EXPERIMENTAL PROOF OF SEASONAL PERFORMANCE OF THE GROUND SOURCE HEAT PUMP SYSTEM APPLYING VARIABLE WATER FLOW CONTROL AND MULTI-SPLIT HEAT PUMP

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Abstract: Field test of the Ground Source Heat Pump (GSHP) system applying variable water volume (VWV) control and multi-split heat pump has been carried out from 2006 to 2009 in order to demonstrate the effect of reduction of circulation pumps' electric power consumption. The short-term test of the GSHP system indicated that the optimum flow rate decreases corresponding to decrease of the cooling output. This suggests that VWV control of the circulation pump contributes to reduction of circulation pumps' electric power consumption the most. Based on the result, the GSHP system applying VWV control has been operated and the system performance has been validated during whole cooling period in 2008. As the result, the GSHP system applying VWV control could reduce approximately 80 % of circulation pumps' electric power consumption compared to constant water volume. Additionally, seasonal performance factor of the GSHP system was 4.51 and this result achieved the target value of 4.5.

Key Words: Ground Source Heat Pump, Variable Water Volume Control, Multi-split Heat Pump, Field Test

1 INTRODUCTION

The Ground Source Heat Pump (GSHP) system can generally operate with higher efficiency than the Air Source Heat Pump (ASHP) system. However, very few of the GSHP systems have been installed in the medium-scale buildings in the moderate climate region, whose area occupies approximately two-third of the total area of the whole buildings in Japan. One of the main reasons is that total efficiency of the GSHP system decreases due to the circulation pumps' electric power consumption.
In order to expand market of the GSHP system in the moderate climate area, the authors have developed the Low Flow Circulation Ground Source Heat Pump (LF-GSHP) multi-split system, which can operate with lower circulation pumps' energy consumption. This system adopts multi-split system in the secondary side and low flow circulation system in the primary side.
In the previous paper (Katsura et al., 2008), field experiment apparatus of the LF-GSHP system was constructed and the system performance including the circulation pump was investigated. In addition, heat extraction or injection performance of the ground heat exchangers was tested when the flow rate decreased (Katsura et al., 2008).
Based on the result of previous paper, the LF-GSHP system applying VWV control has been operated and the system performance has been validated during whole cooling period in 2008. In this paper, the result is introduced.

2 OUTLINES OF FIELD EXPERIMENT

As shown in the previous paper (Katsura et al., 2008), experimental apparatus of LF-GSHP multi-split system had been constructed in experimental field in Ishikari, Japan. Field test has been conducted from June 2007 to March 2009. Ishikari city is neighboring Sapporo city, which is the capital city in Hokkaido Island of Japan. Figure 1 and Figure 2 show plane view of the experimental site and diagram of the experimental apparatus, respectively. Four piles pointed in Figure 1 were connected to the multi-split heat pump unit and used as ground heat exchangers. The heat pump unit and air conditioning units indicated in Figure 2 conduct cooling and heating. Table 1 shows specification of the heat pump unit and air conditioning units. The heat pump unit has a scroll compressor of 10HP. An air conditioning unit with rated heating output of 22.4 kW and cooling output of 25 kW was exchanged with three air conditioning units with rated cooling output of 9 kW (×3 units) and cooling output of 10 kW (×3 units). Thus, the rated heating and cooling output of the system was up to around 30 kW. The hot water boiler in Figure 4 can imitate cooling demand of around 31 kW, which is larger than rated cooling power of the system.
Measurement points are indicated in Table 2. The detailed measurement points have been described in previous paper (Katsura et al., 2008).

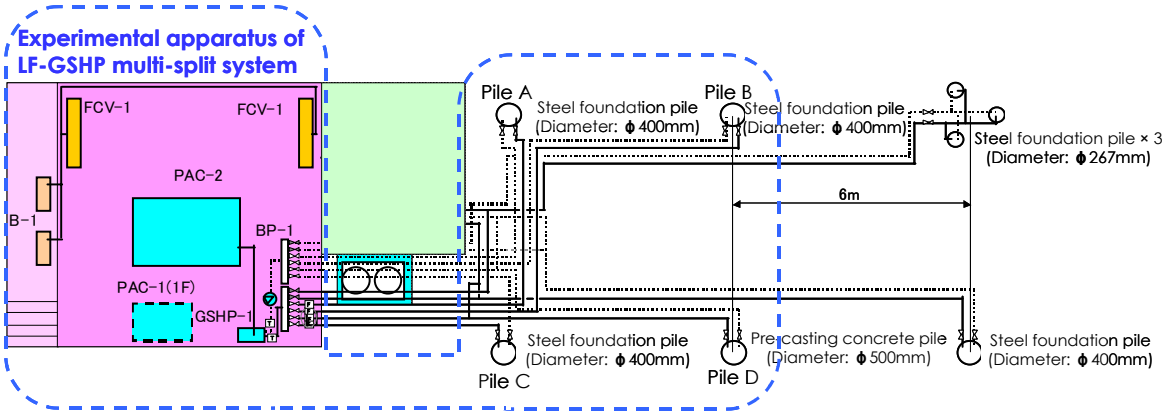


Figure 1: Plane view of field experiment

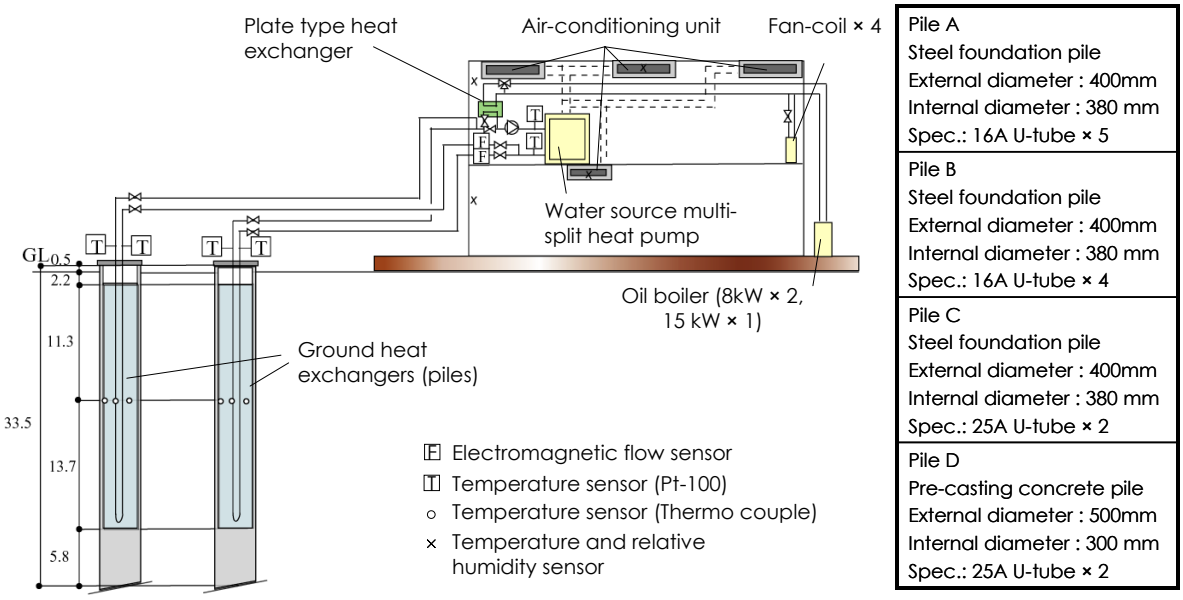


Figure 2: Schematic diagram of experimental set-up

Table 1: Specification of heat pump unit and air conditioning units

Dimensions	Height: 1000 mm × Width: 780mm × Length: 550 mm
Refrigerant	R410A
Compressor	Scroll type, inverter driven Electric power : 6.14 kW(10HP)
Heat exchanger	Plate type
Standard flow rate	96 L/min
Rated capacity	Cooling : 28.0 kW(T_{WB}=19 °C 、 T_{1in}=30 °C) Heating : 31.0 kW(T_{DB}=20 °C 、 T_{1in}=20 °C)
Air-conditioning unit (1st floor)	Cooling : 5.6kW(T_{WB}=19 °C) Heating : 6.2kW(T_{DB}=20 °C)
Air-conditioning unit (2nd floor)	Cooling : 9.0 kW × 3 (T_{WB}=19 °C) Heating : 10.0 kW × 3 (T_{DB}=20 °C)

Table 2: Measurement point

Temperature (Pt-100)	Inlet of ground heat exchangers × 4 piles Outlet of ground heat exchangers × 4 piles Inlet of heat pump unit Outlet of heat pump unit
Temperature (Thermo couples)	Water temperature in pile at 13.5 m deep × 4 piles Internal surface of pile at 13.5 m deep × 4 piles External surface of U-tube at 13.5 m deep × 4 piles
Temperature and relative humidity (Sensor)	Inlet of Air-conditioning unit × 2 (1st and 2nd floor) Outlet of Air-conditioning unit × 2 (1st and 2nd floor) Experimental room × 2 (1st and 2nd floor)
Flow rate (Electromagnetic flow meter)	4 lines lead to Pile A ~ Pile D (The point indicated in Figure 1 and Figure 2)
Electric power (Power meter)	Compressor of heat pump unit Circulation pump
Refrigerant temperature (Sensor)	Inlet of compressor Outlet of compressor Inlet(Heating) or outlet(Cooling) of air conditioning unit
Refrigerant presser (Sensor)	Inlet of compressor Outlet of compressor

3 INVESTIGATION OF OPTIMUM FLOW RATE IN PRIMARYSIDE FOR COOLING

In this paper, optimum flow rate in primary side of the GSHP system is defined as the value that yields the highest system COP (SCOP) on the same condition except for flow rate. The value SCOP is given as the following.

$$SCOP = Q_{hp} \Big/ \left(E_{hp} + E_p \right) \tag{1}$$

Here, the cooling output O_{hpc} is calculated by the following equation.

$$Q_{hpc} = c_f \rho_f G_f \left(T_{1out} - T_{1in}\right) - E_{hp} \quad (2)$$

The optimum flow rate was investigated by using short-term test results of 'constant output operation'. In the test, the flow rate G_f and cooling output O_{hpc} were kept constant as far as possible for more than 30 minute. The example is demonstrated in Figure 3. Then the average values during test were used for evaluation.

Table 3 shows the test results of 'constant cooling output operation'. In addition, COP and SCOP according to cooling output Q_{hpc} and load factor Q_{hpc} /Q_{hpcr} in the test is summarized in Figure 4. When the cooling output is around 14 kW, the flow rate condition of 30 L/min yields the maximum SCOP of 5.31. The reason is that the ratio of circulation pump's electric power in the total power is relatively larger and the reduction of circulation pumps' electric power consumption is more effective. On the other hand, the flow rate condition of 96 L/min gives the highest SCOP value of 3.78 in case where the cooling output is 24~28 kW. This is because increase of compressor's electric power consumption is larger than reduction of circulation pump's electric power consumption on the condition of low flow rate.

This test result suggests that variable water volume (VWV) control of the circulation pump is most likely to reduce circulation pumps' electric power consumption.

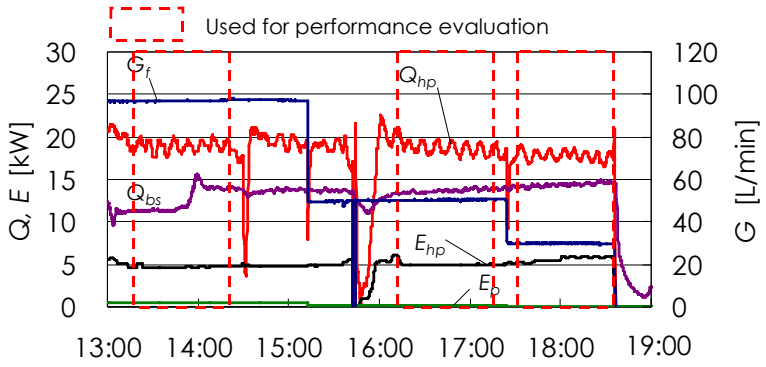


Figure 3: Example of 'constant output operation'

Table 3: Test results of 'constant output operation'

	Test1	Test2	Test3	Test4	Test5	Test6	Test7	Test8	Test9	Test10	Test11	Test12
G_f [L/min]	96	50	30	96	50	30	96	50	30	96	50	30
T_{1in} [℃]	32.7	33.2	33.3	32.20	33.57	33.42	32.79	31.92	31.21	32.75	31.97	32.79
T_{rWB} [℃]	22.7	22.7	22.8	17.90	18.86	17.63	19.34	18.87	19.75	21.72	21.86	21.84
Q_{hpc} [kW]	26.4	24.9	23.7	19.72	20.03	19.68	13.33	13.24	13.89	7.28	7.29	7.30
E_{hp} [kW]	6.6	7.0	7.4	4.70	4.97	5.60	2.40	2.44	2.57	1.26	1.25	1.29
COP [-]	4.00	3.56	3.19	4.20	4.03	3.51	5.56	5.42	5.41	5.77	5.81	5.65
E_p [kW]	0.39	0.09	0.04	0.50	0.11	0.04	0.47	0.11	0.04	0.47	0.10	0.04
SCOP [-]	3.78	3.51	3.18	3.79	3.94	3.49	4.65	5.18	5.32	4.20	5.37	5.46

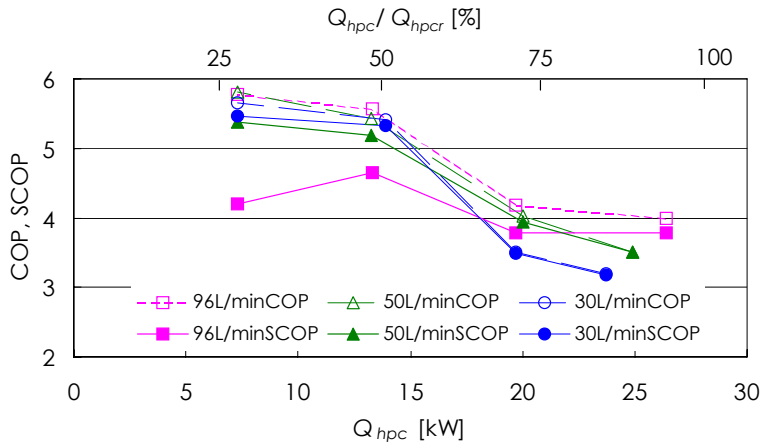


Figure 4: COP and SCOP according to Q_{hpc}

4 EXPERIMENTAL PROOF OF SEASONAL COOLING PERFORMANCE OF THE GSHP SYSTEM APPYING VARIABLE WATER VOLUME CONTROL

4.1 Outlines of variable water volume control

Figure 5 illustrates the variation of optimum flow rate with the value Q_{hpc} /Q_{hpcr} based on the test results of 'constant cooling output operation'. The authors considered the easiness of control and introduced easier VWV control. The variation of flow rate with the value Q_{hpc} /Q_{hpcr} are demonstrated in Figure 5.

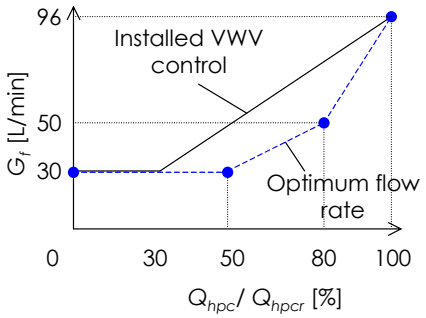


Figure 5: Concept diagram of VWV control

Two types of control method shown in Figure 6 were installed and investigated. The one is constant differential temperature control method. In this method, the temperature difference of heat pump unit is measured and revolution speed of the circulation pump is varied by the signal to keep the measured temperature difference constant. Another method is that the signal of compressor' revolution speed is sent to the converter and revolution speed of the circulation pump is controlled by the signal from compressor.

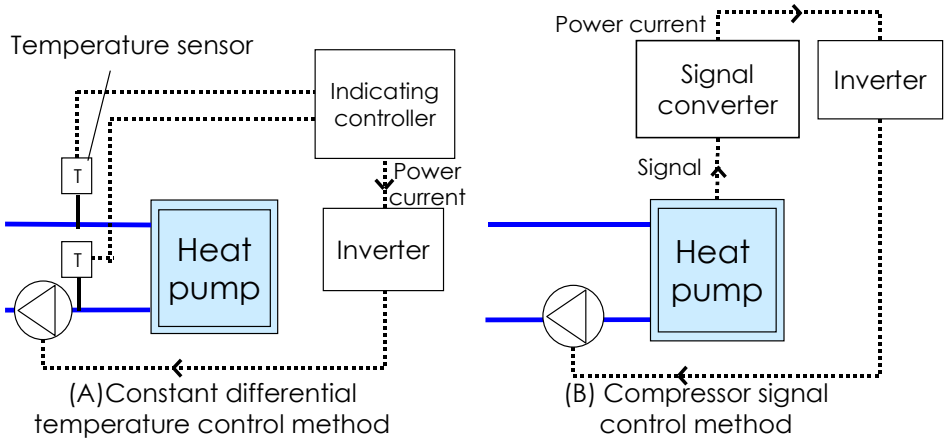


Figure 6: Types of VWV control method

4.2 Follow-up performance test of variable water volume control against cooling output

Step-by-step cooling load such as shown in Figure 7 was imitated and follow-up performance test of VWV control against cooling output was carried out.
As the result of follow-up performance test applying constant differential temperature control, variations of O_{hpc}, E_{hp}, G_f, heat pump inlet temperature T_{1in} and heat pump inlet temperature T_{1out} on October 13th are presented in Figure 8. The temperature difference between T_{1in} and T_{1out} is kept almost constant and the flow rate G_f varies with the rate of O_{hpc}. In addition, the flow rate G_f during cooling operation on October 13th is plotted against O_{hpc} in Figure 9. The error between measured flow rate and set flow rate is less than ±10 L/min in approximately 90 % of the cooling time period. Therefore, the constant differential temperature control is practicable method as the VWV control method.
Results of follow-up performance test applying compressor signal control is demonstrated in Figure 10, which is variations of O_{hpc}, E_{hp}, G_f, heat pump inlet temperature T_{1in}, heat pump inlet temperature T_{1out} on July 16th. Also, the flow rate G_f during cooling operation on July 16th is plotted against O_{hpc} in Figure 11. Variation of G_f in Figure 10 is less than the one in Figure 8 but measured flow rate is not so corresponding to set flow rate as shown in Figure 11. This is caused by overlong signal transmission interval.
Consequently, the authors confirmed that the constant differential temperature control has advantage from the viewpoint of follow-up performance.

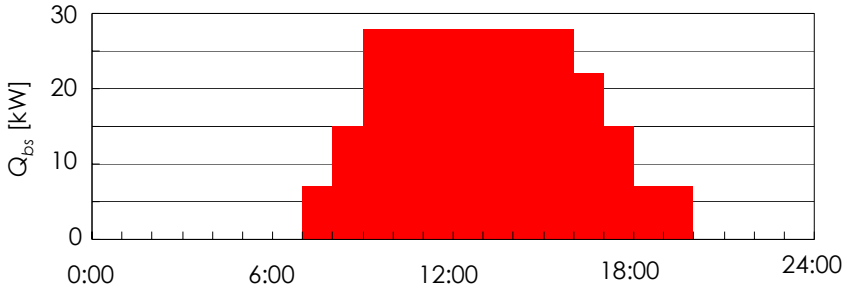


Figure 7: Example of imitated cooling load

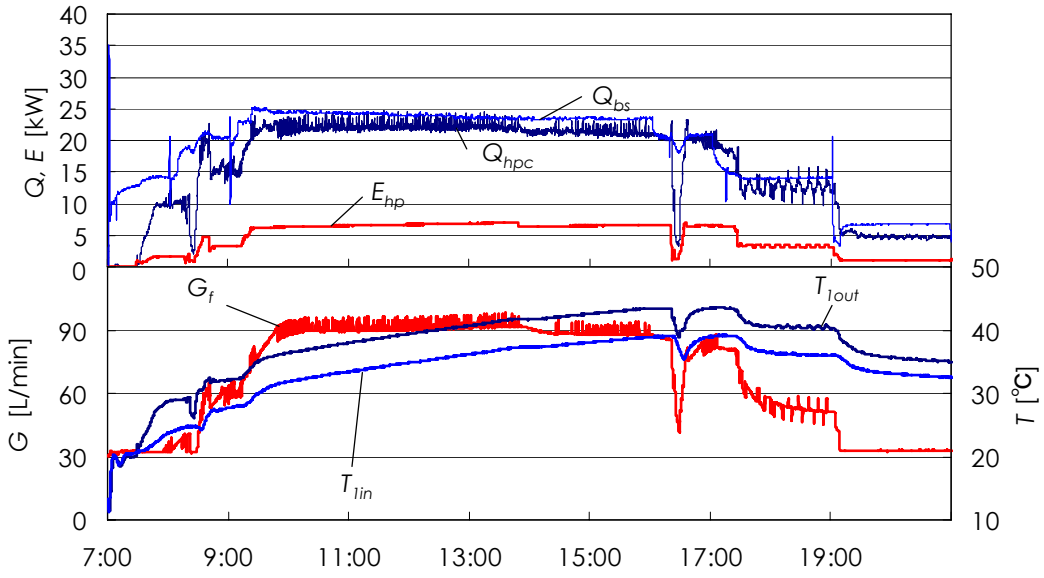


Figure 8: Variations of O_{hpc}, Q_{bs}, E_{hp}, G_f, T_{1in}, and T_{1out} on October 13th

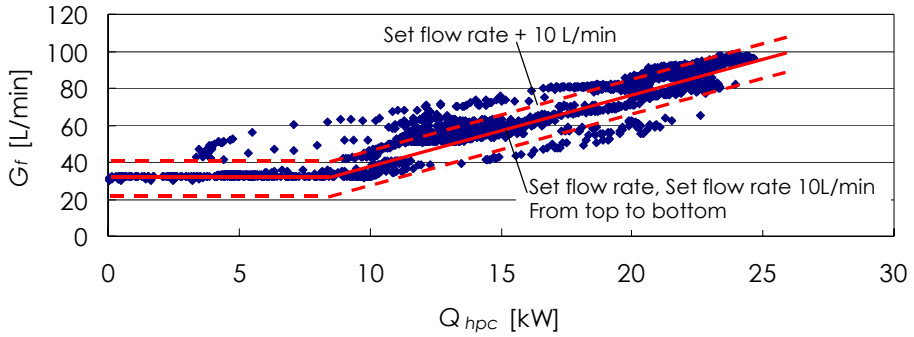


Figure 9: G_f against O_{hpc} during cooling operation on October 13th

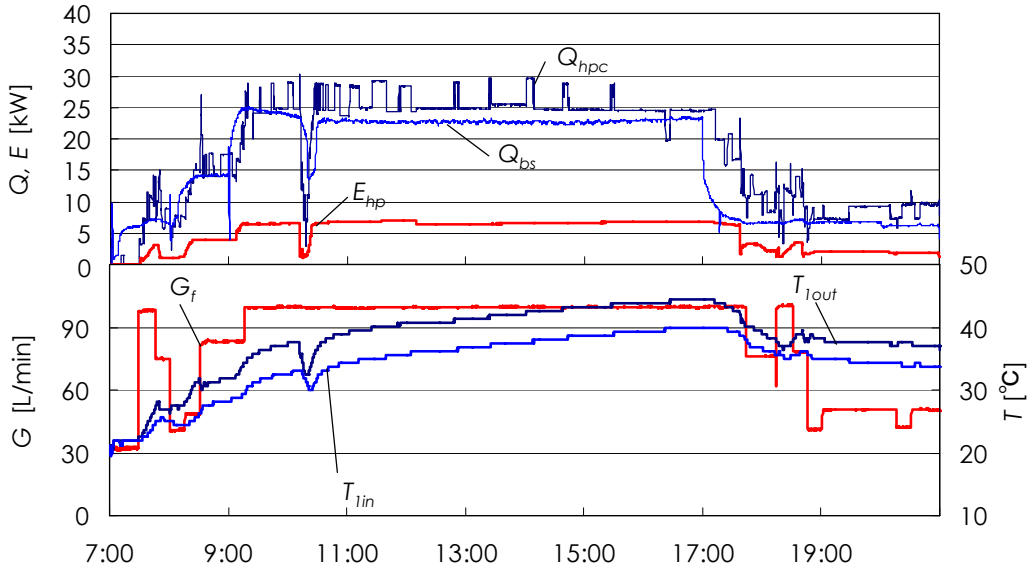


Figure 10: Variations of O_{hpc}, Q_{bs}, E_{hp}, G_f, T_{1in}, and T_{1out} on July 16th

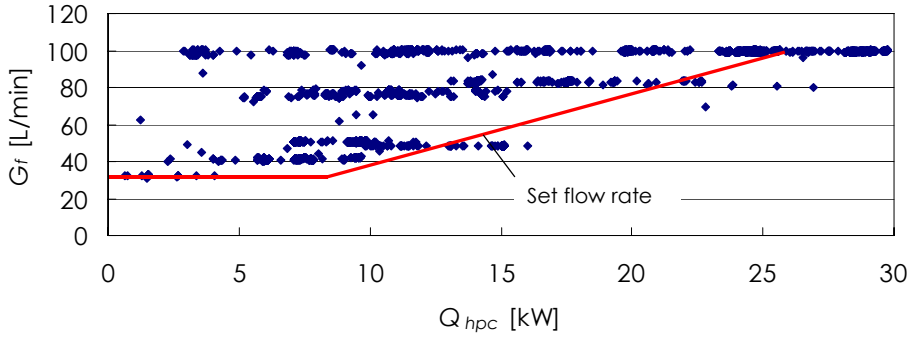


Figure 11: G_f against O_{hpc} during cooling operation on July 16th

4.3 Evaluation of seasonal cooling performance

Figure 12 displays operating time of the tested GSHP system according to load factor Q_{hpc} /Q_{hpcr} during cooling period on 2008, which is from June 4th to October 13th. Operating time according to load factor Q_{hpc} /Q_{hpcr} in the actual building (JRAIA, 2008) is also included in

Figure 12. In this field test, the time of cooling operation with high load factor is much longer in order to carry out the follow-up performance test. However, cooling operation with high load factor is hardly required in the actual building as shown in Figure 12. Thus, the authors excluded excess measured test data of cooling operation with high load factor and evaluated seasonal performance because COP and SCOP with high load factor are smaller than the ones with low load factor as shown in Figure 4.

Shown in Figure 13 is daily-integrated value of cooling output QT_{hpc}, electric power consumption of compressor ET_{hp} and electric power consumption of circulation pump ET_{pv}. Figure 13 also includes the daily-integrated value of electric power consumption of circulation pump ET_{pc} that is obtained by assuming constant water volume (CWV, G_f = 96 L/min). The VWV control can reduce the circulation pump's electric power consumption compared to the CWV. Also, this result indicates that the VWV control is particularly effective if the GSHP system is operated long time with low load factor.

Table 4 summarizes seasonal integrated value of QT_{hpc}, ET_{hp}, ET_{pv} and ET_{hc}. Seasonal performance factors (SPF) of the GSHP system with and without VWV control are also shown in Table 4. The VWV control can reduce approximately 80% of circulation pump's electric power consumption compared to the CWV. The SPF of the GSHP system with VWV control was 4.51 and more than the target value of 4.5.

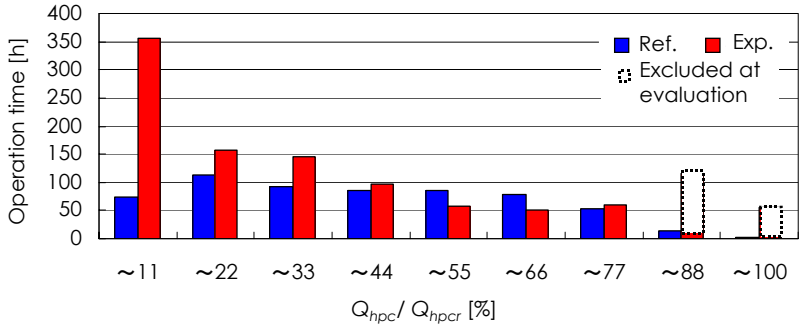


Figure 12: Operating time of GSHP system according to load factor Q_{hpc} / Q_{hpcr} (Ref.: Reference (JRAIA 2006), Exp.: Field experiment)

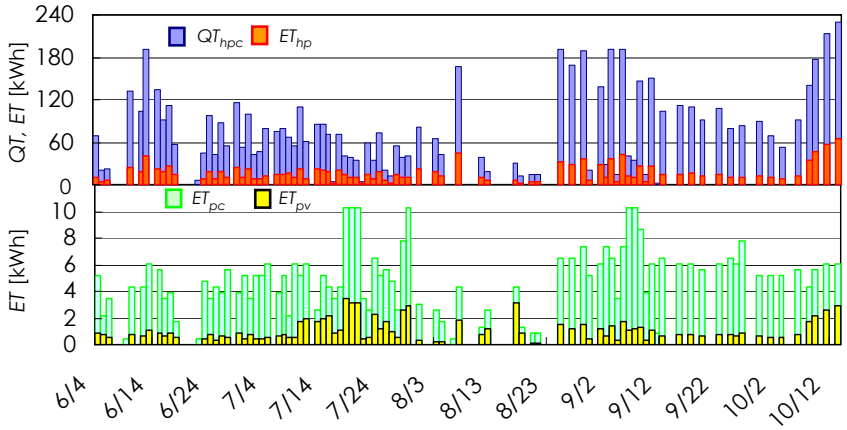


Figure 13: Daily-integrated value of QT_{hpc}, ET_{hp}, ET_{pv} and ET_{pc}

Table 4: Seasonal integrated value of QT_{hpc}, ET_{hp}, ET_{pv}, ET_{pc} and SPF of GSHP system

QT_{hp}	ET_{hp}	Average COP ($=QT_{hp}/ET_{hp}$)	ET_{pv}	$ET_{hp}+ET_{pv}$	SPF ($=QT_{hp}/(ET_{hp}+ET_{pv})$)	ET_{pc}	$ET_{hp}+ET_{pc}$	SPF ($=QT_{hp}/(ET_{hp}+ET_{pc})$)
[kWh]	[kWh]		[kWh]	[kWh]		[kWh]	[kWh]	
6687	1390	4.81	92	1482	4.51	431	1821	3.67

5 SUMMARIES

1) The authors conducted short-term test of 'constant output operation' and investigated the optimum flow rate that yields the highest system COP (SCOP) by using the test result. When the cooling output is around 14 kW, the maximum SCOP of 5.31 is obtained on the condition that the flow rate is 30 L/min. On the other hand, the flow rate condition of 96 L/min provides the highest SCOP value of 3.78 in case where the cooling output is around 24~28 kW. These suggest that variable water volume (VWV) control of the circulation pump can reduce circulation pumps' electric power consumption most.
2) Two types of VWV control method were installed and were investigated by the follow-up performance test against cooling output. The result shows that the constant differential temperature control has advantage form the viewpoint of follow-up performance.
3) The GSHP system applying VWV control has been operated and the system performance has been validated during whole cooling period, which is s from June 4th to October 13th. As the result, the GSHP system applying VWV control could reduce approximately 80 % of circulation pumps' electric power consumption compared to constant water volume. Additionally, seasonal performance factor of the GSHP system was 4.51 and this result achieves the target value of 4.5.

6 REFERENCES

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Katsura T, Y. Nakamura, K. Nagano, Y. Fujiwara, S. Hori and T. Okawada 2008 "Field Tests of Heat Extraction or Injection Using Foundation Piles as Ground Heat Exchangers Applying Low Flow Circulation" Proceedings of 9th IEA Heat Pump Conference 2008, Zurich

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NOMENCRATURE

c: Specific thermal capacity [kJ/kg/K], *E*: Electric power [W], *ET*: Total electric power [Wh], *G*: Flow late [m^3/s], *Q*: Heating or cooling output [W], *QT*: Total heating or cooling output [Wh], *T*: Temperature [^oC], *t*: Time [h], *ρ*: Density [kg/m^3]

Subscript

bs: Boiler system (for imitating cooling load), *f*: Thermal medium, *hp*: Heat pump, *hpc*: Heat pump cooling operation, *hpcr*: Heat pump cooling operation against rated load, *hph*: Heat pump heating operation, *hphr*: heat pump heating operation against rated load, *p*: Pump, *pv*: Pump with VWV control, *pv*: Pump with CWV control, *rWB*: Room wet bulb, *WB*: Wet bulb, *1in*: Inlet in primary side, *1out*: Outlet in primary side