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Optimum Operation of the Open-loop Systems of Ground Source Heat Pump by the Controlled Pumping Water Flow Rate

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ABSTRACT

In the open-loop systems of the ground source heat pump, the decrease of pumping water flow rate enables to lower its power consumption as the air conditioning load decreases, so that it's SCOP (System Coefficient of Performance) is improved than the constant rate of pumping water. The pumping water flow rate can be controlled by the temperature difference between inlet and outlet pumping water (hereinafter referred to as ΔT_{GW}) in the heat exchanger, between the pumping water and the heat pump, to be consistent. The optimum ΔT_{GW} would be different depending on the air conditioning load pattern and the pumping water conditions such as temperature and water level of where the system installed. The purpose of this study is to estimate the value of SCOP at a certain ΔT_{GW} and verify it with demonstration experiment systems so that the optimum ΔT_{GW} can be estimated in any system. We conducted the demonstration experiment at three sites; Gifu, Yokkaichi, and Nagoya, where the air conditioning load and pumping water conditions are different. The calculated SCOP comes from the estimated power consumptions of the heat pump and groundwater pump. The former is calculated by the pumping water temperature, the capacity and power consumption of heat pump including partial load conditions, and the heat output to primary side of heat pump system. The latter is by the relationship between power consumption of groundwater pump and pumping water flow rate. The measured SCOP comes from demonstration experiments in the several ΔT_{GW} at the three sites and monitoring the capacity and power consumption of the heat pump and the power consumption of the groundwater pump. The calculated SCOPs with the change in ΔT_{GW} have similar tendencies to the measured ones at each site. The difference of the optimum ΔT_{GW} between the calculated and measured SCOPs is within 2 K at each site. This result shows that it is possible to estimate the optimum value of ΔT_{GW} at the design stage based on air conditioning load pattern, groundwater temperature and water level.

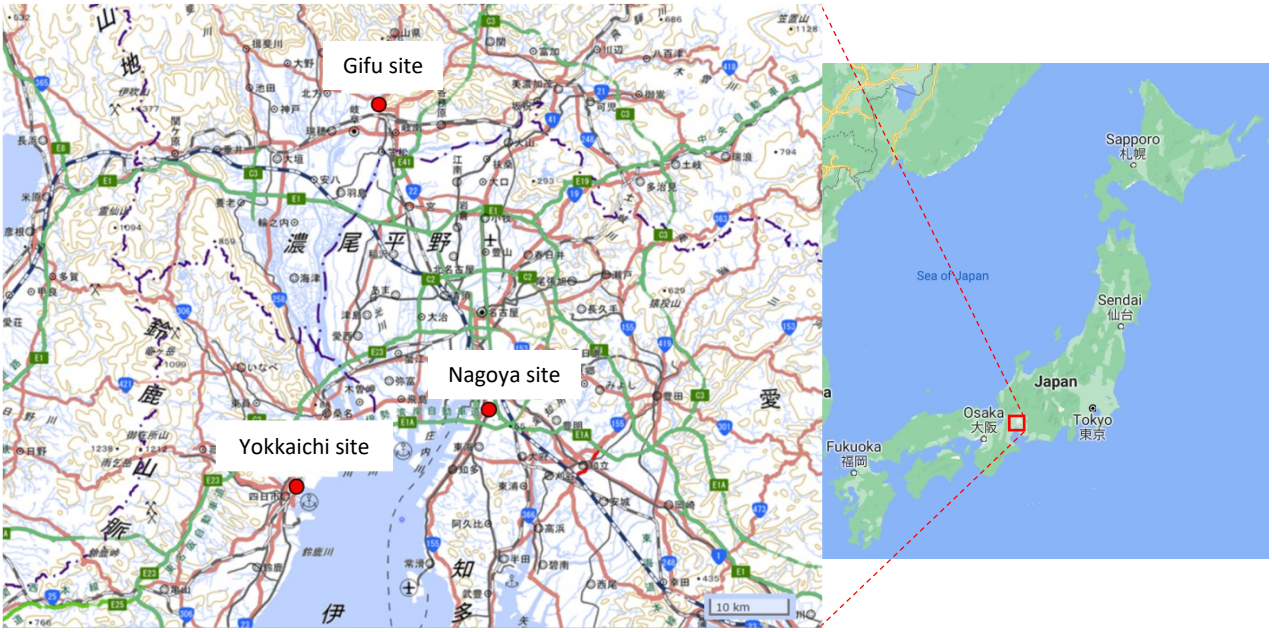
1. INTRODUCTION

Geothermal heat pumps have a higher efficiency than air-source heat pumps theoretically, since the underground temperature is stable regardless of the seasons. In the case of the open-loop system, the system is constructed by not only a heat pump but also a water pump. Total design of the system is important to achieve a higher efficiency in an actual system, because it consists of not only a heat pump but also a water pump and so on. An inverter is often incorporated in a heat pump unit to decrease a heat capacity and an electricity consumption depend on heat demand. When the system is composed of a heat pump with inverter and a water pump without inverter, the flow rate and power consumption are constant regardless of heat demand, in this case, smaller heat demand makes the SCOP lower because the ratio of groundwater pump to the entire power consumption of the system becomes higher. This is one of the problems with the open-loop system of the ground-source heat pump. This can be solved by controlling the water pump with an inverter. By keeping ΔT_{GW} constant at a certain set value, we can control the pumping water flow rate depend on the heat demand. The groundwater temperature, level and pump head differ depending on the installation location. Therefore, the optimum ΔT_{GW} depends on the installation location. The purpose of this study is to estimate the SCOP at any arbitrary ΔT_{GW} and verify it by empirical experiments so that the optimum ΔT_{GW} can be predicted in any system.

2. OVERVIEW OF DEMONSTRATION EXPEIMENT SITES

We conducted the demonstration experiment at three sites; Gifu, Yokkaichi, and Nagoya in central Japan, where the air conditioning load and pumping water conditions are different (Figure 1). The air conditioning load is higher in the order of Nagoya site, Gifu site, Yokkaichi site. Since the air-conditioned area of the Nagoya site is a factory workplace, the thermal load is continuously higher throughout the day. Since the Gifu site is a public hall, the thermal load is basically lower in most of operating days except days when all indoor units are continuously operated. Since the Yokkaichi site is an office, the thermal load is basically lower. Groundwater chemistry of Gifu site shows lowest dissolved components among the three sites, and it is the best groundwater quality for thermal use. That of the Yokkaichi site exhibits higher ionic silica, and the Nagoya site is higher iron. Groundwater temperature of the Nagoya site is constant at about 18 °C throughout the year. Groundwater temperature of the Yokkaichi site ranges from 16 to 18 ℃, and the annual temperature phase coincides with the outside air temperature phase. The groundwater temperature of the Gifu site ranges from 11 to 21 °C, and lower and higher groundwater temperatures appear in summer and winter, respectively. This indicates that the annual change of groundwater temperature in this site shows a phase difference of 0.5 year from that of ambient temperature. We installed a pumping well, an injection well, indirect heat exchangers, and a water-cooled heat pump at each site (Figure 2). The length of the pumping and injection wells is 20 m at the Gifu and Yokkaichi sites, and 30 m at the Nagoya site. In all sites, the pumped groundwater piping from the pumping well to the injection well is kept in a semi-closed condition. The geology of the aquifers at the Nagoya and Gifu sites is the gravel layer, which the Yokkaichi site is a sand layer. Groundwater is pumped up from a pumping well, exchanges its heat with antifreezing fluid in a plate heat exchanger, and then returns into the aquifer through an injection well. The antifreezing fluid is circulated between the plate heat exchanger and the heat pump by a circulation pump. The flow rates of pumped groundwater and heat source water are controlled depend on the heat demand by the groundwater pump and circulation pump with inverter. Table 1 shows an overview of each site. The heat pump installed at the Gifu site can select groundwater or air for heat source, and has an air conditioning capacity of 50 kW. The heat pumps installed at the Yokkaichi and the Nagoya sites are water-source and have an air

conditioning capacity of 28 kW. The rated capacity of the antifreezing fluid circulation pump at each site is 0.4 kW, and that of the groundwater pump is 2.2 kW. Fig. 3 shows the measurement points. Temperature of pumped groundwater and antifreezing fluid is measured by Pt100 platinum resistance thermometers. Flow rates of pumped groundwater and antifreezing fluid are measured by ultrasonic flow meters.



Gifu site：35.424N, 136.758E

Yokkaichi site：34.974N, 136.634E

Nagoya site：35.069N, 136.921E

Figure 1: Locations of the three sites of demonstration experiment.

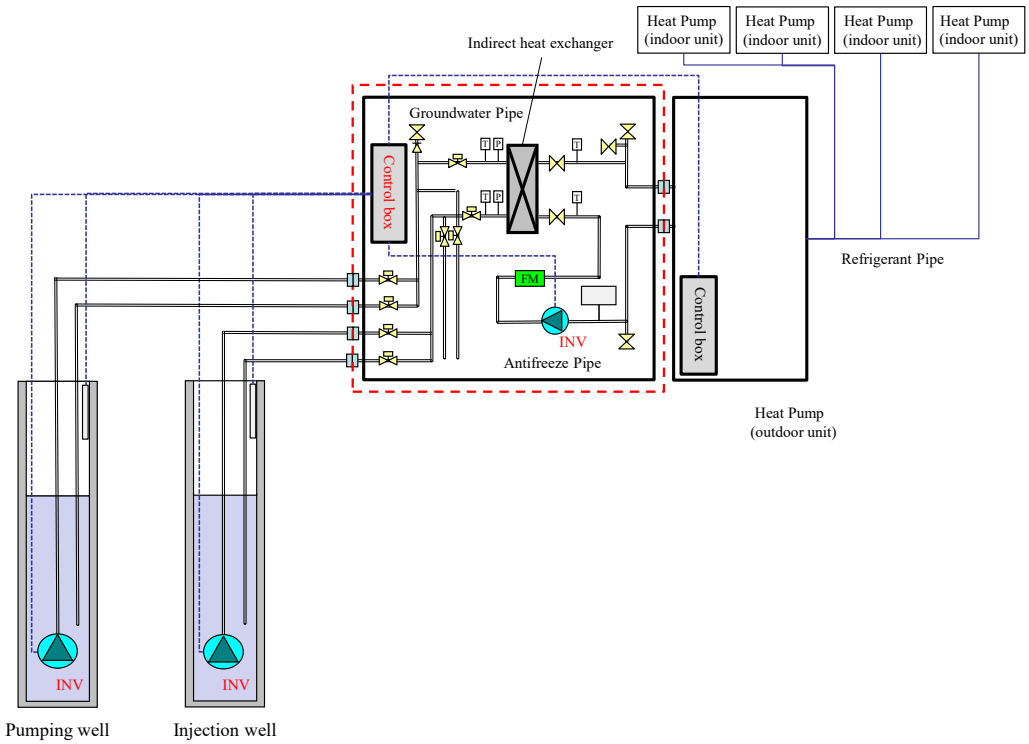


Figure 2 Schematic image of the system of demonstration experiment.

Table 1 An overview of three site of demonstration experiment.

	Gifu Site	Yokkaichi Site	Nagoya Site
Appearance			
Location Facility	Gifu city Meitoku Public Hall	Yokkaichi city Toho Chisui Co., Ltd.Office	Nagoya city Zeneral Heat Pump Industry Co., Ltd. Factry
Heat Pump (outdoor unit)	Air/Water cooled multi-split type air conditioning system 50 kW Model：ZP3-WS504-T	Water cooled multi-split type air conditioning system 28 kW Model：ZP3-WS280-T	Water cooled multi-split type air conditioning system 28 kW Model：ZP3-WS280-T
Heat Pump (indoor unit)	Ceiling suspended 3.6 kW×14 units Ceiling sucpended 5.6 kW×2 units Wall mounted 2.8 kW×1 unit Heat source water circulation pump 0.4 kW	4-way cassette 7.0 kW×1 unit 4-way cassette 5.6 kW×2 units 4-way cassette 4.5 kW×2 units Heat source water circulation pump 0.4 kW	Floor standing 28 kW×1 unit Heat source water circulation pump 0.4 kW
Well Pump	2.2 kW	2.2 kW	2.2 kW
Air Conditioned Area	Lobby, multipourpose room	Office	Factory workspace

3. METHOD

3.1 SCOP measurement from demonstration experiment

The amount of heat obtained from to the primary side of the heat pump per second is calculated by the following formula from the measured temperature and flow rate.

$$Q_1 = f_1 \rho_1 c \Delta T_{\mathrm{GW}} \tag{1}$$

Q_1 : primary side heat capacity [J/s]
f_1 : flow rate of pumped groundwater [m^3/s]
ρ_1: density of pumped groundwater [kg/m^3]
c : specific heat of pumped groundwater [J/kg/K)]
ΔT_{GW}: temperature difference of pumped groundwater between the inlet and outlet of plate heat exchanger [K]

Q_2 is the amount of heat on the secondary side, and the relationship between Q_1, Q_2, and W_1 is as follows.

$$Q_2 = \frac{Q_1}{1000} \pm W_1 \tag{2}$$

Q_2 : secondary side heat capacity [kW]
W_1 : power consumption of heat pump (outdoor unit) [kW]
$+$: heating , - : cooling

SCOP is system COP (Coefficient of Performance), and can be obtained by the following equation.

$$SCOP = \frac{Q_2}{W_1 + W_2 + W_3} \tag{3}$$

W_2 : power consumption of a groundwater pump [kW]
W_3 : power consumption of a circulation pump [kW].

When ΔT_{GW} is larger, the power consumptions of the heat pump is higher, while that of the groundwater pump is lower due to the lower flow rate of pumped groundwater. When ΔT_{GW} is smaller, the power consumptions of the heat pump is lower, while that of the groundwater pump is higher due to the higher flow rate of pumped groundwater. The power consumption of the system is the combined one of heat pump, groundwater pump and circulation pump. The changes of the power consumptions of heat pump and groundwater pump is dependent on ΔT_{GW}. We performed two different ways to estimate the optimal system COP; theoretical calculation and results of demonstration experiments.

3.2. SCOP estimation from Theoretical calculation

The power consumptions of the groundwater and circulation pumps are calculated from total head and total efficiency of the pump reported by the manufacturer.

$$W_1 = \frac{\rho_1 g v_1 H_1}{\eta_1} \tag{4}$$

$$W_2 = \frac{\rho_2 g v_2 H_2}{\eta_2} \tag{5}$$

ρ_1: density of pumped groundwater [kg/m^3]
ρ_2: density of antifreezing fluid [kg/m^3]
g: gravitational acceleration [m/s^2]
v_1: flow rate of pumped groundwater [m^3/s]
v_2: flow rate of antifreezing fluid [m^3/s]
H_1: Total head of pumped groundwater piping [m]
H_2: Total head of antifreezing fluid piping [m]
η_1 : total efficiency of groundwater pump [-]
η_2 : total efficiency of circulation pump [-]

We determined the temperature of pumped groundwater and antifreezing fluid in the plate heat exchanger (Figure 3). In the plate heat exchanger, the flow direction of the pumped groundwater and the antifreezing fluid is counter flow. The mean temperature difference between the pumped groundwater and the antifreezing fluid is shown in the following equation.

$$\Delta T_{\mathrm{LMTD}} = \frac{(T_4 - T_1) - (T_3 - T_2)}{\ln \frac{T_4 - T_1}{T_3 - T_2}} \tag{6}$$

ΔT_{LMTD} : logarithmic mean temperature difference between pumped groundwater and antifreezing fluid [K]
T_1 : pumped groundwater inlet temperature of plate heat exchanger [˚C]
T_2 : pumped groundwater outlet temperature of plate heat exchanger [˚C]
T_3 : antifreezing fluid inlet temperature of plate heat exchanger [˚C]
T_4 : antifreezing fluid outlet temperature of plate heat exchanger [˚C]

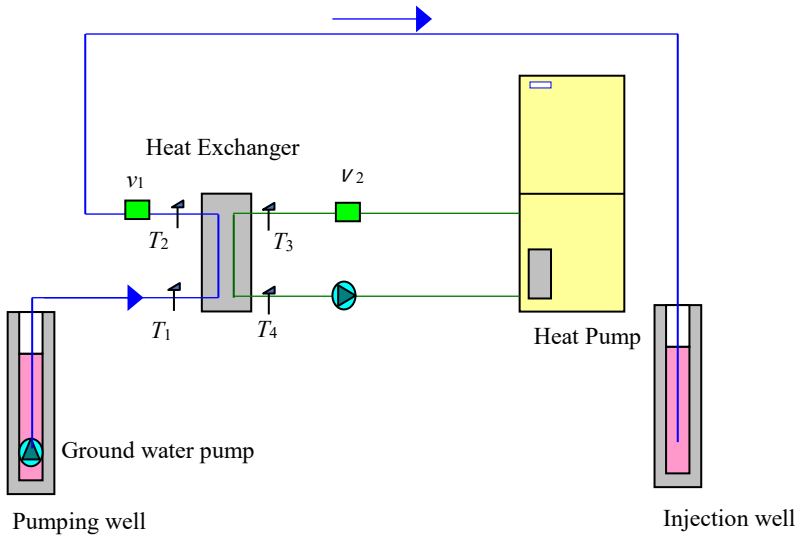


Figure 3: Monitoring points of temperature of pumped groundwater and antifreezing fluid in the plate heat exchanger.

The relationship between logarithmic mean temperature difference and heat at plate heat exchanger is shown in the following equation (The Japan Society of Mechanical Engineers, 2005).

$$Q_1 = KA\Delta T_{\mathrm{LMTD}} \tag{7}$$

K : heat transfer coefficient of plate heat exchanger [J/s/m^2/K]
A : heat exchange area of plate heat exchanger [m^2]

Since the overall heat transfer coefficient and heat exchange area in the plate heat exchanger are constant, *KA* can be considered to be constant. Therefore, the antifreezing fluid outlet temperature at plate heat exchanger (= antifreezing fluid inlet temperature at the heat pump) can be calculated from the pumped groundwater temperature and the difference between the pumped groundwater inlet and outlet temperatures and the antifreezing fluid inlet and outlet temperatures. Based on the antifreezing fluid temperature from the performance curve of the heat pump, the power consumption and primary side capacity of the heat pump can be obtained.

$$T_4 = T_1 \pm \frac{\Delta T_{AF} - \Delta T_{GW}}{1 - \exp(-\frac{KA}{Q_1}(\Delta T_{AF} - \Delta T_{GW})} \tag{8}$$ from equation (1) and (2)

$$\Delta T_{GW} = T_1 - T_2 \tag{9}$$

$$\Delta T_{AF} = T_4 - T_3 \tag{10}$$

ΔT_{AF} : temperature difference of antifreezing fluid between inlet and outlet of the plate heat exchanger [K]

Since the required flow rates of pumped groundwater and antifreezing fluid can be calculated from the primary side capacity and ΔT_{GW} and ΔT_{AF}, the power consumption of the groundwater pump and circulation pump can be calculated. *SCOPn* for each air conditioning load factor can be calculated from the calculated power consumption of the heat pump, groundwater pump, circulation pump and the partial load. The maximum loads for each site are 28.0 kW for cooling and 31.5 kW for heating at the Yokkaichi and Nagoya sites, and 50.4 kW for cooling and 56.0 kW for heating at the Gifu site. The average *SCOPy* can be obtained by dividing the total air conditioning load during the period by the total power consumption of the heat pump and pump during the period. However, here, the total *SCOPn* weighted by the incidence of the air conditioning load factor is used as the period average *SCOPy* of the system. *SCOPy* is calculated for each setting ΔT_{GW}, and the ΔT_{GW} with the maximum *SCOPy* is set as the optimum value.

$$SCOP_y = \Sigma(SCOP_n \cdot a_n) \tag{11}$$

$n = 100\%, 75\%, 50\%, 25\%$
$SCOP_{100\%}$: SCOP at 100% air conditioning load
$SCOP_{75\%}$: SCOP at 75% air conditioning load
$SCOP_{50\%}$: SCOP at 50% air conditioning load
$SCOP_{25\%}$: SCOP at 25% air conditioning load
$a_{100\%}$: weighting factor for 100% air conditioning load
$a_{75\%}$: weighting factor for 75% air conditioning load
$a_{50\%}$: weighting factor for 50% air conditioning load
$a_{25\%}$: weighting factor for 25% air conditioning load

(The Japan Refrigeration and Air Conditioning Industry Association, 2017)

4. RESULTS

4.1 Results of theoretical calculation

Figures 4 to 6 shows the results of the SCOP calculations along with the percentage of power consumed by the heat pump, groundwater pump, and circulation pump. It can be confirmed that the smaller the value of setting ΔT_{GW} is, the higher the percentage of power consumption of the pump becomes. Here, ΔT_{GW} in Figures 4 to 6 means the setting value of ΔT_{GW}. When the setting of ΔT_{GW} is 0.1 K, the flow rate of the groundwater pump becomes larger (or maximum) to try to control ΔT_{GW} toward 0.1 K. But it is impossible to adjust ΔT_{GW} to 0.1 K, when the thermal load of the heat pump is larger. So, the setting value of ΔT_{GW} is not always equal to the actual ΔT_{GW}. For all sites, when the setting value of ΔT_{GW} is 0.1 K and 9 or 10 K, SCOP is lower than for other values of ΔT_{GW}. At the Nagoya site and Yokkaichi site, the setting value of ΔT_{GW} with maximum SCOP is 5 K for both cooling and heating. At the Gifu site, the setting value of ΔT_{GW} with maximum SCOP is 5 K for cooling and 7 K for heating. The air-conditioned room temperature is assumed to be 27°C DB/19°C WB for cooling and 20°C DB for heating.

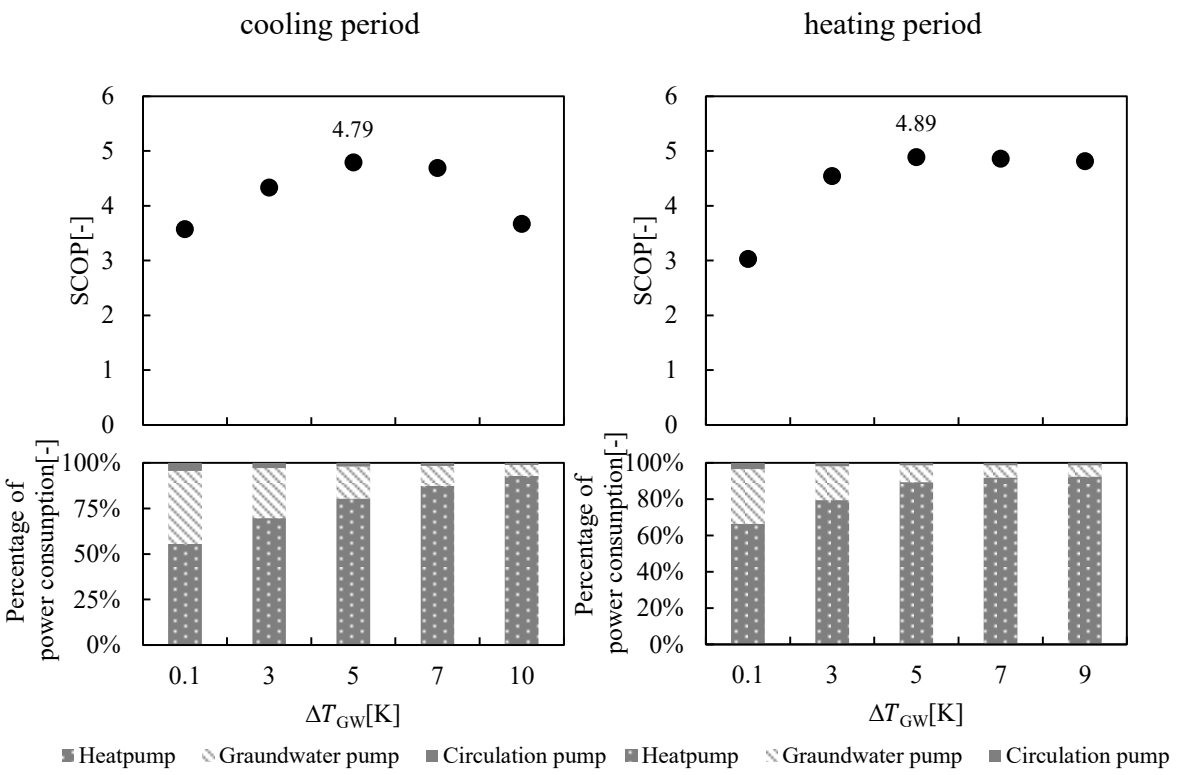


Figure 4 SCOP and setting value of ΔT_{GW} at Nagoya site.

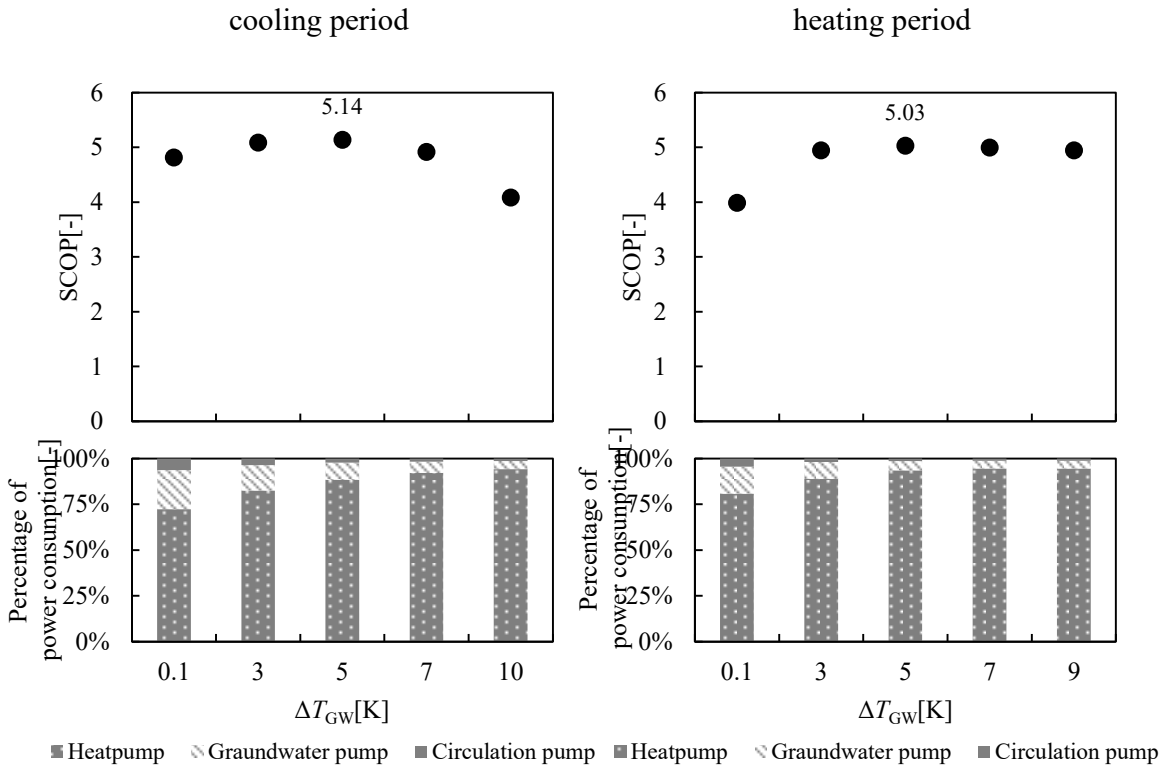


Figure 5 SCOP and setting value of ΔT_{GW} at Yokkaichi site.

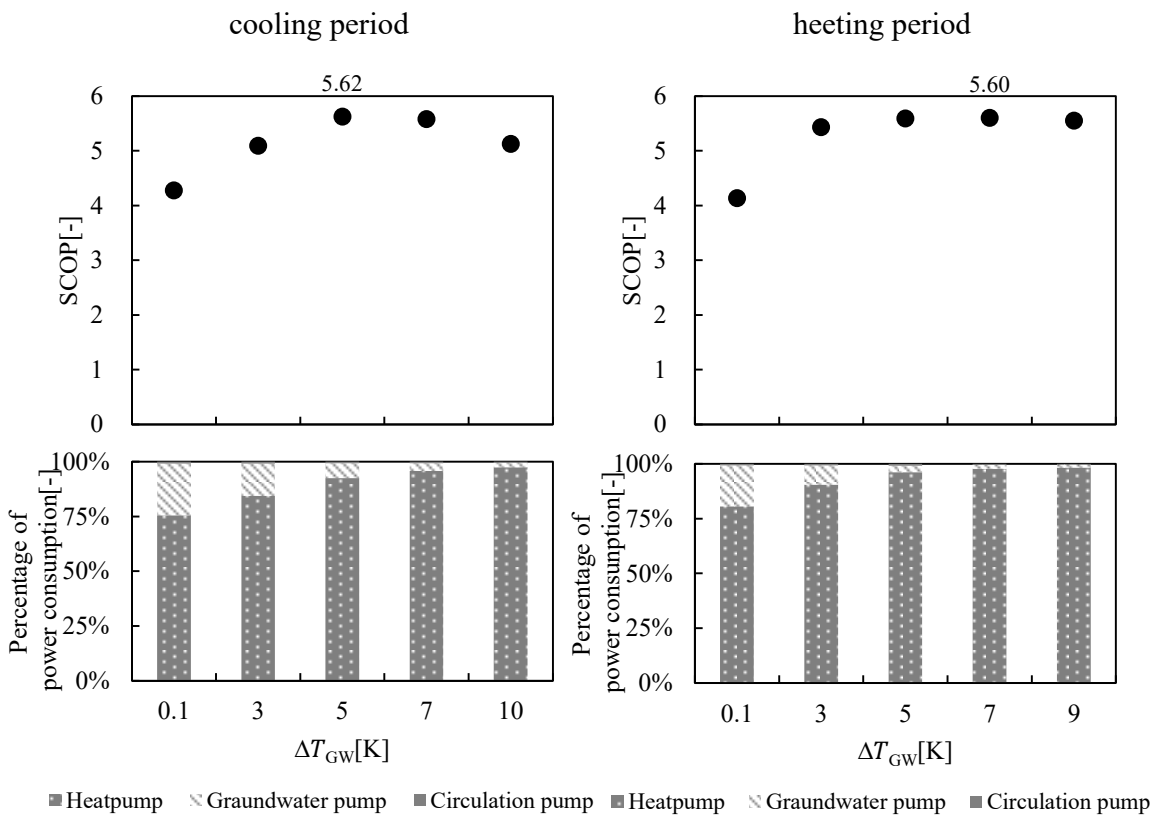


Figure 6 SCOP and setting value of ΔT_{GW} at Gifu site.

4.2 Results of Demonstration Experiments

In the demonstration test facility at each site, the open loop system was operated by changing ΔT_{GW} setting values every day. The setting values of ΔT_{GW} are 0.1, 3, 5, 7, 9, and 10 [K]. SCOP was calculated from the measured temperatures, flow rate and power consumption.

The setting value of ΔT_{GW} is the target of ΔT_{GW} and it is not always equal to its actual value of ΔT_{GW}. When the system is operated at 0.1 K of the setting value of ΔT_{GW}, the flow rate of the pumped groundwater is controlled at higher rate to make the actual ΔT_{GW} closer to the setting ΔT_{GW}. Although the requested flow rate of the pumped groundwater becomes very high at higher heating/cooling demand, the flow rate has a maximum limitation due to the water pump capacity and it cannot be increased above the limitation. In this case, the actual ΔT_{GW} becomes higher than the setting ΔT_{GW}. When the system is operated at 10 K of the setting value of ΔT_{GW}, the flow rate of the pumped groundwater is controlled at lower rate to make the actual ΔT_{GW} closer to the setting ΔT_{GW}. Although the requested flow rate of the pumped groundwater becomes very low at lower heating/cooling demand, the flow rate has a minimum limitation due to the invertor control and it cannot be decrease under the limitation. In this case, the actual ΔT_{GW} becomes lower at the lower and higher setting ΔT_{GW}.

Figures 7, 8, and 9 show the relationship between the measured SCOP and the setting ΔT_{GW} at the three experimental sites. The air conditioning load processed by the heat pump and the ratio of power consumption of the heat pump and groundwater pump and circulation pump are also shown. Each figure clarifies that the measured SCOP becomes lower at the setting ΔT_{GW} of 0.1 K. The maximum measured SCOPs of cooling are 4.51 at the setting ΔT_{GW} of 7 K (Nagoya site; Figure 7), and 5.22 at the setting ΔT_{GW} of 7 K (Gifu site; Figure 9). Those of heating are 4.15 at the setting ΔT_{GW} of 4 (Yokkaichi site; Figure 8), and 3.39 at the setting ΔT_{GW} of 5 K (Gifu site; Figure 9).

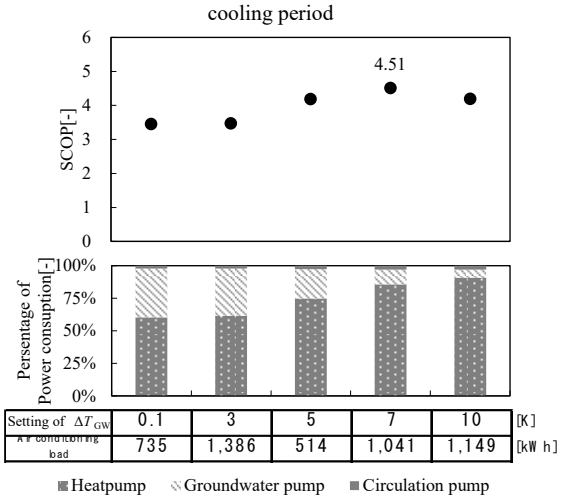


Figure 7 SCOP and setting value of ΔT_{GW} at Nagoya site.

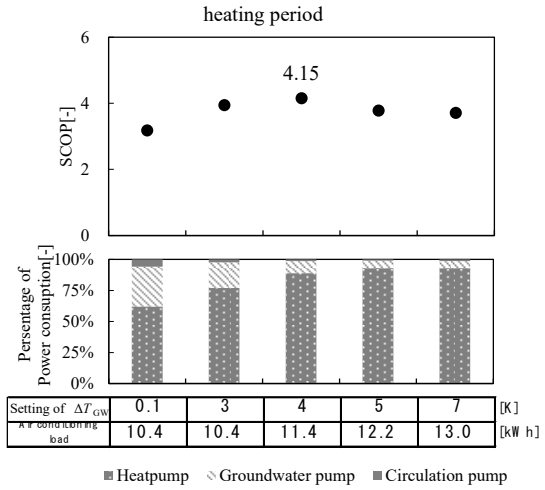


Figure 8 SCOP and setting value of ΔT_{GW} at Yokkaichi site

(The demonstration experiment time is short at the Yokkaichi site, about 30 minutes for each setting.)

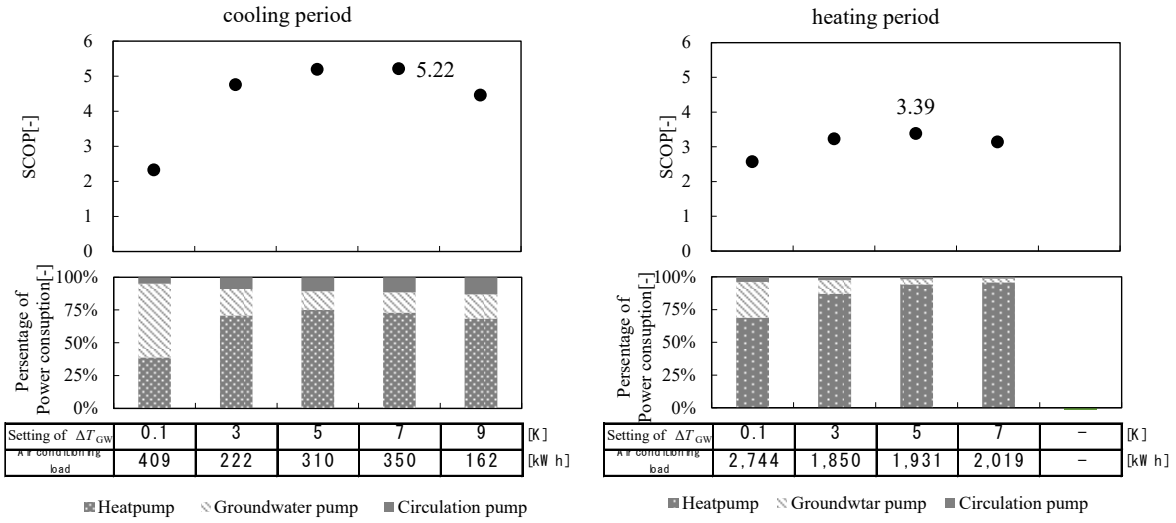


Figure 9 SCOP and setting value of ΔT_{GW} at Gifu site

Figure 10 shows the relationship between the measured SCOP and the actual ΔT_{GW} at Gifu site of heating period. The actual ΔT_{GW} with lower load factor such as < 25 % is not close to the setting ΔT_{GW}. That with higher load factor is similar to the setting ΔT_{GW}.

Overall, the SCOP was lower in the results of demonstration experiment than in the theoretical calculations. The room temperature assumed in the theoretical calculation and the room temperature in the demonstration experiment were not compared. The difference in room temperature may be one of the reasons for the discrepancy between the demonstration experiment and theoretical calculation results of SCOP. The capacity correction due to the length of the refrigerant piping from the outdoor unit to the indoor unit of the heat pump could also be one of the factors. All ΔT_{GW} settings show that the measured SCOP becomes lower from 2 K to 0 K of the actual ΔT_{GW}. The measured SCOP is almost constant above 2 K of the actual ΔT_{GW} at 0.1 K, 3 K, and 5 K of the setting ΔT_{GW}, which it becomes lower toward the higher actual ΔT_{GW} above 2 K at 7 K of the setting ΔT_{GW}. These reflect the relationship between SCOP and electric power consumption of the heat pump and the water pump. The electric power consumption of the heat pump changes depending on the heat load. It is higher at medium load and lower at lower and higher load. The electric power consumption of the water pump changes depending on the actual ΔT_{GW}. It is higher at medium ΔT_{GW} and lower at lower and higher ΔT_{GW}. SCOP tends to be high at 5 K of the actual ΔT_{GW}.

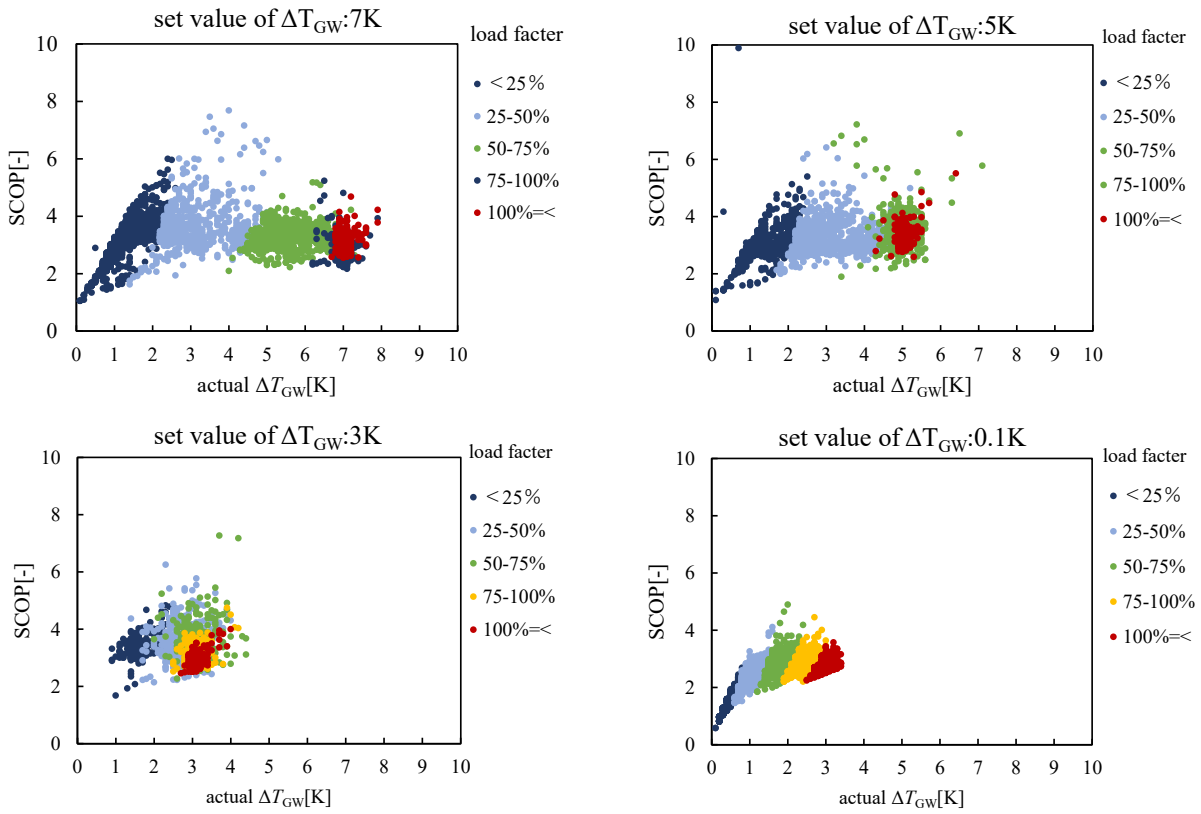


Figure 10 SCOP and actual value of ΔT_{GW} at Gifu site

5. DISCUSSION

Table 2 shows the results of comparison between actual measurement and theoretical calculation of optimum ΔT_{GW}. The difference between the results of the theoretical calculation and the demonstration experiments of the optimum ΔT_{GW} at all sites is within 2 K, indicating some agreement.

Table 2: Comparison between actual measurement and theoretical calculation of optimum ΔT_{GW}

		Nagoya site	Yokkaichi site	Gifu site
cooling	calculation	5	5	5
	demonstration experiments	7	-	7
heating	calculation	5	5	7
	demonstration experiments	-	4	5

[K]

Under conditions where ΔT_{GW} is too small, the flow rates of pumped ground water become constant and maximum. In this case, SCOP decreases because the ratio of the power consumption of the ground water pump to the total power consumption becomes large. Also, when ΔT_{GW} is too large, although the power consumption of the ground water pump can be reduced, the temperature condition of antifreezing fluid supplied to the heat pump becomes worse, this results in the decrease of COP of the heat pump and SCOP also decreases. It was confirmed that the difference in the setting value of ΔT_{GW} is meaningless at lower load operation where the flow rate of pumped groundwater is less than the minimum flow rate of the groundwater pump. On the other hand, in the operation of the load where ΔT_{GW} is in accordance with the setting value, SCOP differed depending on the setting value of ΔT_{GW}, and the maximum SCOP value is mostly obtained at 5 or 7 K of ΔT_{GW}.

In the future, we will improve the theoretical calculation system by taking into account the inside air temperature conditions in the area to be air-conditioned by the heat pump. The final goal is to be able to estimate the optimum ΔT_{GW} for an open-loop system at an arbitrary point in the design phase.

6. CONCLUSION

Measured SCOP of the open loop system at three sites with different conditions (Gifu, Yokkaichi and Nagoya, central Japan) were compared with SCOP estimated by theoretical calculation to obtain the optimum ΔT_{GW}. Demonstration experiment at each site was performed under the several patterns of setting ΔT_{GW}. The difference between the results of the theoretical calculation and the demonstration experiments of the optimum ΔT_{GW} at all sites is within 2 K, indicating some agreement.

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