Inc, and Sunpot Co. Ltd. We also would like to thank to S.Nakamura, Y. Tanaka, T. Kotani, M. Sekiyama, and A. Saito of Sapporo city government.

## NOMENCRATURE

$E$: Heating output [W], $G$: Flow late [m$^3$/s], $Q$: Heating output [W], $T$: Temperature [$^o$C], $t$: Time [h]

Subscript

$f$: Thermal medium, $S0$: Soil Initial ($t$ = 0 h)