EVALUATION OF BOREHOLE GSHP PERFORMANCE FOR GREENHOUSE IN JAPAN

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Abstract: A ground source heat pump (GSHP) system with 78 boreholes has been installed in huge existing orchid greenhouses in Akabira city in Hokkaido. Two GSHP units with the same characteristics have been set up simultaneously to work in this system. To evaluate the performance of the system, temperature, electricity consumption and flow rate were measured from Oct.1st 2010 to Dec.31st in 2010. The results obtained showed that the average heat extraction rate of the system was about 35W/m of borehole length, and average temperature declined 5°C. COP and SCOP were 3.0 and 2.7, respectively.

Key Words: Ground Source Heat Pump System, borehole, greenhouse

1 INTRODUCTION

GSHP system has been widely used in residential houses, office buildings and greenhouses as a sustainable technology, because of the low energy consumption, low CO_2 emission and high efficiency compared with conventional heating and cooling systems. The huge GSHP system composed by 78 boreholes in Akabira city of Hokkaido was built for orchid greenhouses to provide cooling in summer and heating in winter. This project is an attempt to operate a large borehole field GSHP system in Japan, since its results will provide valuable experiences for designing and operating similar systems in the future. Moreover, the data obtained from the operation will provide useful references for the operation of the large GSHP system not only in cold regions but also in warm ones. In this article the configuration of the borehole field heat exchanger and GSHP system is introduced, as well as a monitoring and analysis of some parameters of seasonal operation from Oct.1 and Dec.31.

2 GREENHOUSE SYSTEM DESCRIPTION

2.1 Greenhouse and borehole heat exchanger

The greenhouse located in Akabira, a small city in the middle of the Hokkaido. Annual climate condition varies from the highest about 30°C in Aug. to the lowest -16°C in Dec. with a snow cover lasting for around 5 months, from Nov. to March.

The greenhouse and borehole's arrangement is shown in Figure 1.The twelve greenhouses were located into two columns, where each greenhouse has the total area of about 450m^2. Different types of orchids are cultivated inside the greenhouses all year round. GSHP system was applied as heating and cooling system to provide a proper temperature environment (about 20°C) for orchid growth.

The borehole system, which consists of 78 boreholes with depths of 85m and diameters of 125mmΦ, has been recognized as the biggest one in Japan. The total length of the boreholes was 6,630 m. 25 A single U-tubes has been equipped as ground heat exchanger in each borehole. Figure 3 shows the arrangement of the boreholes that was done into 6 lines (13 boreholes for each), with intervals of 4 m. Six observation wells were drilled along the borehole as shown in Fig.3. Three wells are used for temperature observation. Well 3 is located inside the borehole field while wells 2 and 6 are located outside. The other wells (1,4 and 5) are used for temperature and water level observation. Thermal couples were installed in each well at depths of 10 m, 20 m, 40 m and 85 m.

Regarding to soil properties, mudstone formation appeared under around 20m from the ground level, and sand covered up it. Effective thermal conductivity λ_s measured from the thermal response test was 1.5W/(m.K). In addition, the measured ground temperature was 10.5°C.

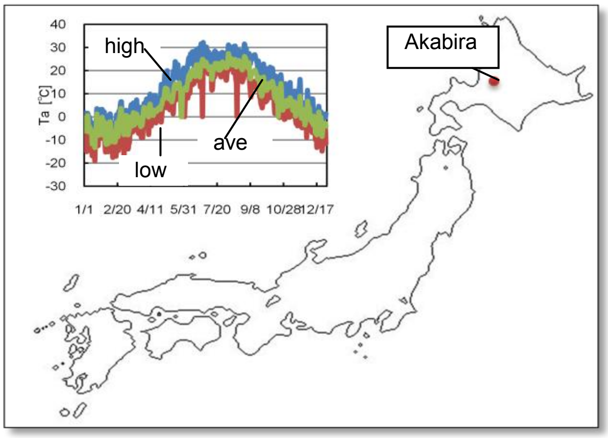

Figure 1: Location of Akabira

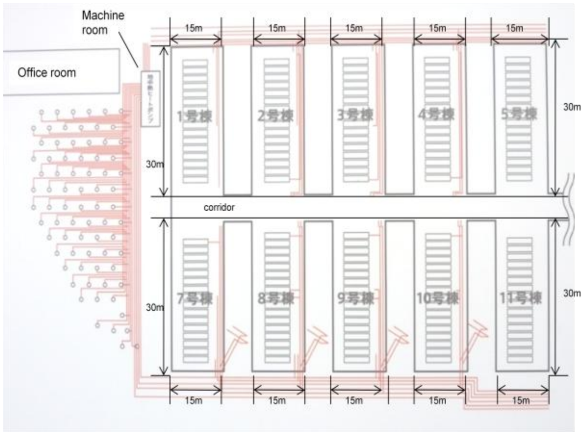

Figure2: greenhouse and borehole distribution

2.2 GSHP system description

The GSHP system configuration is shown in Figure 4. Two large GSHP units (HP1 and HP2) with 135 hp (horse power) of each has been used, and they produce total heating output of about 640 kW. Each large unit has three identical GSHP units with an individual 45 hp connected with each line, consist of 13 boreholes; therefore one large GSHP unit consisted of 39 boreholes as the primary side. The water in the tank (4,000m^3) is circulated inside the greenhouses through a piping system where the final heat exchange is done with the close environment.

Temperature sensors (Pt100) were installed to measure the inlet and the outlet temperature of the HP, as electromagnetic flow meters were settled to monitor flow rates at different positions as shown also in Figure 4.

The GSHP system for heating operation is controlled by the tank water temperature. When the temperature is below 50°C, the HP will work while when its over 50°Cit will stop. Water entering the greenhouse through the piping system was around 39°C(measured at T_{2o}) and return temperature (measured at T_{2in}) was around 36°C, when the system is functioning. The temperature difference between T_{2o} and T_{2in} effect the heat released to the greenhouse.

3 DAILY PERFORMANCE OF GSHP SYSTEM

The GSHP system was operated under 3 different modes from the beginning of Aug. The first mode started from Aug. 1st to Sept. 8th when both HP units worked in cooling mode. The second mode started from Sept. 9th to Sep. 23rd when HP2 turned to heating mode, while HP1 continued in cooling mode. And the third mode started from Sep.23rd when both of the units worked in heating mode. By the end of the Oct., the outside temperature was around 5°C, at which point both units started working continuously for almost the whole day. The data analysed in this paper correspond to the third mode from Oct.1st to Dec.31st.

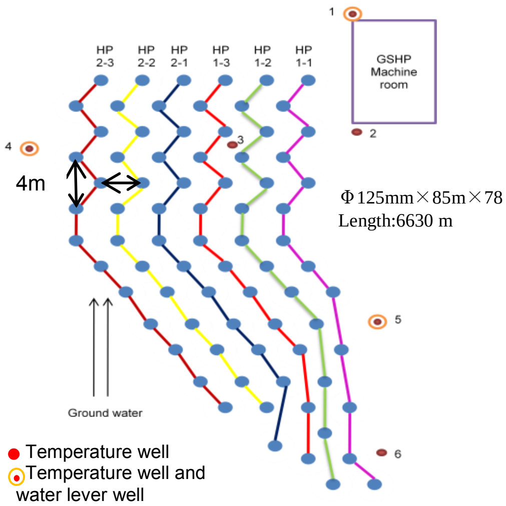

Figure3: layout of boreholes

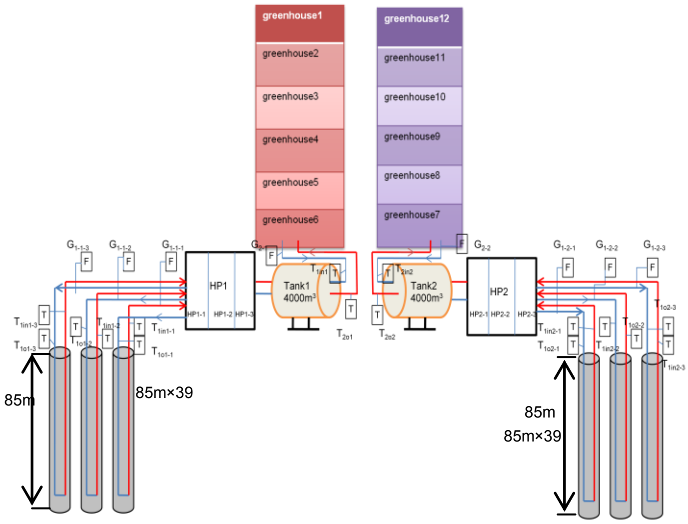

Figure4: GSHP system configuration

To demonstrate the performance of the system, the data from the coldest day registered during the operation (Dec.26th,-15°C) was analysed.

Figure 5 shows HP1 data results in Dec. 26th. It can be seen in the bottom the outdoor temperature of the day, the temperature variation in the primary side (T_1), secondary side (T_2), as well as the greenhouse (T_r). The top shows the electrical consumption of the compressor (E_{hp1}), extracted heat (Q_{1-1}) as well as COP and SCOP. Because the normal operation of the heat pump stops every hour, small variations can be observed every time the system restarts. Outdoor temperature (T_a) varies from lowest as -15°C around 7 am to highest as 3°C at 12 am. Average inlet temperature of primary side was-1.2°C.During the cooling period, heat is injected in the ground and the highest temperature gradient is located around the middle, where HP1-3 is located. Therefore, the primary side temperature of these boreholes ($T_{1in1-3,}T_{1in1-2}$)was higher than the HP1-1 (T_{1in1-1}). Additionally, average supply temperature T_{2o1} in the secondary side was kept around 40.6°C, with an average return temperatureT_{2in1}kept around 38.7°C. Greenhouse temperature was good maintained at 20°C. Flow rate in the primary side was about 260 L/min for each small HP, and in the secondary side it was approximately 800L/min during operation.

Regarding to the heat balance of HP1, heat output to the greenhouse Q_{2-1} was about 126 kW, extracted heat by HP1-1.HP1-2 and HP1-3 was about 32.9kW,30.7kW, 33.9kW respectively, which was calculate by equation (1). Electrical consumption of compressor was about 60kW. It was found that there was no temperature sensors installed in the secondary side of the HP system directly(as shown in Fig.7), so released heat to the greenhouse is lower than real released heat by the HP. Based on this, COP1 and SCOP1were calculated from the extracted heat of primary side and electricity consumption of compressor indirectly through equation (2) and equation (4). They were about 2.7 and 2.5 respectively.

Figure 6 shows HP2 data results in Dec.26th. As the same with Figure 5, the outdoor temperature (T_a) of the day, the temperature variation in the primary side (T_1), secondary side (T_2) as well as greenhouse temperature (T_r) was shown in the bottom, while the top was the electrical consumption of the compressor (E_{hp2}), extracted heat (Q_{1-2}) and COP, SCOP. System stopped for a while in the middle of the day when the outside temperature rose to about 0°C as shown, however, greenhouses temperature was still around 20°C. Average primary side inlet temperatures were from -3.6°C to -0.9°C.T_{1in2-1} of HP2-1 was higher than T_{1in2-2} of HP2-2 and T_{1in2-3} of HP2-3 especially, this was supposed to the same reason with that of $T_{1in1-3.}$ as explained before. In the secondary side, average supply temperature T_{2o2} and average return temperature T_{2in2} was kept about 38.2°C and 34.7°C respectively. Flow rate in the primary side was around 720L/min, while, it was about 980 L/min in the secondary side which was much higher than that of HP1.

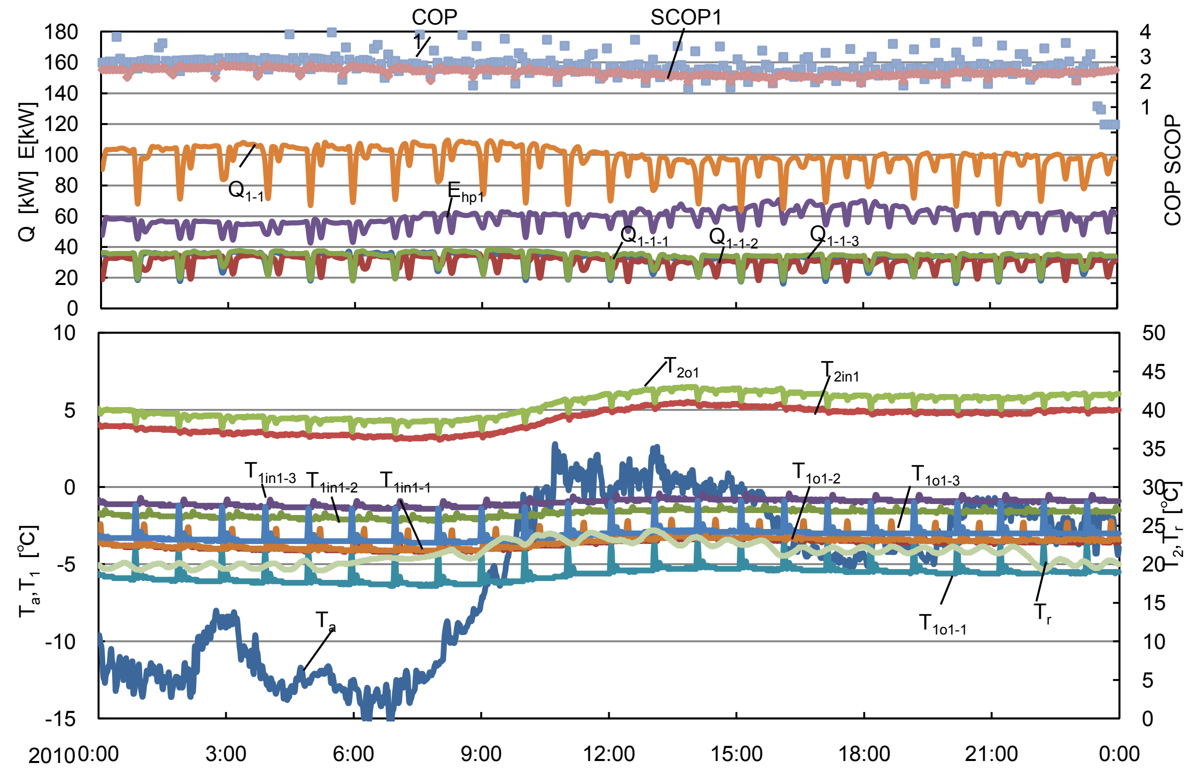

Figure5: Variations of heating output, extracted heat, electricity consumption and temperature of HP1 on Dec.26th 2010

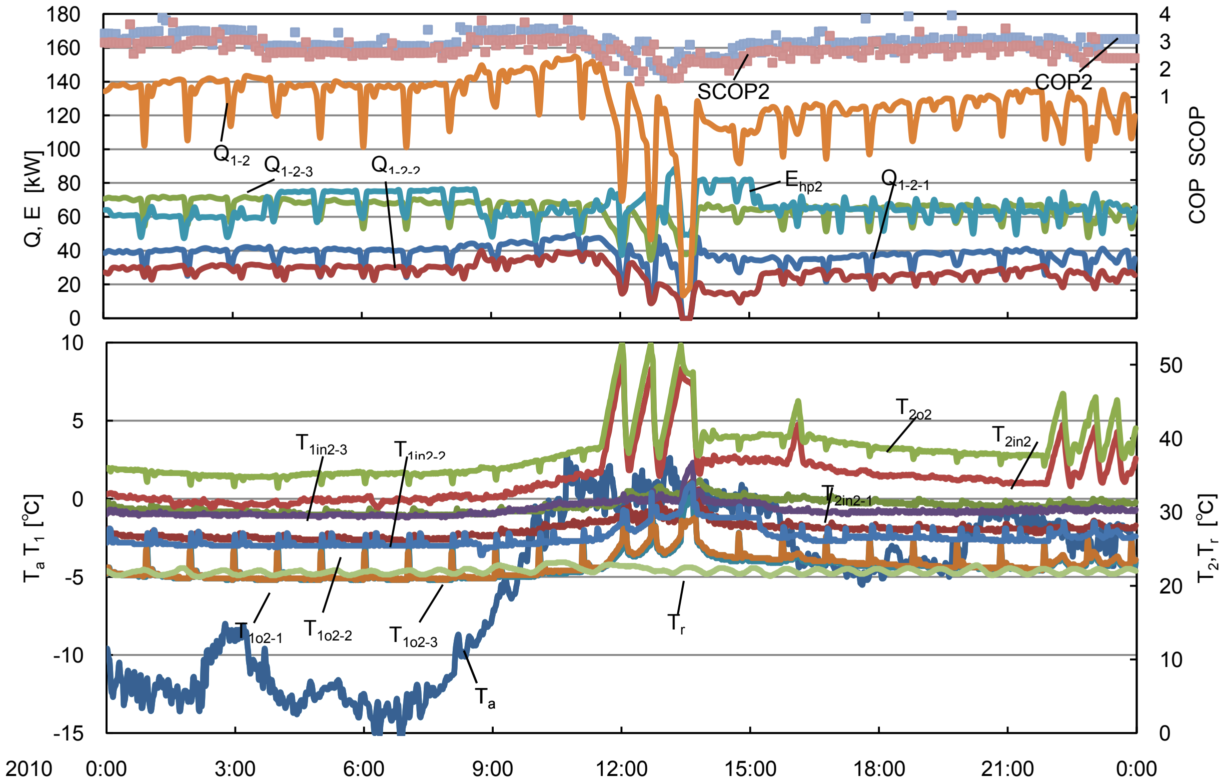

Figure6: Variations of heating output, extracted heat, electricity consumption and temperature of HP2 on Dec.26th 2010

Average extracted heat by HP2-1, HP2-2 and HP2-3was approximately 37.6 kW, 27.0 kW and 64.7 kW respectively, while extracted heat from HP2-2 was found rather low and HP2-3 was relatively high, that was caused by different temperature difference between inlet and outlet in the primary side. Electrical consumption of the compressors was about 59 kW. Regarding to COP2 and SCOP2, which were calculated from equation (3) and equation (5) were about 3.1 and 2.7 respectively.

Definition of COP and SCOP are as follows

$Q_1=C_b \times \rho \times \Delta T \times G_1$ (1)
$COP1=(Q_{1-1-1}+Q_{1-1-2}+Q_{1-1-3}+E_{HP1})/E_{HP1}$ (2)
$COP2=(Q_{1-2-1}+Q_{1-2-2}+Q_{1-2-3}+E_{HP2})/E_{HP2}$ (3)
$SCOP1=(Q_{1-1-1}+Q_{1-1-2}+Q_{1-1-3}+E_{HP1})/(E_{HP1}+E_{cP1})$ (4)
$SCOP2=(Q_{1-2-1}+Q_{1-2-2}+Q_{1-2-3}+E_{HP2})/(E_{HP2}+E_{cP2})$ (5)
Q_{1-1-1},Q_{1-1-2},Q_{1-1-3}:Extracted heat from HP1-1, HP1-2,and HP1-3;
Q_{1-2-1},Q_{1-2-2},Q_{1-2-3}:Extracted heat from HP2-1, HP2-2,and HP2-3;
E_{HP} :electrical consumption by compressor;
E_{cp}:electrical consumption by circulation pump ;
C_b:Specific heat of brine;ρ:density of brine. G:flow rate in the primary side

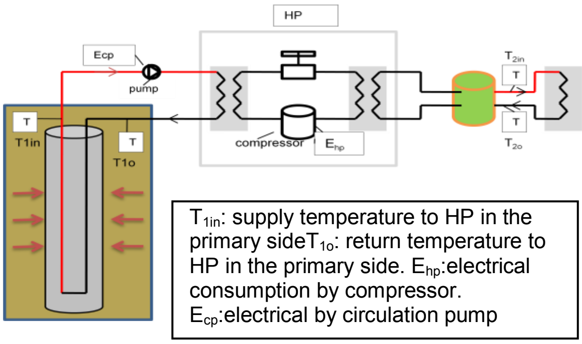

Figure 7: system principle diagram

4 ANALYSIS OF GROUND SOURCE HEAT PUMP

4.1 Seasonal Heating Operation

It is seen that HP1 worked continual and stable from Nov. in figure 8. Primary side inlet temperatures decrease from 4°C to about -2°C after 4 months operation. Average inlet temperature of the three was about 0.14°C.Due to the cooling in September, heat was rejected to the ground, which increased the ground temperature we can find from figure 10 that at the beginning of Oct, the ground temperature has an average of about 8°C to 9°C.there are bigger temperature difference between ground and T_{1out} ,so at the beginning temperature decreased faster as shown in Figure 8 that the temperature in Oct.1st to Oct.31st were changed greatly from other periods. Supply water to the greenhouse kept around 41.5°C, while return temperature kept around 39.6°C. Regarding to the heat balance, average extracted heat by each small HP in HP1 unit was approximately the same, with the value of about 35 kW. Electrical consumption of HP1 unit was about 60kW. Average COP and SCOP was around 3.1 and 2.8, respectively, however, both of them decreased with continuous operation by the reduction of extracted heat. At Oct. heating demand from the greenhouse is less than the other month, so GSHP system didn't work on the whole day, so the COP and SCOP is stable. Flow rate in primary side was 780L/min, while it was 800L/min in Oct. and Nov. and 1000 L/min in Dec. in secondary side.
HP2 worked not as stable as HP1seen from figure 9. Since small fault of the system happened at the beginning of Dec. data during this period was not included in this article. Average primary side inlet temperatures decrease from around 3°C to about -1°C during operation. Average inlet temperature of the three was about 0.37°C. Supply water to the greenhouse was kept around 41°C, while return was around 37.5°C. Extracted heat was about 60kW by HP2-3, which caused by high flow rate and temperature difference between inlet and outlet, while extracted heat by HP2-2 went to the contrary side was only 25kW due to low flow rate and temperature difference, it was about 35kW by HP 2-1, almost the same as in HP1. Flow rate in the primary side was about 710L/min, and 1000L/min at the secondary side. It has an average COP and SCOP 2.8 and 2.6, respectively. At Oct. COP and SCOP is not stable with caused by the same reason with HP1 explained before. However, they increased gradually during heating operation and reached to about 3.3 and 3.0 respectively.

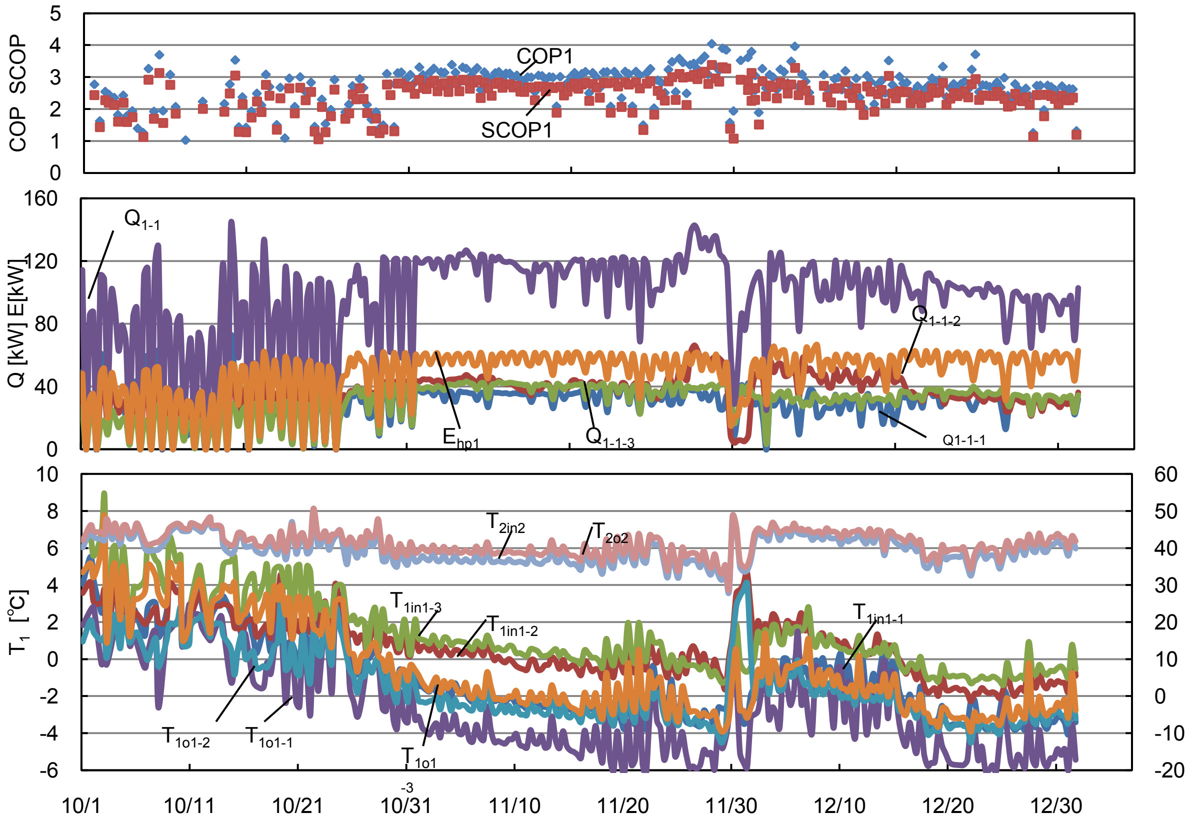

Figure8: Variations of heating output, extracted heat, electricity consumption and temperature of HP1 during seasonal operation

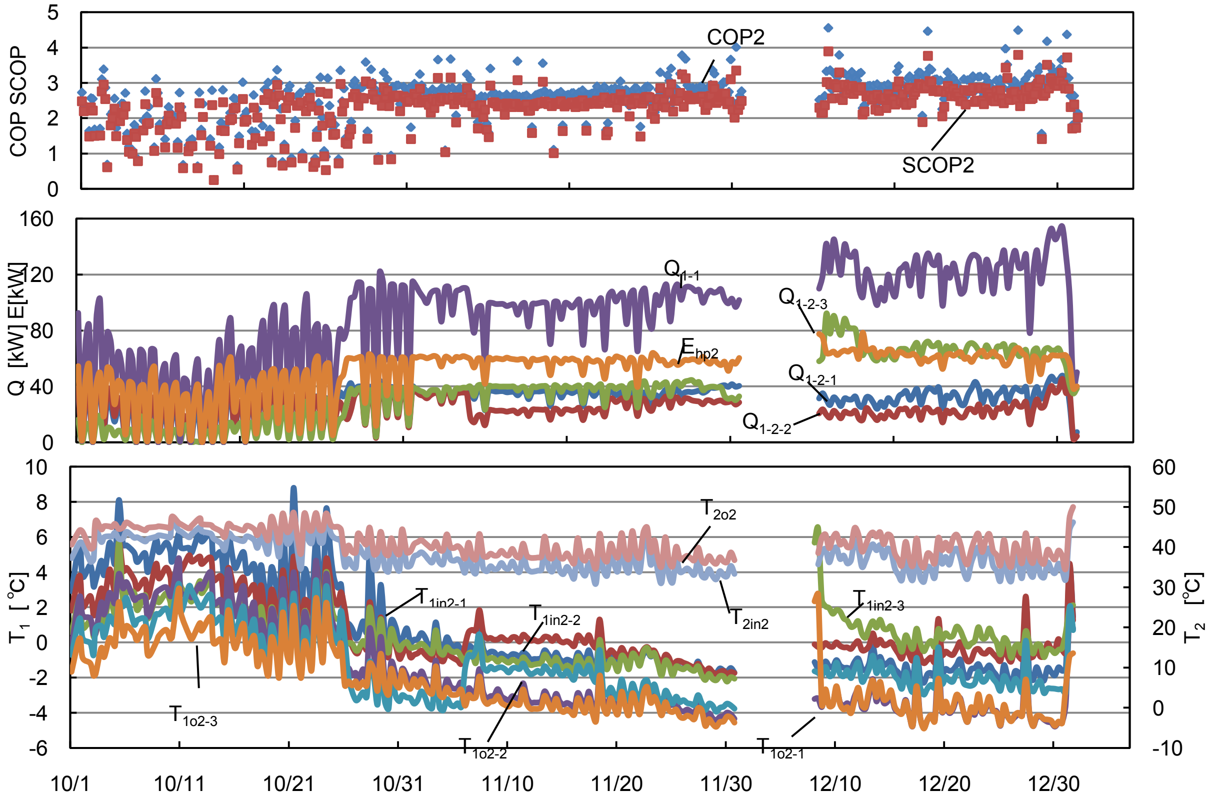

Figure9: Variations of heating output, extracted heat, electricity consumption and temperature of HP2 during on seasonal operation

4.2 Temperature variation in the ground

The ground temperature variation during system operation could be good reflected from the temperature distribution in observation well 3 (shown in Figure 10) which was located inside of the borehole field. At the beginning of Oct. ground temperature at 4 different depths was around 8°C-9°C, however, they declined to about 3°C after heating operation, about 5°C -6°C declined by heat extraction. Temperature at the depth of -10m,-20m and -40m decreased affected by increasing amount of extraction of HP according to temperature decrease. Greenhouse temperature was shown in Figure 10 as well presented by T_{r1} (greenhouse 1) and T_{r8}(greenhouse 8).

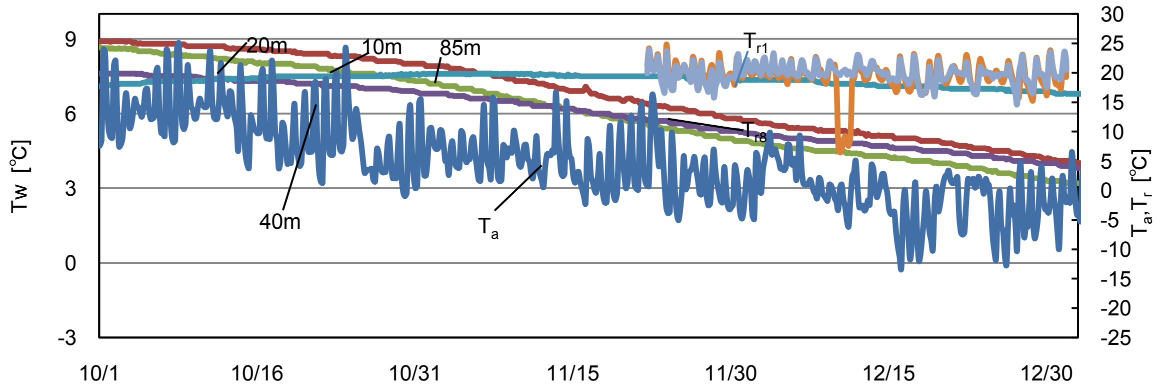

Figure10: temperature of outside as well as in well3

Table 1: Heat balance of HP1 during heating season

	E_{cp1} (MWh)	E_{HP1} (MWh)	Q_{1-1} (MWh)	$\overline{T}_{1in}$ (°C)	$\overline{T}_{2out}$ (°C)	COP1	SCOP1
Oct.	3.37	26.89	55.33	2.39	43.10	3.06	2.72
Nov.	4.89	39.16	82.13	-0.63	38.87	3.10	2.75
Dec.	3.95	39.80	72.50	-0.71	41.96	2.82	2.53
Total	12.3	105.85	209.6	0.35	41.33	3.00	2.67

Table 2: Heat balance of HP2 during heating season

	E_{cp2} (MWh)	E_{HP2} (MWh)	Q_{1-2} (MWh)	$\overline{T}_{1in}$ (°C)	$\overline{T}_{2out}$ (°C)	COP2	SCOP2
Oct.	2.97	26.86	44.37	2.59	43.76	2.65	2.39
Nov.	4.65	41.67	71.32	-0.77	38.73	2.71	2.44
Dec.	3.78	45.17	82.40	-0.38	39.92	2.82	2.66
Total	11.41	113.70	198.09	0.48	40.80	2.73	2.50

it is found that the temperature in the greenhouse kept around 20°C all the time which ascribe to the continues work of GSHP.

5 CONCLUSIONS

A borehole GSHP system for heating and cooling in Akabira greenhouses was introduced in this paper. The system performance during heating mode was evaluated by seasonal data analyse. The followings are the conclusions obtained.

1) The average heat extraction rate during heating operation and seasonal operation with a heat pump was calculated around 35 W/m, 28 W/m of borehole length, respectively.

2) Extracted heat through boreholes was about 408MWh while ground temperature decreased about 5°C seen from Figure 6, which means that 81.6MWh heat is needed for per temperature recovery.

3) Temperature difference between supply and return pipes in the secondary side of HP1 unit was only 2°C, which was mainly caused by rapid flow rate, so a low flow rate of water circulation in the greenhouses piping system is expected to increase temperature difference in order to save energy consumption for circulation.

4) The performance of the GSHP system was found to be between 2.7 to 3.1 for COP, whereas it was between 2.5 and 2.78 for SCOP. They are lower than the expected values from the factory data (about 3.5). So some modification of the HP units, such as checking of appropriate filled refrigerant amount, control of expansion values, as well as cleaning heat exchanger, are needed in order to improve the performance.

5) Depending on the temperature of the greenhouse and outside environment, heating energy from HP units can keep greenhouse at 20°C shown from Figure 10.

6 REFERENCES

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NOMENCRATURE

T	Temperature [°C]	E	Electricity consumption of compressor in HP [kW]
Q	Extracted heat or released heat [kW].		

Subscript

1in	primary side into HP	1-1-1	primary side of first small HP in HP1
1o	primary side out of HP	1-1-2	primary side of second small HP in HP1
2in	secondary side into the HP	1-1-3	primary side of third small HP in HP1
2o	secondary side out of HP	1-2-1	primary side of first small HP in HP2
1-1	primary side of HP1	1-2-2	primary side of second small HP in HP2
1-2	primary side of HP2	1-2-3	primary side of third small HP in HP2
2-1	secondary side of HP1	2-1-1	secondary side of first small HP in HP1
2-2	secondary side of HP2	2-1-2	secondary side of second small HP in HP1
a	outside	2-1-3	secondary side of third small HP in HP1
b	brine	2-2-1	secondary side of first small HP in HP2
2-2-2	secondary side of second small HP in HP2		
2-2-3	secondary side of third small HP in HP2		