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IMPROVEMENT OF OPERATIONAL SCENARIO FOR AN ENHANCED AQUIFER THERMAL ENERGY STORAGE (E-ATES) SYSTEM BASED ON NUMERICAL SIMULATIONS

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The E-ATES system was constructed at Shinshu University, Japan. Since November 15, 2011, a pilot plant of groundwater-source heat pump (GSHP) system coupled with the E-ATES has been put into operation for cooling and heating two lecture rooms of a building. The result of the experiment from 2011 to 2012 revealed that the GSHP system with E-ATES is superior to the conventional air-source HP systems. The result of numerical simulations for E-ATES optimization shows that the recovery of stored thermal energy can be significantly improved by changing a scheme of pumping and recharging.

Keywords: groundwater, aquifer thermal energy storage, numerical simulation, well system, optimization

INTRODUCTION

A typical ATES system uses pumped groundwater as a heat source while discharged heat from air-conditioning process is stored in aquifer systems. However, the stored thermal energy may be lost under the condition of flowing groundwater due to heat conduction and dispersion without proper control of groundwater flow and heat transport. The idea of the E-ATES is to construct a withdrawal/injection well system by controlling groundwater flow by means of withdrawal and injection of groundwater. This system enables maximization of cool and warm recovery by optimizing withdrawal and injection rates at wells.

Figure 1 illustrates the E-ATES system constructed for cooling and warming two rooms (108 m2 each) of a lecture building at Shinshu University [1]. Pumped groundwater is first treated at a pre-water quality treatment unit to reduce suspended solids and dissolved minerals, then sent to heat pumps connected with fan coil units (FCU) and air conditioners. After heat exchange at the heat pumps, used groundwater is delivered to a post-water treatment unit for de-aeration and finally to injection wells of C1 or C2. On the other hand, a conventional air-source HP (ASHP) system was also constructed for a room of the same building for comparing the efficiency of both systems.

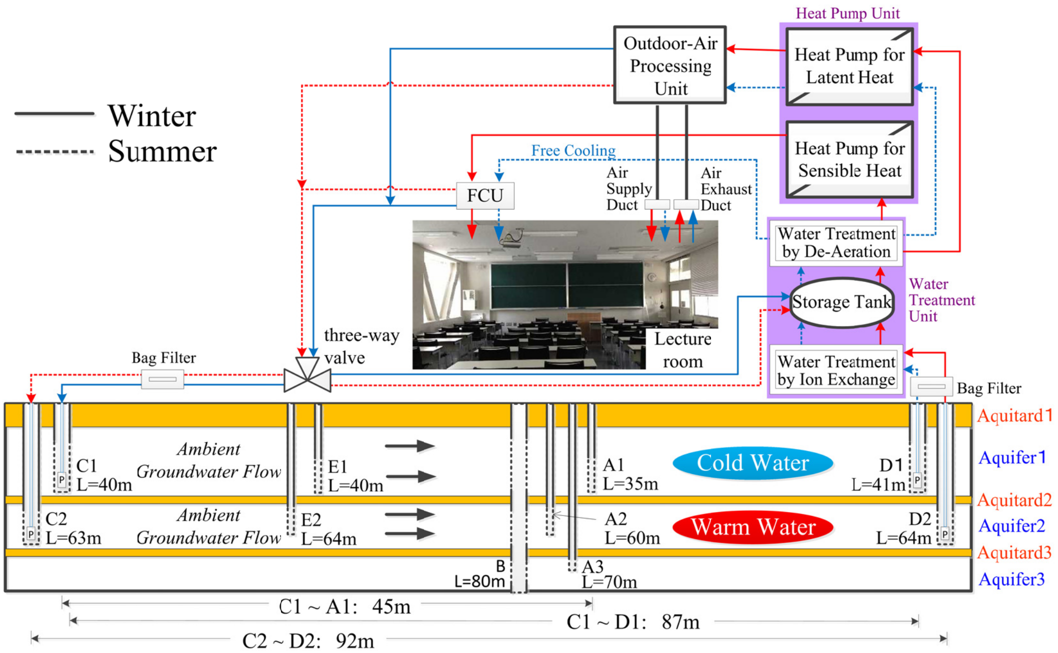

Figure 1. A schematic diagram of the groundwater-source HP system based on the E-ATES.

RESULTS OF THE OPERATION

We operated the developed system during the period of November, 2011 to October, 2012 so that SCOP is improved by modifying the whole system [2] [3]. The comparison of the SCOP between E-ATES GSHP and ASHP shows that the E-ATES GSHP is superior to the ASHP all over the seasons as shown in Figure 2. Further, the monitoring data of the GSHP system under the cooling experiment showed much higher performance than the warming experiment.

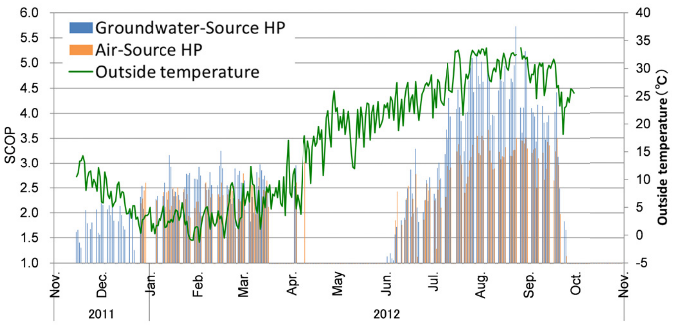

Figure 2. Comparison of SCOP between Groundwater-SHP and Air-SHP

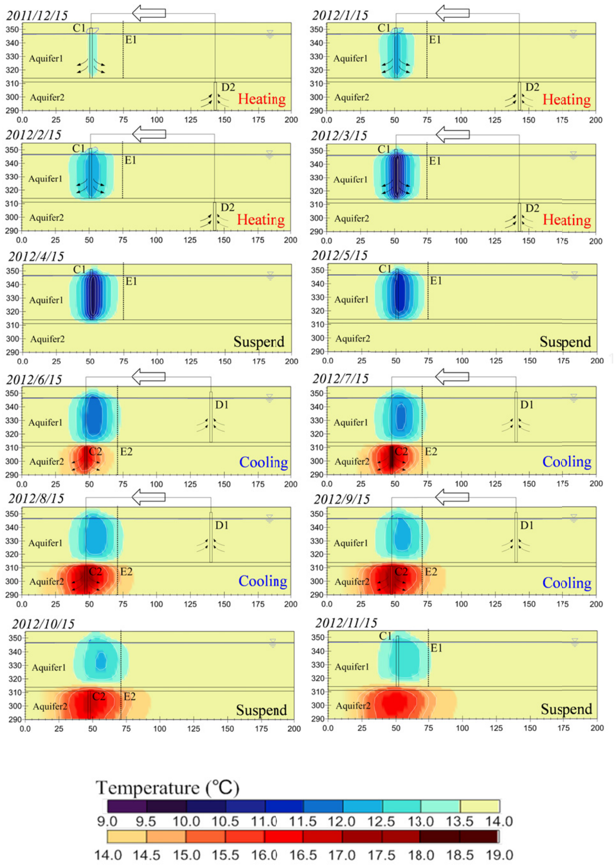

Figure 3. The results of numerical simulation based on an actual operating conditions by SWATER3dp

However, as the results of numerical simulation based on the actual system operating conditions by SWATER3dp (Subsurface Water and Thermal Energy Resources; 3-dimensional model using prism finite elements) as shown in Figure 3 and the results of field observation, the stored cool during winter and the warm during summer were not recovered as we first planned due to small flow velocity of groundwater, which is attributed to accuracy of field tests.

SYSTEM OPTIMIZATION BY NUMERICAL SIMULATIONS

Scenario

Numerical simulations by SWATER3dp were performed to analyze coupled phenomena of groundwater flow and heat transport in the aquifer system in order to optimize the E-ATES GSHP system.

Hereafter, we name the past operation scenario "Operation 1" and a new pumping and recharging scenario "Operation2" and "Operation3" that are based on the evolved groundwater conditions for numerical simulation as shown in Table 1. In "Operation2", groundwater is pumped from D1 well and recharged into C1 well during summer, while in winter pumped from C1 and recharged into D1. In "Operation3", groundwater is pumped from D2 well and recharged into C2 well during summer, while in winter pumped from C2and recharged into D2.

Table 1. Scenario for optimize the E-ATES GSHP system.

Scenario	Well system for air-conditioning			
	Cooling		Heating	
	Pumping	Injection	Pumping	Injection
Operation1 (baseline)	D1	C2	D2	C1
Operation2 (improved)	D1	C1	C1	D1
Operation3 (improved)	D2	C2	D2	C2

Results of the numerical simulations

Figure 4(a) shows the simulated groundwater temperature profile of Operation 1, and Figure 4(b) and Figure 4(c) show that of Operation 2 and Operation 3, respectively. The stored energy is recovered in Operation 2 and Operation 3 whilst not in Operation 1. The calculated recovery rate of thermal energy for each scenarios are shown in Table 2. The result of Operation 1 shows that stored energy can hardly be recovered. With regard to Operation 2, 50.4% of the stored cold energy and 20.4% of the stored warm energy can be recovered in the third year. In case of Operation 3, the stored energy can be recovered, but the recovery rate was inferior to the Operation 2. This reason is assumed that aquifer 2 is the width of aquifer shallower than aquifer1. Therefore, in Operation 2 by using aquifer1, the stored heat has remained a lot by around the injection wells.

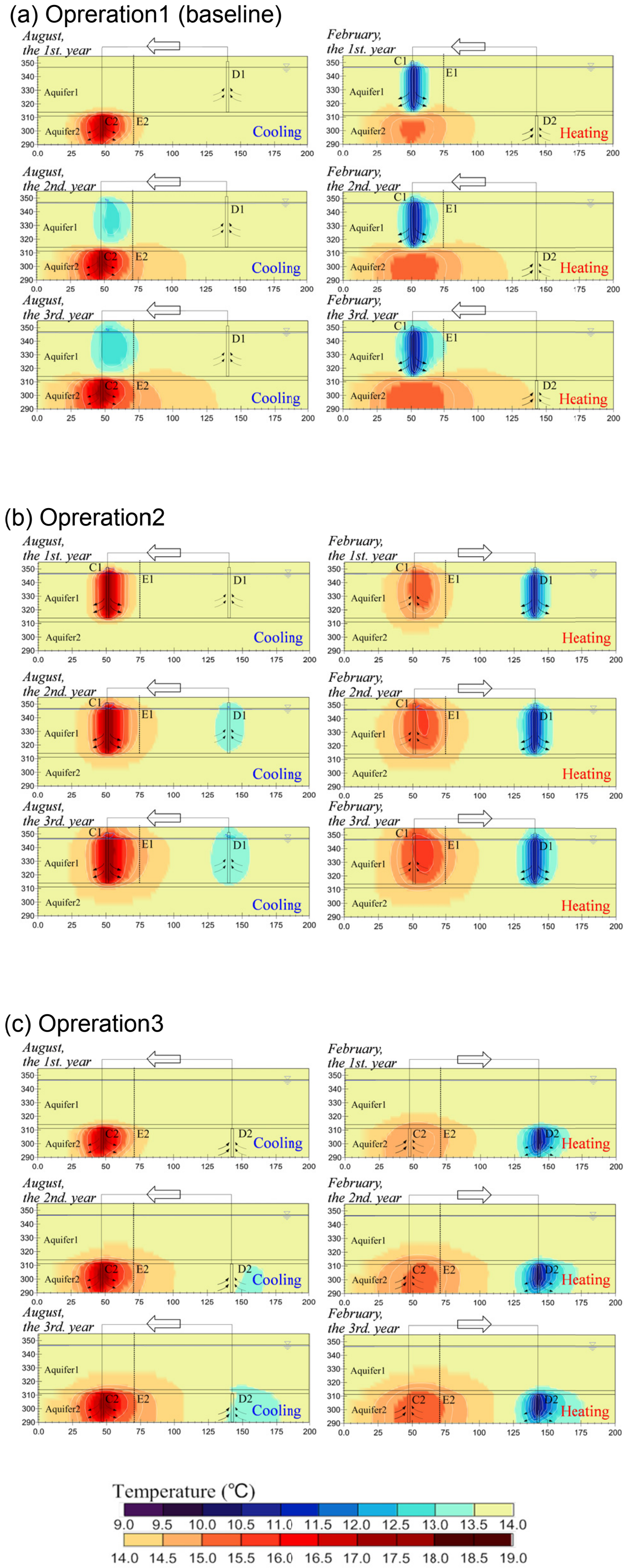

Figure 4. Simulated groundwater temperature of each scenarios.

Table 2. Calculated heat recovery rate.

Scenario		Heat Recovery rate		
		1st.year	2nd.year	3rd.year
Operation1 (baseline)	Cold Water	-	0.0%	0.0%
	Warm Water	0.0%	0.0%	0.4%
Operation2 (improved)	Cold Water	-	46.1%	50.4%
	Warm Water	18.1%	19.5%	20.4%
Operation3 (improved)	Cold Water	-	26.2%	28.5%
	Warm Water	13.6%	14.9%	15.8%

CONCLUSION

The SCOP of the GSHP system coupled with the E-ATES during the winter and summer season of 2011-2012 has been improved by several modifications of the GSHP system and was favorably compared with that of the ASHP system. However, the E-ATES still has a potential to improve its efficiency by recovering and utilizing the cool and warm recharged into aquifers. Thus, we performed numerical simulations for optimizing the operational scenario of the well system. The results of the simulations show that the heat recovery rate will be remarkably improved by thermal energy recovery associated with modification of the well system. The predicted numerical simulations show that the recovery rate of stored heat can be accelerated by using Aquifer 1.

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Appendix

The governing equation for flow of water in saturated-unsaturated zone with variable-density fluid is given by

$$\nabla \bullet \{\frac{\mu_r K_r}{\mu}(\nabla h_r + \frac{\rho}{\rho_r}\nabla z)\} - \sum_{i=1}^{n_q} Q_i \delta_i = \rho(S_e S_s \frac{\partial h_r}{\partial t} + C_s \frac{\partial h_r}{\partial t}) + \varepsilon S_e \frac{\partial \rho}{\partial t} \quad (1)$$

where ρ and ρ_r are the density of water; μ and μ_r are the dynamic viscosity of freshwater; S_e is the fractional effective water saturation; S_s is the specific storage; h_r is the pressure head in terms of water of a reference temperature; $C_s(=\varepsilon \partial S_e / \partial h_r)$ is the soil water capacity; ε is the fractional porosity; K_r is the hydraulic conductivity in terms of water of a reference temperature; Q_i is the withdrawal rate of a pumping well i; δ_i is the Dirac delta function for the pumping or injection well; z is the upward vertical coordinate.

For unsaturated porous media, van Genuchten [4] provided functional relations for the parameters S_e and K_r in Equation (1) as follows:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{(1+|\alpha h_f|^{\beta})^{r}}, \quad (\gamma = 1 - \frac{1}{\beta}) \quad (2)$$

$$K_r = K_{rs} {S_e}^{1/2} \left\{1 - \left(1 - {S_e}^{1/\gamma}\right)^{\gamma}\right\}^2 \quad (3)$$

where θ, θ_s and θ_r are the volumetric water content (VWC), the saturated VWC, and the residual VWC, respectively; α and β are the characteristic constants of soil to be evaluated from experiments; K_{rs} is the saturated hydraulic conductivity in terms of a reference temperature.

The governing equation for heat transport in the saturated-unsaturated zone is given by

$$\nabla \bullet (\boldsymbol{\lambda} \nabla T) - \theta(\rho C)_w \nabla \bullet (\mathbf{v} T) = (\rho C)\frac{\partial T}{\partial t} \quad (4)$$

Where T is temperature; $(\rho C)_w$ is the volumetric heat capacity of water phase. Assigning $(\rho C)_s$ of the volumetric heat capacity of solid phase and $(\rho C)_a$ of the volumetric heat capacity of air phase, the bulk volumetric heat capacity (ρC) is calculated by

$$(\rho C) = \varepsilon S(\rho C)_w + \varepsilon(1-S)(\rho C)_a + (1-\varepsilon)(\rho C)_s \quad (5)$$

The tensor element of $\boldsymbol{\lambda}$ is given by

$$\lambda_{ij} = \lambda_{ed} + (\lambda_{md})_{ij} = (\rho C) D_{ij} \quad (6)$$

where λ_{ed} and λ_{md} are the bulk thermal conductivity and the mechanical thermal dispersivity; D_{ij} is the hydrodynamic dispersion coefficient. And the dispersion tensor is defined by

$$D_{ij} = \alpha_{ijkm}|v_k||v_m|/|v| + \kappa_e$$
$$\alpha_{ijkm} = \alpha_T \delta_{ij}\delta_{km} + (\alpha_L - \alpha_T)(\delta_{ik}\delta_{jm} + \delta_{im}\delta_{jk})/2 \quad (7)$$

where v is the average velocity; v_k and v_m are the velocity components of two coordinate directions, k and m; δ_{ij} is the Kronecker Delta; κ_e is the bulk thermal diffusivity; α_L is the longitudinal dispersivity; α_T is the transverse dispersivity