PERFORMANCE TEST AND FEASIBILITY STUDY OF INTEGRATED GROUND SOURCE HEAT PUMP FOR LOW ENERGY HOUSE

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Abstract: This study aims at development of integrated heat pump systems, which can operate for space heating (SH), space cooling (SC), and domestic hot water (DHW) with higher efficiency. In this paper, the authors introduce performance test and feasibility study of the integrated ground source heat pump (GSHP). The GSHP unit has a de-superheater and it can generate two types of hot waters with different temperature level, which is used for SH and DHW. First, performance test of the prototype integrated GSHP unit was carried out. Then, the approximate equations to evaluate the COP and heating output were obtained. Next by simulation of the GSHP system operation in annual, it was confirmed that the GSHP system with the integrated GSHP unit can satisfy the whole heat demand including for SH, SC, and DHW. Additionally, approximate 50% of CO_2 emission can be reduced by installing the GSHP system.

Key Words: ***Integrated Ground Source Heat Pump, Low Energy House, De-superheater, Performance Test, System Simulation***

1 INTRODUCTION

Installation of the heat pump system for space heating (SH) and space cooling (SC) of the low energy house, which has high performance of thermal insulation and air tightness, is effective for energy saving and reduction of CO_2 emission. In the heat pump designing process for such the low energy house, it is important to consider the domestic hot water (DHW) supply as well as the heating and cooling. The reason is that proportion of energy consumption for DHW in the total energy consumption is higher. In these days, integrated heat pump units for residential SH, SC, and DHW have been commercialised. However, air source heat pump (ASHP) system cannot operate with high efficiency in the cold region due to defrosting operation. Thus, heat pump systems require utilizing other heat sources such as ground heat, exhausting heat, solar heat, etc.
The authors have developed an integrated ground source heat pump (GSHP) unit for residential house. This unit can utilize the ground heat and it has some advantages described below:

1. All-in-one package unit including a compressor, circulation pumps, expansion tanks, etc
2. Inverter driven compressor supplies variable heating (or cooling) output according to heat demand
3. A de-superheater can generate two types of hot waters with different temperature level for SH and DHW at the same time
4. Partial load characteristics of the heat pump unit might provide higher energy efficiency

5. Only one heat pump might reduce installation cost of the GSHP system

By simulation with a design tool for the GSHP system, the authors demonstrate that whole heat demand of SH, SC, and DHW of a residential house in cold region can be satisfied by the GSHP system with the integrated heat pump unit. First, the authors conduct performance test of the prototype integrated GSHP unit and investigate the COP and heating output (for SH, DHW, and Total) according to the inlet and outlet temperature, flow rate of water for DHW, and compressor revolution speed. Then, approximate equation to estimate the COP and heating output, which is obtained by the performance test, is installed in the design tool. In addition, the GSHP system operation in annual is simulated when the GSHP system is installed in the low energy house in Sapporo city. Finally, reduction effect of CO_2 emission by installing the system is estimated from the result of the performance in annual.

2 PERFORMANCE TEST OF INTEGRATED GROUND SOURCE HEAT PUMP UNIT

2.1 Performance test apparatus and heat pump unit

Figure 1 and Figure 2 shows appearance and schematic diagram of performance test apparatus and a prototype integrated GSHP (water-water heat pump) unit, respectively. The unit is connected to three water tanks in the apparatus, which imitate primary side as heat source, secondary sides for SH and DHW. This apparatus can automatically keep the inlet and outlet water temperature of the heat pump unit constant.
The unit has an inverter-controlled compressor and can vary the revolution speed and heating or cooling output according to heat demand like a heat pump air-conditioner. Also a plate type heat exchanger is installed before a four-direction valve in order to generate two types of hot water with different temperature level, which are used for SH and DHW, at the same time. The heat exchanger so-called de-superheater generates hot water for DHW with temperature of more than 60 ^{o}C by utilizing the heat of superheated vapour mainly.

2.2 Test procedure and experimental conditions

In this performance test, temperatures and flow rates at each part indicated in Figure 2 are measured at five-second intervals by keeping revolution speed of the compressor constant. After the temperatures almost reach steady state, additional measurement is conducted for ten minutes. Performance of the heat pump unit is analysed by using the average values in ten minutes.
Here, total heating output Q_{2t}, heating output for SH Q_{2SH}, and COP of the heat pump unit are calculated by the following equations.

$$Q_{2t} = Q_{2SH} + Q_{2DHW} \quad (1)$$

$$Q_{2SH} = c_{f2}\rho_{f2}G_{f2}(T_{2out} - T_{2in}) \quad (2)$$

$$Q_{2DHW} = c_{fd}\rho_{fd}G_{fd}(T_{dout} - T_{din}) \quad (3)$$

$$COP = Q_{2t} \Big/ E \quad (4)$$

Common experimental conditions are shown in Table 1. The authors suppose that heating output for SH and DHW and the ratio depend on the condition of the inlet and outlet temperature, flow rate, and total heating output. Therefore shown in Table 2 is given each other as the experimental condition. Several times of the tests on each condition were carried out by changing the compressor revolution speed. The speed was changed at 1,800, 3,600, and 5,400 rpm in Exp.1, Exp.2, and Exp.3 and at 1,800, 2,700, 4,500, and 5,400 rpm in Exp.4, Exp.5, and Exp.6, respectively.

2.3 Results and discussions

2.3.1 Total heating output and COP

The COP according to total heating output Q_{2t} in the several tests is summarized in Figure 3. For clarity, not all the results are shown in Figure 3. In almost conditions, the COP rises with the Q_{2t} decrease. Especially, the gradient is larger in the case where the outlet temperature for SH T_{2out} is lower. We can obtain the maximum COP on the condition of the heating output of 2~5 kW. Since the most part of heating demands for SH in the standard residential house are less than 5 kW, it is expected that this heat pump unit can operate with higher efficiency by this partial load characteristics. The total heating output in each case is the almost same when the revolution speed is the same. In addition, almost COP of the heat pump with the de-superheater is little higher than that without the de-superheater. These results suggest that it is possible to evaluate the COP with the de-superheater by using the test result of the heat pump unit without the de-superheater.

2.3.2 Heating output for space heating and domestic hot water

Ratio of heating output for SH to total heating output Q_{2SH} / Q_{2t} according to Q_{2t} is shown in Figure 4. The ratio Q_{2SH} / Q_{2t} becomes smaller fundamentally by increase of the flow rate G_{fd}. On the other hand, the ratio Q_{2SH} / Q_{2t} rises as the temperature T_{din} becomes larger or the temperature T_{2out} becomes smaller. Also, when the temperature T_{2out} is large value (e.g. T_{2out} = 40 ^{o}C), the ratio Q_{2SH} / Q_{2t} drops with reduction of Q_{2t}.

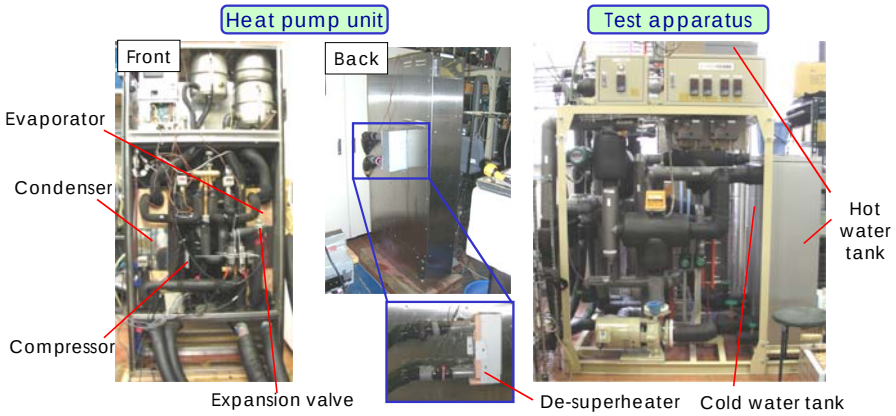


Figure 1: Appearance of performance test apparatus and heat pump unit

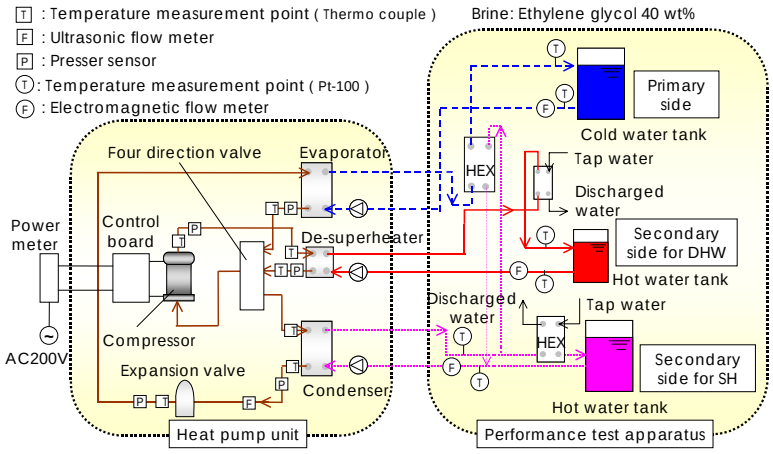


Figure 2: Schematic diagram of performance test apparatus and heat pump unit

Table 1: Common experimental condition

T_{1in} [°C]	G_{f1} [L/min]	G_{f2} [L/min]
0	25	20

Table 2: Conditions for each experiment

	De-super heater	T_{2out} [°C]	T_{din} [°C]	G_{fd} [L/min]
Exp.1-1-1	With	30	10	0.5
Exp.1-1-2				1.5
Exp.1-1-3				2.5
Exp.1-2-1			20	0.5
Exp.1-2-2				1.5
Exp.1-2-3				2.5
Exp.1-3-1			30	0.5
Exp.1-3-2				1.5

	De-super heater	T_{2out} [°C]	T_{din} [°C]	G_{fd} [L/min]
Exp.2-1-1	With	35	10	0.5
Exp.2-1-2				1.5
Exp.2-2-1			20	0.5
Exp.2-2-2				1.5
Exp.2-3-1			30	0.5
Exp.2-3-2				1.5
Exp.2-3-3				2.5

	De-super heater	T_{2out} [°C]	T_{din} [°C]	G_{fd} [L/min]
Exp.3-1-1	With	40	10	0.5
Exp.3-1-2				1.5
Exp.3-2-1			20	0.5
Exp.3-2-2				1.5
Exp.3-2-3				2.5
Exp.3-2-1			30	0.5
Exp.3-2-2				1.5
Exp.3-2-3				2.5

	De-super heater	T_{2out} [°C]	T_{din} [°C]	G_{fd} [L/min]
Exp.4	Without	30	-	-
Exp.5		35		
Exp.6		40		

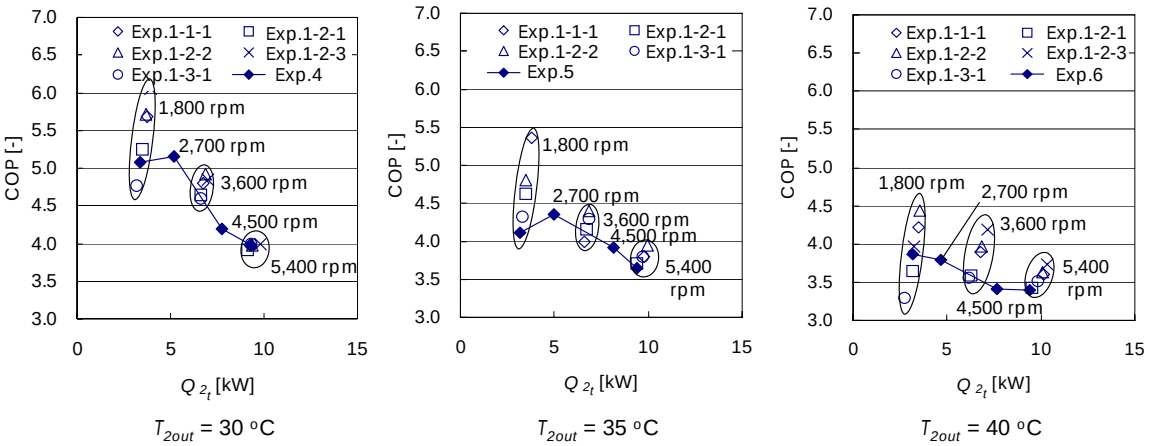


Figure 3: COP according to total heating output

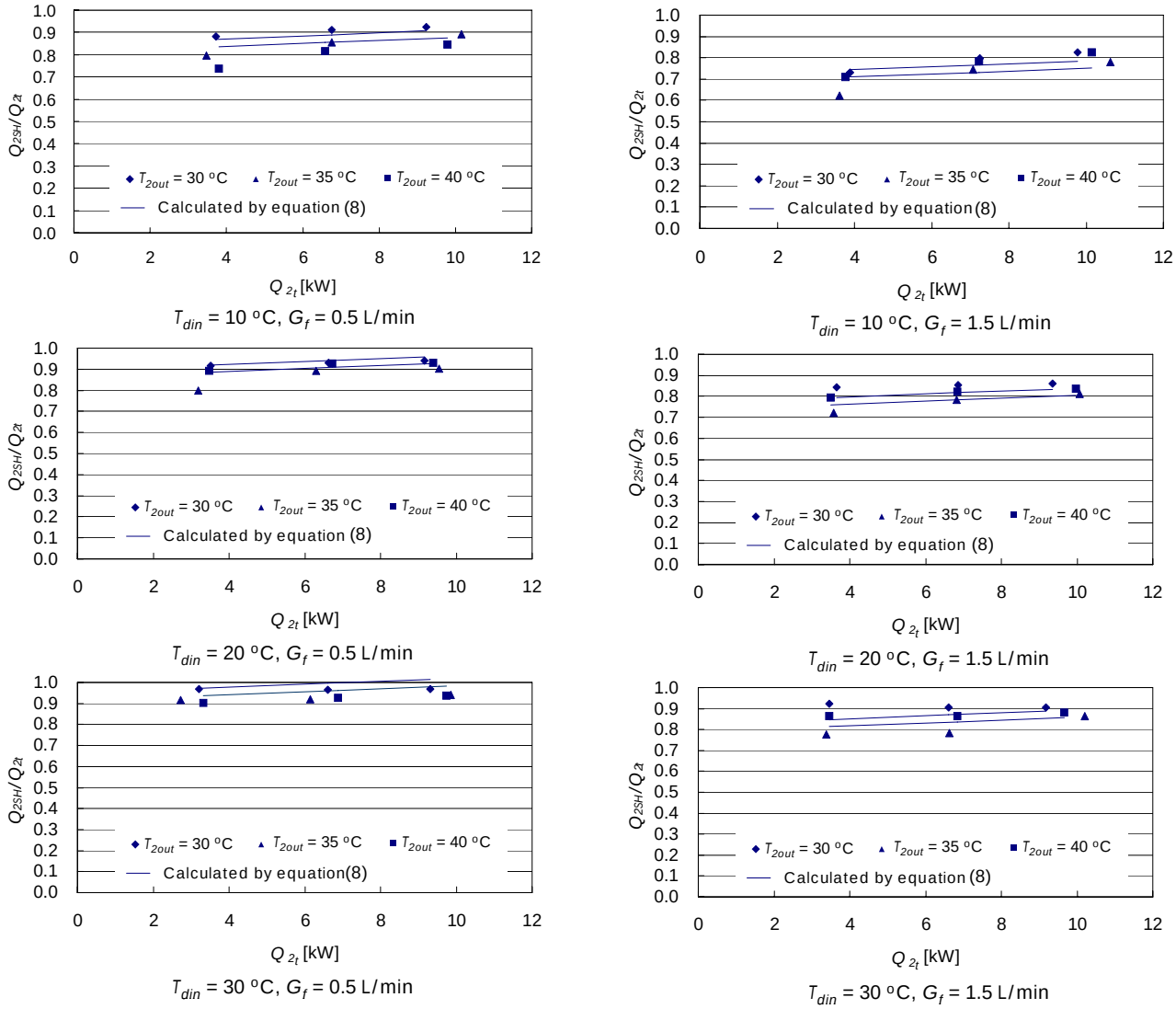


Figure 4: Ratio Q_{2SH} / Q_{2t} according to Q_{2t}

3 FEASIBILITY STUDY OF INTEGRATED GROUND SORUCE HEAT PUMP SYSTEM

3.1. Calculated conditions

3.1.1 Calculated subject

Table 3 indicates outlines of a residential house and GSHP system as the calculated subject. These conditions are set basis on the low energy house actually located in Sapporo city, which has high performance of thermal insulation and air tightness. The hourly heat demand for SH and SC was calculated by a building heating and cooling demand calculation software "SMASH for Windows".

Initial ground temperature of 11.0 °C and soil average effective thermal conductivity of 2.5 W/m/K are given from the result of the thermal response test conducted in the garden of the house. Soil heat capacity is set at 3000 kJ/m^3.

Two borehole ground heat exchangers with length of 75 m are applied and they have double U-tubes. The integrated GSHP unit tested in this paper are used.

3.1.2 Ground source heat pump system operation

Figure 5 shows schematic diagram during operation for SH and DHW. The GSHP unit is connected to two borehole ground heat exchangers. The amount of DHW used in a day is also indicated in Figure 5. The ground heat exchangers extract heat from the ground. By using this extracted heat, the GSHP unit generates two types of hot water. The first one, whose preset outlet temperature T_{2out} is 30~35 ^{o}C, is supplied to floor heating system with area of 180 m^2. The other one with higher temperature generated by the de-superheater is provided to DHW tank of 400 m^3. The flow rates G_{f1}, G_{f2}, and G_{fd} are kept constant, respectively. Therefore, the temperature of hot water generated by the de-superheater varies according to the heating output for DHW Q_{2DHW}, which depends on Q_{2t}, T_{2out}, and G_{fd}. If only heat demand for SH is generated, the circulation pump in secondary side for DHW is stopped and only the hot water for SH of 30~35 ^{o}C is produced.
Next, when only the hot water for DHW is required, the GSHP system is operated for only DHW as shown in Figure 6. In this operation, the de-superheater functions as the condenser. The hot water temperature is preset at 65 ^{o}C.
Schematic diagram of the GSHP system for SC and DHW is drawn in Figure 7. Operation of the GSHP unit is similar to that for only DHW. When the heat demand for SC is generated, the cold water is produced by operation of the GSHP for DHW and heat injection to the ground and it is provided to the fan-coils. If the DHW is not needed, only the circulation pump in primary side is operated and the system is the same as the direct cooling system without refrigerator.

3.1.3 Outlines of calculation

Calculation of the GSHP system is carried out with a design tool for the GSHP system that the authors developed and the detail is described in the previous reports.
Water temperature in the DHW tank is calculated by dividing the water into seven layers as shown in Figure 8. Then, the following equations provide the water temperature at n layer T_{wn}.
T_{w1}, T_{w7} ($G_f \neq 0$)

$$\frac{dT_w}{dt} = \frac{G_f}{V_{Dt}R}\left(T_{in} - T_{wn}\right) + \frac{K_{n-out}A_{n-out}}{V_n c_w \rho_w}\left(T_{outside} - T_{wn}\right) \tag{5}$$

Here,

$$R = R_0 + 0.4t^*$$
$$R_0 = l_0 / L_t$$
$$t^* = G_d t / V_{Dt}$$
$$l_0 = 0.7 d_0 Ar_{in}^{-0.5}$$
$$Ar_{in} = d_0^{-0.5} g\left(\Delta\rho / \rho_0\right) / u^2$$
$$u = 4G_d / \pi d_0^{\,2}$$

T_{w1}, T_{w7} ($G_f = 0$) and T_{w2} ~ T_{w6}

$$\frac{\partial T_w}{\partial t} = a_w \frac{\partial^2 T_w}{\partial Z^2} - \frac{G_f}{A_{n-out}}\frac{\partial T_w}{\partial Z} + \frac{K_{n-out}A_{n-out}}{V_n c_w \rho_w}\left(T_{outside} - T_{wn}\right) \tag{6}$$

The COP of the GSHP unit in this calculation is evaluated by using the following approximate equation. This was obtained by using the result of performance test of the GSHP unit without

the de-superheater shown in Figure 9 since the COP with the de-superheater is just little larger than the one without the de-superheater as shown in **Chapter 2.3**.

$$COP = 0.154 T_{1in} - 0.127 T_{2out} - 0.189 Q_{2t} + 9.729 \quad (7)$$

The COP obtained by this approximate equation is also illustrated in Figure 9.
In addition, the ratio Q_{2SH} / Q_{2t} is approximated as the following.

$$Q_{2SH}/Q_{2t} = 0.0053 T_{din} - 0.0069 T_{2out} - 2.1048 G_{fd} + 0.0068 Q_{2t} + 1.060 \quad (8)$$

The approximated ratio Q_{2SH} / Q_{2t} is drawn in Figure 4.
When the GSHP unit is operated for only DHW, the following equation provides the COP.

$$COP = 0.093 T_{1in} - 0.0496 Q_{2t} + 1.638 \quad (9)$$

If the used domestic hot water temperature is lower than 42 ^{o}C, the heat for raising the temperature to 42 ^{o}C is regarded as shortage heat and it is calculated by the following.

$$Q_s = c_w \rho_w (42 - T_{w1}) \times 0.6 / 3600 \quad (10)$$

Here, the value 0.6 is flow rate of the used domestic hot water (10 L/min =0.6 m^3/h).
The authors simulate the operation of the GSHP system for two years by giving the hourly heat demand.

3.2. Results and discussions

3.2.1 System performance

Figure 10 shows hourly variations of temperature T_{2out}, T_{1out}, T_{1in} and $T_{p\text{-}ou}$ in annual as the second year's result. Differences of T_{1out}, T_{1in} and $T_{p\text{-}out}$ between the start of the second year's operation on Sep. 27 th and the end on Sep. 26 th are hardly observed. These temperature variations have almost achieved periodical steady state. Therefore, this result suggests the possibility of long year's operation. Shown in Figure 11 are hourly variations of heating and cooling output Q_{2SH}, Q_{2SC}, Q_{2DHW} (with and without the de-superheater) in annual. The heating output Q_{2DHW} with the de-superheater is generated during heating period and this reduces Q_{2DHW} without the de-superheater.
Also, variations of temperature in the DHW side on Jan. 20 th is illustrated in Figure 12. When the temperature T_{w7} decreases, T_{dout} is lower than T_{w1}. This yields T_{w1} decrease and heat shortage at the peak demand as shown in Figure 13.
Thus, a three-direction valve is installed like Figure 14 in order to prevent T_{w1} decrease due to mixing hot water with lower temperature in the top layer with the highest temperature. In this operation, the hot water generated by the de-superheater is sent to the sixth layer from the top, if the temperature T_{dout} is lower than T_{w1}. As the result, variation in the DHW side on Jan. 20 th shown in Figure 14 is obtained. The temperature T_{w1} is kept more than 50 ^{o}C all the day so that no heat shortage is observed in Figure 15. Furthermore, to install the three-direction valve hasten T_{w7} increase. This effect to reduce the heating output Q_{2DHW} and electric power required to generate this heat.
Shown in Table 4 is the calculated system performance during the heating and cooling season. Heat demand for DHW of 13 ~ 15 % can be covered by heating output from the de-superheater. Total electric power consumption of the GSHP system with the three-direction valve is less than the one without the three-direction valve. As these results, we confirmed that the GSHP system with only one GSHP unit can satisfy the whole heat demand including for SH, SC, and DHW by using this integrated GSHP unit.

3.2.2 Installation effect

The GSHP system is compared the CO_2 emission with the conventional system, which applies oil boiler systems for SH and DHW and an air-air heat pump system for SC. The result is shown in Figure 17. The GSHP system using the integrated GSHP unit can reduce approximately 50% of CO_2 emission compared with the conventional system. This is almost equal to that of the conventional GSHP system with uncombined heat pumps.

Table 3: Calculated subject

City		Sapporo
Building	Heat loss coefficient [W/m^2/K]	0.94
	Total floor area [m^2]	210
Heating period		Sep. 26th ~ Jun. 8th
Cooling period		Jun. 9th ~ Sep. 25th
Total heating demand [GJ] (Maximum demand [kW])		26.4 (6.8)
Total cooling demand [GJ] (Maximum demand [kW])		3.5 (19.8)
Secondary system for SH		Floor heating × 50m^2
Secondary system for SC		Fan-convector × 4
Soil	Ground temperature [℃]	11.0
	Effective thermal conductivity [W/m/K]	2.5
	Density [kg/m^3]	1500
	Specific heat [kJ/kg/K]	2.0
Ground heat exchanger	Borehole with double U-tube: External diameter of U-tubes [m]	0.032
	Internal diameter of U-tubes [m]	0.026
	Borehole diameter [m]	0.15
	Grout thermal conductivity [W/m/K]	1.8
Heat pump unit	Compressor	4-horse power
Electric power consumption of circulation pumps [W]		Primary side : 150 W
Heat carrier fluid (Brine)		Organic acid group 40%

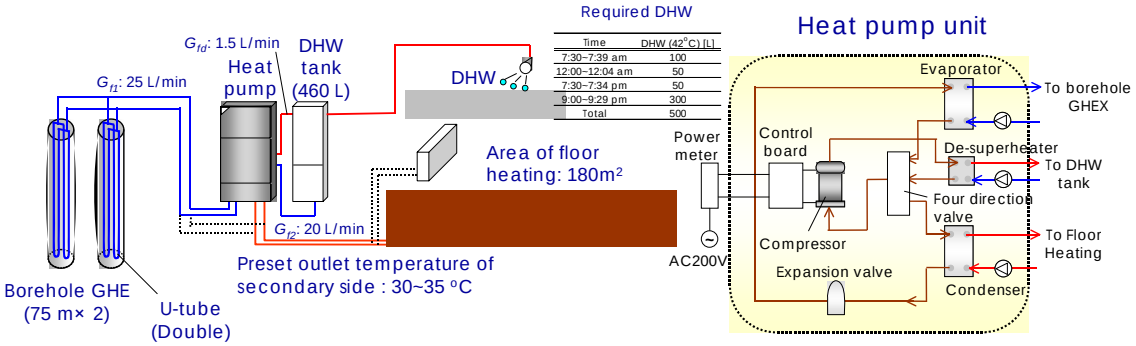


Figure 5: Schematic diagram of the GSHP system for SH and DHW

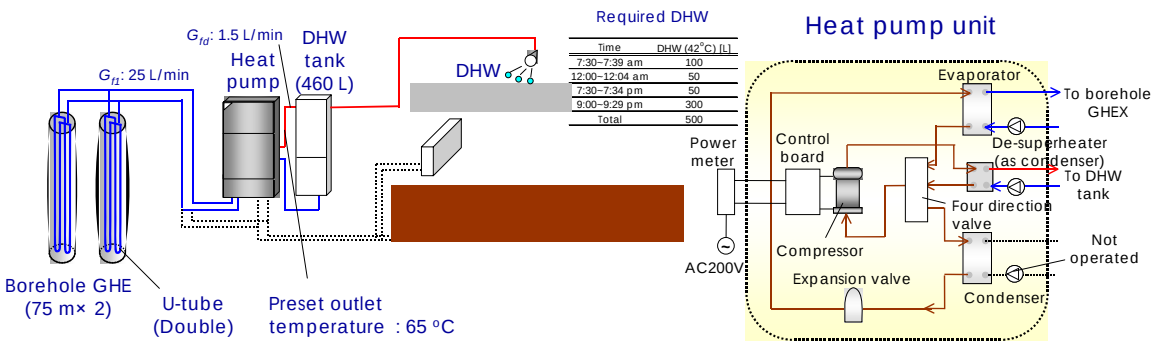


Figure 6: Schematic diagram of the GSHP system for only DHW

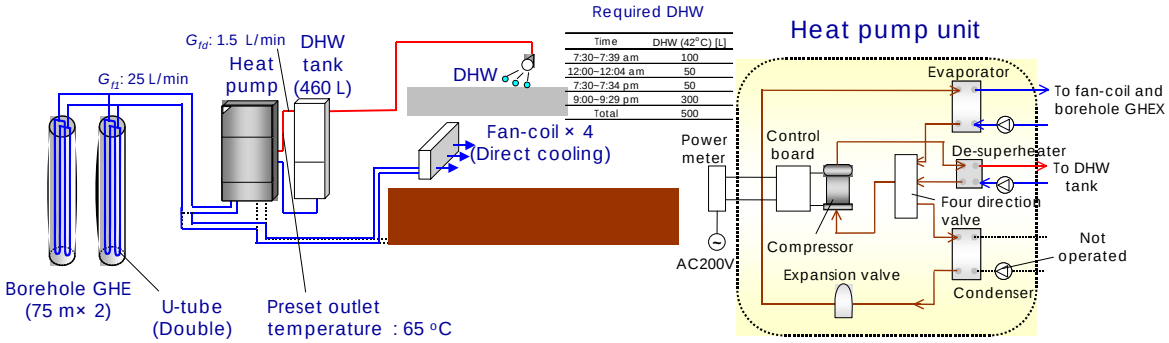


Figure 7: Schematic diagram of the GSHP system for SC and DHW

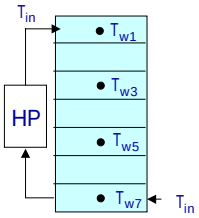


Figure 8: Schematic diagram of water temperature calculation in DHW tank

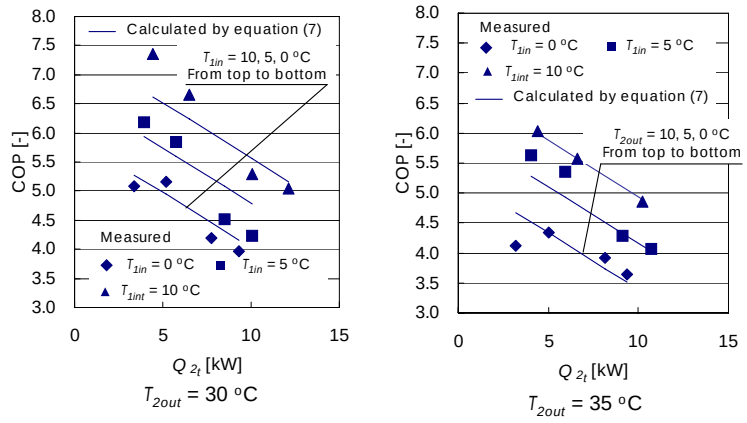


Figure 9: COP according to total heating output in case of without de-superheater

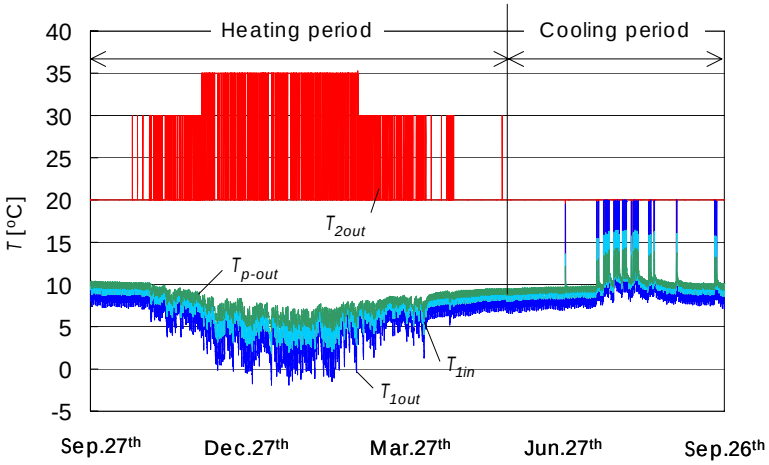


Figure 10: Hourly variations of temperatures in each part in annual

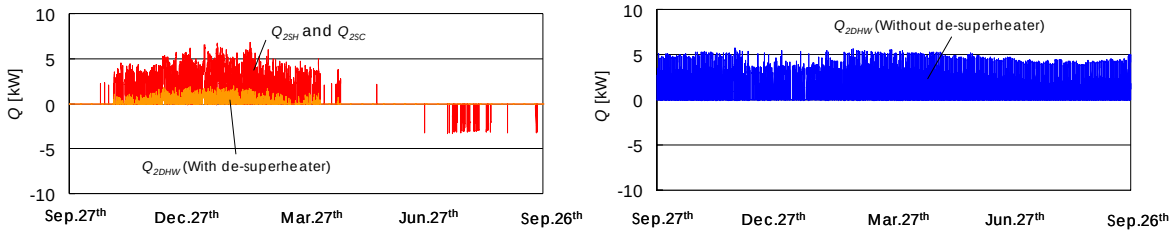


Figure 11: Hourly variations of heating and cooling output in annual

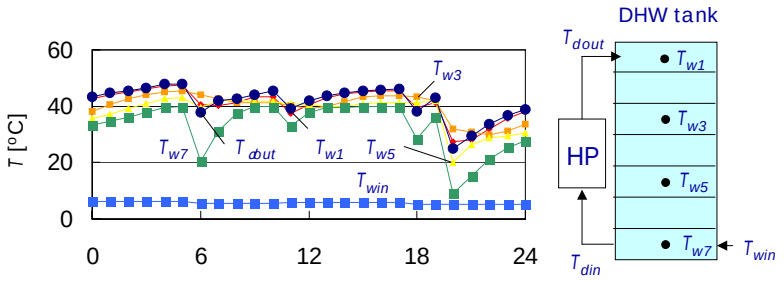


Figure 12: Variations of temperature in the DHW side on Jan. 20th without three-direction valve

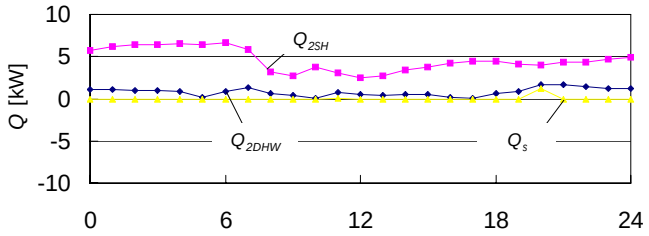


Figure 13: Variations of heating output on Jan. 20th without three-direction valve

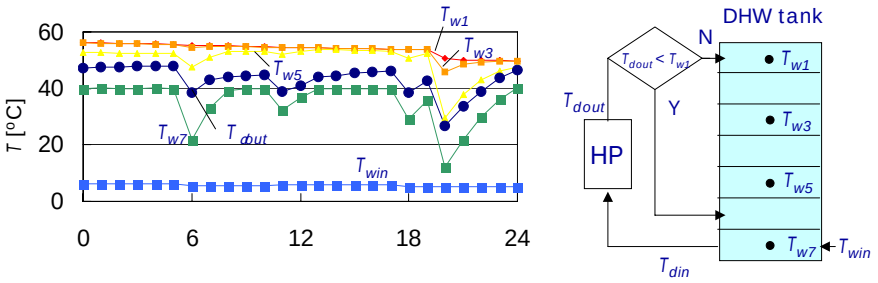


Figure 14: Variations of temperature in the DHW side with three-direction valve on Jan. 20th

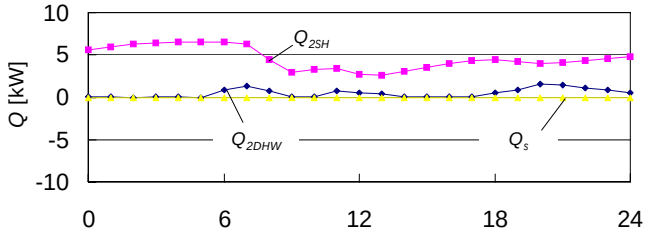


Figure 15: Variations of heating output on Jan. 20th with three-direction valve

Table 4: Seasonal system performance

	Three-direction valve	without	with
SH	H1. Heating output for SH [kWh]	7333	7333
	H2. Heating output for DHW with de-superheater [kWh]	1193	969
	H3. Electric power consumption of compressor for SH [kWh]	1604	1533
	H4. Electric power consumption of circulation pumps [kWh]	303	346
	H5. Heat shortage for DHW [kWh]	30	0
	H6. Average COP of heat pump unit during operation for SH (=H1/H3)	5.32	5.42
	H7. Seasonal performance factor (=H1/(H2+H3))	4.42	4.42
SC	C1. Cooling output for SC [kWh]	342	343
	C2. Electric power consumption of compressor [kWh]	0	0
	C3. Electric power consumption of circulation pump [kWh]	21	21
	C4. Average COP of heat pump unit during operation for SC (=C1/C2)	-	-
	C5. Seasonal performance factor (=C1/(C2+C3))	16.29	16.33
DHW without de-superheater	D1. Heating output for DHW [kWh]	6860	6257
	D2. Electric power consumption of compressor for DHW [kWh]	3150	2823
	D3. Electric power consumption of circulation pumps [kWh]	194	170
	D4. Average COP of heat pump unit during operation (=D1/D2)	2.18	2.22
	D5. Annual performance factor (=D1/(D2+D3))	2.05	2.09

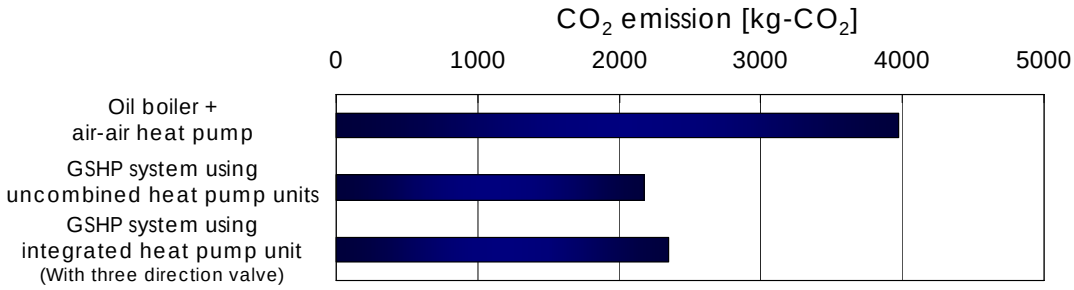


Figure 16: Comparison of CO_2 emissions

4 CONCLUSIONS

1) Performance test of the prototype integrated GSHP unit was carried out and the COP and heating output according to the inlet and outlet temperature, flow rate, and compressor revolution speed were investigated. As the result, approximate equations to evaluate the COP and heating output for SH and DHW were obtained.
2) The integrated GSHP system operation in annual was simulated with the design tool in the case where the GSHP system is installed in the low energy house in Sapporo city. The results were the followings.

    1. Heat demand for DHW of 13 ~ 15 % can be covered by heating output from the de-superheater.
    2. The three-direction valve to prevent temperature decrease of the top layer by mixing hot water with lower temperature also effects to reduce total electric power consumption.
    3. By using the integrated GSHP unit, the GSHP system with only one GSHP unit can satisfy the whole heat demand including for SH, SC, and DHW.
    4. The GSHP system using the integrated GSHP unit reduces approximately 50% of CO_2 emission compared with the conventional system.

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NOMENCRATURE

A: Area [m^2], *a*: Thermal diffusivity [m^2/s], *Ar*: Archimedes number [-], *c*: Specific thermal capacity [kJ/kg/K], *d*: Diameter [m], *E*: Electric power [W], *G*: Flow late [m^3/s], *g*: gravitational constant [m^2/s], *K*: Overall heat transfer coefficient [$W/m^2/K$], *L*: Length [m], *Q*: Heating output [W], *T*: Temperature [^oC], *t*: Time [h], *u*: velocity [m/s], *z*: Distance for *z* axis [m], *ρ*: Density [kg/m^3]

Subscript

d: De-superheater, *DHW*: DHW, *Dt*: DHW tank, *f*: Thermal medium, *in*: Inlet, *out*: Outlet, *outside*: Outside, *p*: Pipe (Ground heat exchanger),*SH*: Space heating, *SC*: Space cooling, *t*: Total, *1*: Primary side, *2*: Secondary side, *-in*: Inside, *-out*: Outside