

NUMERICAL SIMULATION OF GROUND HEAT AND WATER TRANSFER FOR GROUNDWATER HEAT PUMP SYSTEM

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Abstract: By utilizing the relatively stable temperature of groundwater, groundwater heat pump systems can achieve a higher coefficient of performance and can save more energy than conventional air-source heat pump (ASHP) systems. However, the regulations for making the well and pumping in the centre of cities are too strict. For the optimization of design and operation of GWHP systems, it is necessary to develop a method for considering heat flow under the ground and the building's condition comprehensively. This paper describes the optimization of GWHP systems based on an air-conditioning experiment utilizing real-scale equipment and 3D numerical heat-water transfer simulation. Analysis results were compared with the experimental results, and the validity of the simulation model developed in this study was confirmed. Furthermore, optimum operation methods have been considered by calculating the coefficient of performance for various groundwater and well conditions.

Key Words: *Groundwater heat pump system, Numerical simulation, Real-scale experiment, Groundwater flow*

1 INTRODUCTION

The groundwater heat pump system is an open-loop system that draws water from a well or surface water, passes it through a heat exchanger and discharges the water into an injection well or nearby river. By utilizing the relatively stable temperature of groundwater, this system can achieve a higher coefficient of performance and offers a more energy-saving solution than the conventional air-source heat pump (ASHP) system. However, the benefit of utilizing groundwater may not be fully achieved everywhere because system performance depends significantly on hydrologic and geological conditions (for example, aquifer depth, groundwater quality, the cooling and heating pattern, building load, etc.). In order to optimize the design and operation of GWHP systems, it is necessary to develop a method that comprehensively considers the underground heat flow and building conditions. Research into utilizing GWHP systems has been conducted since the first large commercial applications installed in the late 1940s. Kavanaugh S.P. and Rafferty K. explained the proper design, installation and operation of the system and reference the optimization of GWHP systems (Kavanaugh S.P. and Rafferty K. 1997). Rees S.J. and Spitler J.D. have studied GWHP system performance using the standing column well by developing groundwater and well models with a finite volume model (Rees S.J. et al. 2004). In Japan, much research has been conducted which uses groundwater for media of heat storage (Umemiya H. and Aoyagi T. 1991; Ochifuji K. et al. 1992) or for as a source for space heating and cooling (Nakamura M. et al. 2002). However, in spite of these researches, GWHP systems have not seen widespread use in Japan because of restrictions introduced in the 1960s on the pumping in the centre of cities in order to prevent ground subsidence. On the other hand, the groundwater level in Tokyo has risen gradually and serious effects on the foundation of buildings have

been reported. Therefore, in order to optimize these systems, it is necessary to deliberately consider below-ground hydrologic, geological and thermal environmental conditions in design. This paper describes the numerical simulation of water and heat transfer for the GWHP system based on an air-conditioning experiment utilizing real-scale equipment.

2 ANALYSIS SUMMARY

In this section, a numerical simulation was conducted to develop an analysis model for predicting the heat exchange rate and to estimate the effect of this system on the underground environment. In order to accurately calculate the groundwater pumped from a well, it is necessary to analyze the heat transfer and groundwater flow simultaneously. In this analysis, FEFLOW was used, which can simulate groundwater flow and heat transfer in the ground and is widely used in the fields of hydrology, geology, and geotechnical engineering. This code is based on the following three equations of conservation for mass, momentum, and energy for the combination of soil particles, liquid water, and gas.

Mass conservation equation

$$\frac{\partial}{\partial t}(\varepsilon_\alpha \rho^\alpha) + \frac{\partial}{\partial x_i}(\varepsilon_\alpha \rho^\alpha v_i^\alpha) = \varepsilon_\alpha \rho^\alpha Q_\rho^\alpha \quad (1)$$

Momentum conservation equation

$$v_i^\alpha + \frac{k_{ij}^\alpha}{\varepsilon_\alpha \mu^\alpha} \left(\frac{\partial p^\alpha}{\partial x_j} - \rho^\alpha g_j \right) = 0 \quad (2)$$

Energy conservation equation

$$\frac{\partial}{\partial t}(\varepsilon_\alpha \rho^\alpha E^\alpha) + \frac{\partial}{\partial x_i}(\varepsilon_\alpha \rho^\alpha v_i^\alpha E^\alpha) + \frac{\partial}{\partial x_i}(j_{iT}^\alpha) = \varepsilon_\alpha \rho^\alpha Q_T^\alpha \quad (3)$$

Here, α is each phase such as liquid water, vapor water, and the soil solid particles, ε_α is the volume ratio of each phase α ($0 \leq \varepsilon_\alpha \leq 1$), ρ_α is the density of phase α [kg/m^3], v_i^α is the velocity vector of phase α [m/s], k_{ij}^α is the permeability tensor [m^2], μ^α is viscosity [kg/ms], Q_ρ^α and Q_T^α are mass and energy generation terms, respectively, and j_{iT}^α is the heat flux.

3 REAL-SCALE EXPERIMENT

3.1 Experiment Summary

An experimental facility was built on-site at the University of Tokyo campus in Chiba. Chiba is to the east of Tokyo, and the average annual air temperature is about 15.4°C; the average air temperature is about 26.4°C in August and 5.4°C in January. The plan of the experimental facility and the system configuration are shown in Figure 1. This system used an existing ground source heat pump system facility. It has five wells (Ø100 mm, depth 20 m) of which two are utilized for pumping and injection, and two rooms in which a fan coil unit and a radiation air conditioner are installed. Thermostat and electrical valves control the amount of water supplied to the fan coil unit. The system employed in this experimental equipment consists of a water-to-water heat pump with a reciprocating compressor (4.6kW in cooling, 5.7kW in heating). Cold and hot water circulates through a fan coil unit and a radiation panel, respectively, in these two examination rooms. During heating or cooling operations, groundwater is pumped from the production well and injected into the return well after heat exchange by the heat pump.

Fig. 1(b) shows a section of the well. Well Nos. 4 and 2 were used as the production and return wells respectively, at a distance of 32 m apart.

The heat pump in this system was operated from 9:00 to 18:00, Monday to Friday, as in typical office buildings. It was not operated on Saturday or Sunday. During the cooling experiment (from 9th Oct. to 22nd Oct.), heat was discharged (sunk) into the groundwater. However, because the cooling load in October was insufficient compared with that in summer, the electric heating pads (750 W×2) and room air-conditioner (heating 2.8 kW) were used to produce an artificial load.

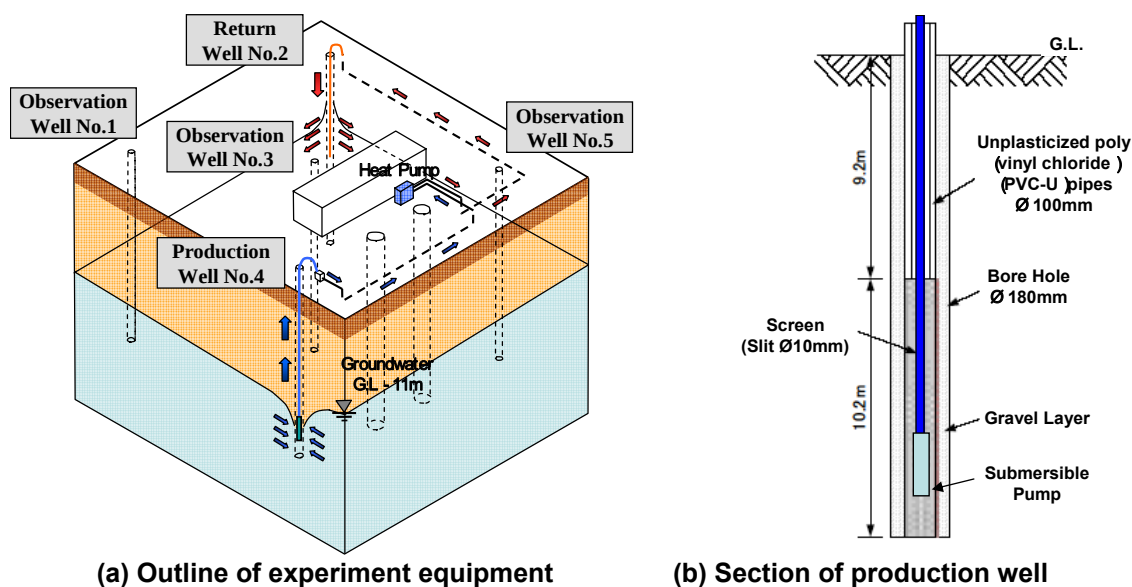


Figure 1: Outline of system

3.2 Experiment Results

Figure 2 shows the results of the heating experiment in winter. The temperature of the groundwater from the production well remained at approximately 18°C for the entire experimental period. The heat exchange rate was calculated from the pumping rate of the groundwater and the temperature difference between the inlet and outlet at the heat pump. In the cooling experiment, the average heat exchange rate was 5.5kW with an average pumping rate of 47 L/min (28.2 m³/day). It could achieve greater than 10 kW during the heating experiment during which the heating load was raised by opening a window. In this experiment, groundwater temperature and groundwater levels at the observation wells have been measured, and will be compared with simulation results in next section.

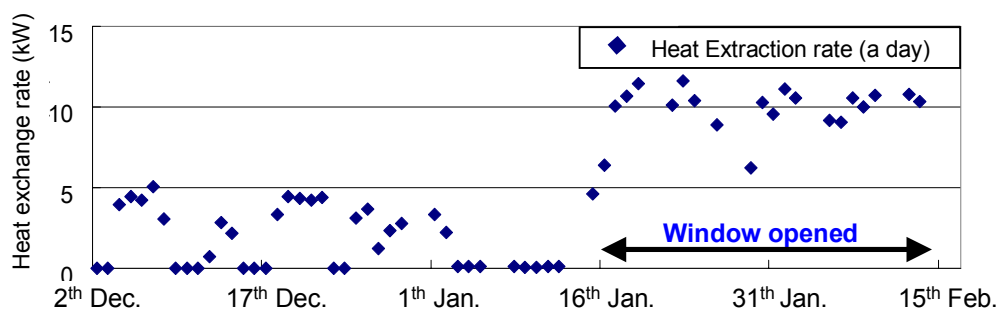


Figure 2: Heating experiment results

4 COMPARISON ANALYSIS

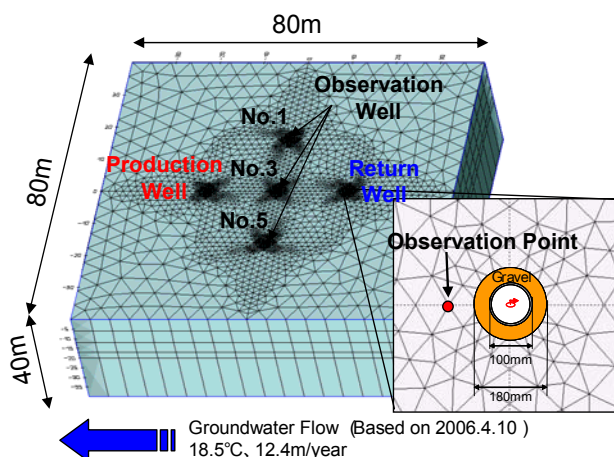


Figure 3: Simulation model

The analysis model shown in Figure 3 has five wells located 16m apart in an 80 m × 80 m × 40 m area. Groundwater is at a depth of 10.85 m and the groundwater flow velocity is given by Darcy's equation with the water level gradient. A screen is installed 10 to 20 m underground, and the groundwater flux is set to the same value as the experimental pumping rate. Heat flux is calculated from the temperature and the amount of pumping water for the assumed cooling and heating load, which is given at the return well. The soil properties and other analysis conditions are shown in Table 3. These conditions are based on the results obtained from a boring test at the Chiba experimental station.

Table 1; Calculation conditions

Depth (m)	6	12	40	Gravel
Porosity	0.8	0.4	0.35	0.3
Hydraulic conductivity (10^{-4} m/s)	0.1	1.3	2.1	100
Heat conductivity (W/mK)	1.7	2.4	2.7	2.7
Heat capacity (10^6 J/m ³ K)	3.9	3.0	2.9	2.9

Figure 4 shows the calculation results: distributions of hydraulic head (a) and ground temperature (b) at a depth of 17 m at 3 p.m. on 30th January, 2007. The groundwater flow around the well and the heat diffusion boundaries are presented.

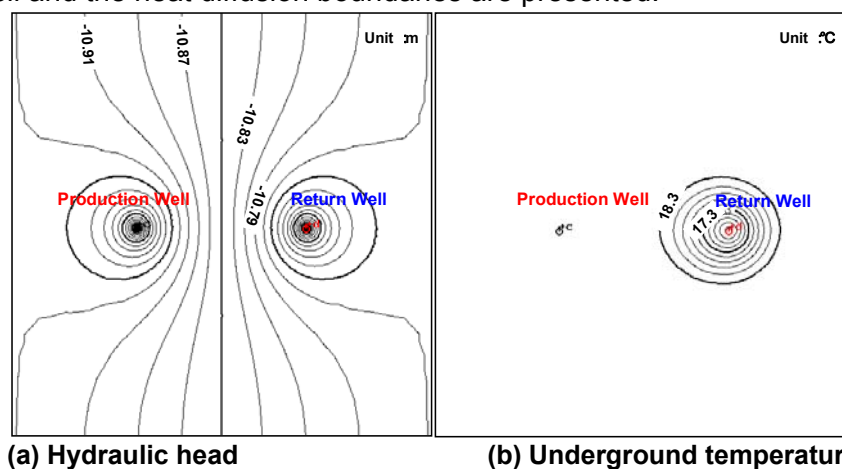


Figure 4: Simulation results

Figure 5 (a) shows the variation in groundwater temperature at the production well and compares the simulation and experimental results. Although the simulation results were lower than the experiment, this represents a slight fall in temperature at the return well, which was due to extraction of heat from the groundwater during the heating operation. Moreover, the hydraulic head of groundwater at Well No. 3 was compared in Figure 5 (b). Both results were for a groundwater depth of about 10.85 m, and the simulation results agreed well with the experiment.

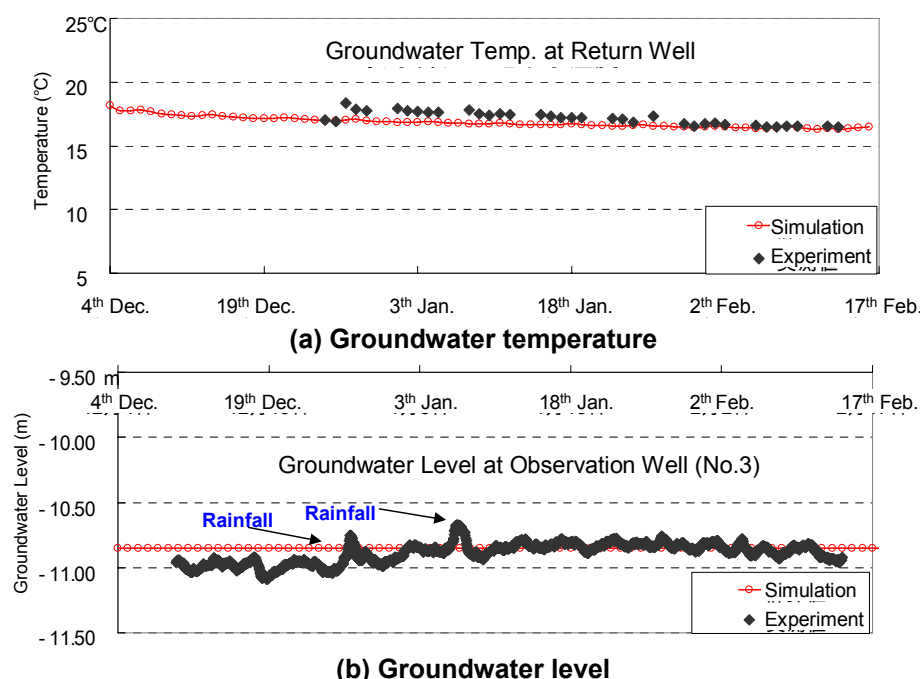


Figure 5: Comparison of simulation and experiment results

5 CASE STUDY ANALYSIS

5.1 ANALYSIS SUMMARY

The performance of GWHP system significantly depends on the groundwater conditions and the underground thermal properties. For the optimum use of this system, it is necessary to design the system and decide the operation method based on the conditions of the site. In this paper, the effects of groundwater flow and pumping rate on system COP have been estimated by numerical analysis.

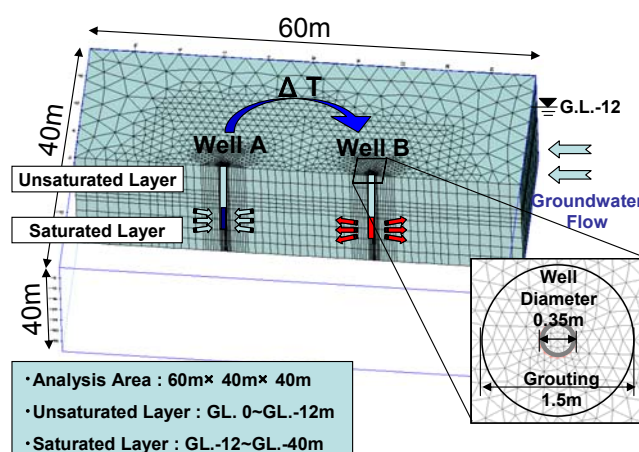


Figure 6: Analysis model

The simulation model is assumed as an office building (total floor area 23,000m³) site in Tokyo, Japan. Annual heating and cooling load of the building are 2230GJ and 4503GJ, respectively. The building has eight wells available for pumping and injection and two of these are used for the analysis model. The analysis model shown in Figure 6 has two wells located at a 20-m distance in a 60 m × 40 m × 40 m area. In summer, the groundwater is pumped from well A, heat is exchanged, and the water is injected to well B. In winter, it is pumped from well B, and injected to well A after the heat exchange. The groundwater and well conditions are given in Table 2. The velocity and direction of groundwater are set as parameters in order to capture the suitable well design according to the groundwater condition. In this calculation, operation methods are set four patterns (Table 3). Patterns 1 and 2 are the operations which used heat sources from groundwater only. Patterns 3 and 4 utilize both air source and groundwater heat pump systems. Here, ΔT is the difference of water temperature between pumping and injection. Heating and cooling were performed in December to February and June to August, respectively, from 8:00 to 18:00, Monday to Friday. Heat and water fluxes in the cooling and heating periods were calculated by the temperature and groundwater pumping rate set at the surface of each mesh, which is assumed to be the well screen (depth -20 m to -30 m). Analysis period is set at 3 years and the performance of the entire system in each case is estimated by the pumping temperature during the operation periods.

Table 2; Condition of groundwater and wells

Case	V (m/year)	Natural direction of groundwater flow
A	0	Horizontally, from Well B towards A
B	22	Horizontally, from Well B towards A
C	44	Horizontally, from Well B towards A
D	44	Vertically, from ground surface down
E	44	Horizontally, from Well A towards B

Table 3; Operation patterns

Operation Patterns	ΔT (°C)		Pumping rate (m ³ /day)		Load of GWHP (GJ)		Load of ASHP (GJ)	
	C	H	C	H	C	H	C	H
1	5	5	295	295	2230	2230	2273	0
2	10	10	147.5	147.5	2230	2230	2273	0
3	5	5	641	295	4503	2230	0	0
4	10	20	320.5	65.7	4503	2230	0	0

*C : Cooling / H : Heating

5.2 ANALYSIS RESULTS

In this paper, the case with the highest system COP is selected as the optimum method because heat pump COP depends on the temperature of heat source. The COP of GWHP can be evaluated by the temperature of pumping water and performance curve. Figure.7 shows performance curve used in this research, which is calculated when the outlet temperature from heat pump to room is 7°C (return temperature 12°C) in the cooling mode and 45°C (return temperature 40°C) in the heating mode. Figure 8 (a) to (d) shows calculation results of heat pump COP. Generally, the higher the velocity of groundwater flow is, the more significant the recovery of ground temperature. In case A (condition of no groundwater flow), cooling COP in patterns 1 and 2 is relatively high, but heating COP is lower than that in patterns 3 and 4. This result indicates that in patterns 3 and 4, which utilize

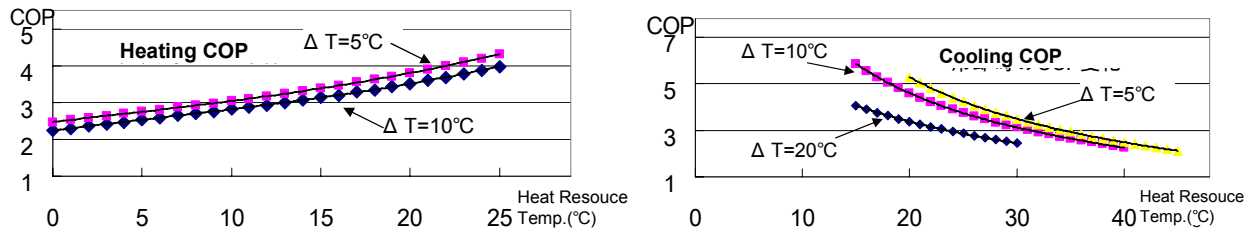


Figure 7: Performance curve of heat pump

only GWHP system for the building loads, more heat emitted during summer is stored more than patterns 1 and 2. On the other hand, in the case in which there is groundwater flow, for cooling operation, the higher the velocity of groundwater is, the faster the recovery of temperature around the well. Therefore, COP increases. In pattern 2, in which ΔT is 10°C, the reduction of heat storage by advection of groundwater is more dominant than the recovery of temperature by groundwater flow during system operation. In heating operation, in which the water is pumped up from the lower hydrological side of the pumping well, the pumping temperature is affected by the cooled heat on the upper side of the well when the velocity of groundwater is high. Thus recovery of the temperature is significant, and COP becomes lower. It was found that the gradient of groundwater between two wells affects the pumping temperature in cooling and heating operation.

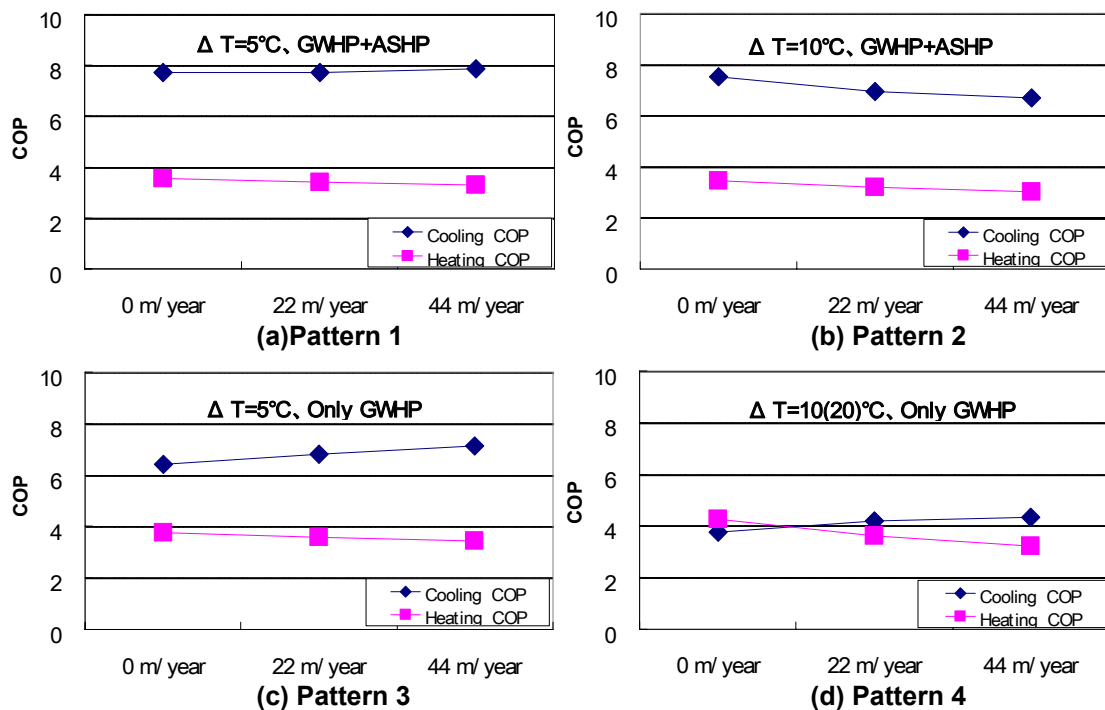


Figure 8: Variation of heat pump COP according to groundwater flow

Furthermore, system COP (S.COP) is calculated by annual heating and cooling loads for

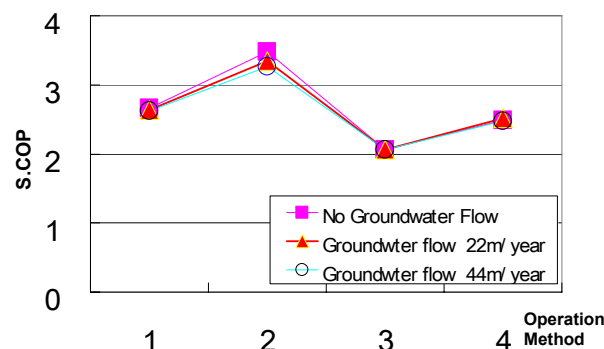


Figure 9: Variation of system COP according to operation method

total consumption of electric power in pump, groundwater heat pump, and air source heat pump (assumed 6.0, average COP). The consumption of pump is the value obtained by assuming that a submersible pump (20 m lift) and heat storage tank are used. The result of the calculation for System COP is shown in Figure.9. COP of a heat pump, when ΔT is 5°C, was shown to be higher than that in other cases. However, when the total consumption of electric power is taken into account, the results are found to be different from that mentioned above. System COP in method 2 ($\Delta T=10^\circ\text{C}$), in which the operation method utilizes GWHP and ASHP simultaneously, is the highest because the consumption of electric power in a pump is low. Therefore, method 2 is considered to be the optimum case.

6 CONCLUSIONS

In this paper, numerical analysis was conducted using 3-D ground heat and groundwater transfer simulation tools, based on experiments with real-scale equipment, in order to study the optimization of design and operation for GWHP system. The simulation results were compared with the experimental results, and good agreement was found. Furthermore, in order to determine the optimum system for the groundwater heat pump system, case study analyses under several conditions were conducted. Through these analyses, it was confirmed that the condition of groundwater flow and the position of a well should be taken into account in order to optimize system operation. In the future, studies on ways to develop optimizations for this system will continue by utilizing the simulation tool coupled with the underground and building models.

7 REFERENCES

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