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Numerical Study on System Performance of Groundwater Heat Pumps

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ABSTRACT

Groundwater heat pumps have great potential where the groundwater resources are sufficient. System Coefficients of Performance (COPs) are used measures of performance of groundwater heat pump systems. Head and power of submersible pumps, heat pump units, piping, and heat exchangers are expressed in the polynomial equations, and theses equations are solved numerically to find the system performance. Coefficients of polynomial equations are found from product data by using regression analysis. Cooling and heating capacities of water to water heat pumps use EnergyPlus water to water heat pump equations. Results shows that the system performance drops as the water level drops, and the lowest flow rates generally achieve the highest system performance. The system COPs are employed to compare the system performance of various system configurations. The groundwater pumping level and temperature provide great effect on the system performance of groundwater heat pumps along with the submersible pumps and heat exchangers. The effects of groundwater pumping levels, and groundwater temperatures, and the heat exchanger UA values on the system performance are given and compared. The analysis needs to be included in the design process of groundwater heat pump system, possibly with analysis tools that include wide range of product data.

1. INTRODUCTION

A large portion of energy use in buildings is in heating and cooling. The operation of the buildings is reported to contribute more to energy use and climate change than either transportation or industry with an estimate of global energy consumption. (Mendler 2012) The buildings are known to offer the largest low-cost greenhouse gas consumption reduction potential in all over the world.(IPCC 2007) Geothermal heat pumps are known as the most environment-friendly and efficient method for heating and cooling buildings, and could have the largest greenhouse gas emission mitigation potential.

Groundwater heat pumps are possibly the oldest geothermal heat pumps and also the oldest commercial heat pumps. Equitable Building is Portland, which initiated heating and cooling using groundwater heat source in 1948, was recorded as a National Mechanical Engineering Landmark by American Society of Mechanical Engineers.

Proper design of groundwater heat pump systems can provide both the low installation cost and low operation cost. (Kavanaugh and Rafferty 1997) While ground-source heat pumps can be installed almost anywhere, groundwater heat pumps can be successfully constructed and operated only where the aquifer can sustainably provide the groundwater to the heat pump units. Adequate site characterization and system design are essential for stable operation and efficiency.

Pumping systems and their operating conditions greatly influence groundwater heat pump system performance. Groundwater usually provides favorable operating conditions for heat pump units as compared to ground-source heat pumps, with the higher coefficients of performance (COPs) of heat pump units for groundwater heat pump systems. However, open-loop groundwater pumping power consumption increases rapidly as the groundwater level drops.

In this study, the system efficiency of groundwater heat pump systems is analyzed based on the system heating and cooling coefficients of performance (COPs). The system COPs are calculated by employing polynomial models for heat pump units and pumps. The coefficients of polynomial models are found by employing regression analysis for the manufacturers' product data. The effect of groundwater level and temperature on the system performance is analyzed, and the effect of the heat exchanger UA value on the system performance is also analyzed. The analysis will be helpful in determining the system performance during the design process of groundwater heat pump system, possibly with analysis tools that include wide range of heat pump unit and pump product data.

2. GROUNDWATER HEAT PUMP SYSTEM

Groundwater heat pump (GwHP) systems may consume a smaller amount of energy in operating heat pump units than ground source heat pump (GSHP) systems, since their heat pumps units usually operate under more favorable operating conditions due to groundwater temperature which remains stable throughout the year. However, GwHP systems could consume more energy in pumping the groundwater in some instances. The pumping energy consumption increase greatly as the groundwater level becomes low from the ground and the pumping flow rate increases.

Water table is maintained in the well and unconfined aquifer when no water is pumped from the well. The static water level is the distance from the ground surface to the water level in the well. When water is pumped from the well, water level in the well drops from the static water level. The water level in the well while pumping is called as the pumping water level. The distance between the static water level and the pumping water level is a drawdown. (Banks 2012, Sachs 2002) The pumped water level is used in calculating the GwHP system performance.

GwHP systems are composed of one or more production water wells, heat pump units, submersible and circulation pumps, and heat exchangers. Their layouts can vary significantly with design intents and the number of production wells, heat exchangers and other components. Some of GwHP systems do not include the heat exchangers between the heat pump units and the submersible pumps, allowing the groundwater to pass through the heat pump unit. This configuration is called direct GwHP system and sometimes used, especially in the smaller capacity applications. In large commercial systems, indirect GwHP systems are widely used, which include the heat exchanger between the groundwater submersible pump and the heat pump units.

In this study, the GwHP system is composed of one groundwater production well, one submersible pump, one water to water heat pump unit, one circulation pump, and one heat exchanger as shown in Figure 1. Air handling units or fan coil units that are connected to the water to water heat pump unit are not included in calculating the system performance of the current GwHP system. The flow rates and inlet temperature to air handling units are predefined and assumed to be unchanged. The authors follow the same system configuration of their preceding publication. (Kim and Nam 2014)

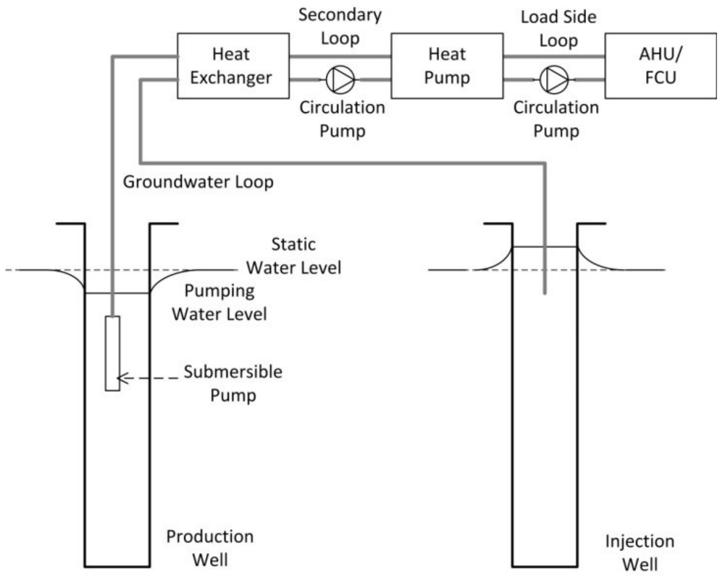

Figure 1: Groundwater Heat Pump System Layout

The submersible pump installed in the production well pumps the water, transfers it through the heat exchanger and sends it to the injection well or any other use. When the heat pump unit is in the heating mode, the heat of groundwater is transferred to the circulation water in the heat exchanger. The groundwater is cooled and the circulation water is heated inside the heat exchanger. The circulation fluid from the heat exchanger is sent to the heat pump unit by a circulation pump in the secondary loop. The heat of circulation water is transferred to the refrigerant loop inside of the heat pump unit. And the circulation water from the heat pump returns to the heat exchanger in the secondary loop. The heat pump unit produces hot water with the capacity of summing the absorbed heat from the circulation water in the secondary loop and the electricity consumed by the compressor. Hot water produced by the heat pump units are sent to the air handling units or fan coil units to heat the space or the process. In the heating mode, the heat from the groundwater moves to the space or the process through heat exchanger, heat pump unit and the air handling units.

In the cooling mode, the heat of the space or the process is transferred to the refrigerant loop inside of the heat pump unit via the air handling units and the circulation water in the load side loop. The circulation water in the secondary loop was chilled by the heat pump unit. Inside the heat exchanger, the heat travels from the circulation water to the groundwater, and thus the circulation water becomes cooler and the groundwater becomes hotter. The groundwater from the injection well is heated in the heat exchanger, and returns to the injection well or is sent to other use.

3. COMPONENT MODELS

The GwHP system of this study is composed of one submersible pump installed in the groundwater production well, one water to water heat pump unit, one circulation pump, and one heat exchanger. (Kim and Nam 2014)

In order to calculate the power consumption and the heating and cooling capacities of GwHP system, power consumption, head, and heating and cooling capacities of components need to be modeled in the mathematical forms in terms of flow rate and temperature values. When the flow rate varies in the GwHP system, the temperature distribution in heat exchanger and heat pump unit varies. Accordingly, the heating and cooling capacities of the GwHP have different values.

3.1 Submersible Pump and Circulation Pump Model

Submersible pumps are generally composed of multiple stages with identical impellers and housings installed serially and electric motors installed at the end. Head and power consumption of submersible pump are calculated by multiplying the number of stages (n) of the pump and the associated values for the single stage.

$$H_p = n \cdot h_p \tag{1}$$

$$W_p = n \cdot w_p \tag{2}$$

Head and power consumption for the single stage of submersible pump are modeled in cubic polynomial equations in terms of flow rate V (in *LPM*, liters per minute)

$$w_p = A_0 + A_1 \cdot V + A_2 \cdot V^2 + A_3 \cdot V^3 \tag{3}$$

$$h_p = B_0 + B_1 \cdot V + B_2 \cdot V^2 + B_3 \cdot V^3 \tag{4}$$

Eight coefficients in the equations (3) and (4) can be obtained through regression analysis from the product data. For the single stage h_p and w_p are the head (in *m*) and power consumption (in *kW*). Groundwater production well is assumed to be capable of providing the necessary flow rate to the heat exchanger or the heat pump unit, and maintain the pumping water level throughout the operation.

Circulation pumps in the secondary loops have the similar characteristics as the submersible pumps. The same equation forms for the head and power consumption are used.

3.2 Heat Pump Model

When the circulation fluid of the secondary loop passes the heat exchanger installed inside the heat pump unit to exchange heat with refrigerant, the head loss along with temperature change occurs for the circulation fluid. The head loss in the secondary circulation loop circulation flow inside the heat pump unit H_{hp} is expressed in the following way. The same equation is used for the lead loss occurred the load side loop circulation water inside the heat pump units.

$$H_{hp} = C_{hp} \cdot V^2 \tag{5}$$

Temperature variations inside the heat exchanger and flow rate variations in the secondary loop cause the heat pump unit produce different cooling and heating capacities Q_c and Q_f (in *kW*) and consume different amounts of electricity W_c and W_f (in *kW*).

$$\frac{Q_c}{Q_{c,ref}} = D_0 + D_1\left(\frac{T_{S,in}}{T_{ref}}\right) + D_2\left(\frac{T_{L,in}}{T_{ref}}\right) + D_3\left(\frac{V_S}{V_{ref}}\right) + D_4\left(\frac{V_L}{V_{ref}}\right) \tag{6}$$

$$\frac{Q_h}{Q_{h,ref}} = E_0 + E_1\left(\frac{T_{S,in}}{T_{ref}}\right) + E_2\left(\frac{T_{L,in}}{T_{ref}}\right) + E_3\left(\frac{V_S}{V_{ref}}\right) + E_4\left(\frac{V_L}{V_{ref}}\right) \tag{7}$$

$$\frac{W_c}{W_{c,ref}} = F_0 + F_1\left(\frac{T_{S,in}}{T_{ref}}\right) + F_2\left(\frac{T_{L,in}}{T_{ref}}\right) + F_3\left(\frac{V_S}{V_{ref}}\right) + F_4\left(\frac{V_L}{V_{ref}}\right) \tag{8}$$

$$\frac{W_h}{W_{h,ref}} = G_0 + G_1\left(\frac{T_{S,in}}{T_{ref}}\right) + G_2\left(\frac{T_{L,in}}{T_{ref}}\right) + G_3\left(\frac{V_S}{V_{ref}}\right) + G_4\left(\frac{V_L}{V_{ref}}\right) \tag{9}$$

Subscripts S and L indicate the secondary loop and the load side loop, and subscript *ref* is the reference value for the corresponding variables. Product data of a water to water heat pump unit can be used to find coefficients by using regression analysis. Performance table includes the cooling and heating capacities and power consumption for source and load side water temperature and flow rates. (US DOE, 2012)

3.3 Piping Model

The head loss occurs when the fluid passes inside the pipes and piping accessories. Pipe diameters and lengths, and fluid properties influence the heat loss occurred in secondary loop and groundwater loop. The equation of the head losses expressed in terms of flow rate is given as follows.

$$H_{piping} = C_{piping} \cdot V^2 \tag{10}$$

3.4 Heat Exchanger Model

Plate frame plate heat exchangers are normally used as heat exchangers installed between heat pump units and groundwater submersible pumps in the indirect GwHP systems. The heat transfer occurs between the groundwater and the circulation fluid of secondary loop inside the heat exchanger. When the flow rate of either groundwater or circulation fluid or both changes, the output temperatures vary in the following way.

$$H_{hx} = C_{hx} \cdot V^2 \tag{11}$$

$$Q_{hx} = \Delta T \cdot V \tag{12}$$

$$Q_{hx} = UA \cdot \Delta T_{LM} \tag{13}$$

$$\Delta T_{LM} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \tag{14}$$

Subscript *hx* indicates the heat exchanger. *UA* is a heat exchanger characteristic and ΔT_{LM} is the logarithmic temperature difference of the heat exchanger as defined in Equations (13) and (14).

4. GWHP SYSTEM CONFIGURATION

The indirect GwHP system layout of this study is composed of one submersible pump installed inside the groundwater production well, one water to water heat pump unit, one circulation pump, and one heat exchanger. (Kim and Nam 2014)

Four inch diameter submersible pump SP 75S of Grundfos is considered here. (Grundfos 2012) All of the pump models of single stage through sixteen stages are assumed to be available in this series of product. Eight coefficients of equations (3) and (4) for the single stage are obtained by regression analysis of product data as shown in Table 1.

Table 2: Pump Model Coefficients for the Single Stage

A_0	A_1	A_2	A_3
1.022E1	-1.351E-2	2.5313E-5	-1.1589E-7
B_0	B_1	B_2	B_3
2.07403E-1	8.9077E-4	3.467E-6	-9.95602E-9

McQuay GRW360 model is used as water to water heat pump, which uses R407a refrigerant and has the nominal capacity of 30 refrigeration ton. (McQuay 2007) Twenty coefficients from equations (6) through (9) are calculated from manufacturer's data by regression analysis as shown in Table 2. Reference values used in equations (6) through (9) and head loss coefficients of equation (5) is also given in Table 2.

Table 2: Heat Pump Model Coefficients

D_0	D_1	D_2	D_3	D_4
-3.70415E0	-2.26533E0	6.75804E0	3.322E-2	7.447E-2
E_0	E_1	E_2	E_3	E_4
-6.28243E0	7.83147E0	-6.663E-1	9.162E-2	3.253E-2
F_0	F_1	F_2	F_3	F_4
-6.42E0	5.66874E0	1.32662E0	-1.106E-1	1.483E-2
G_0	G_1	G_2	G_3	G_4
-8.35467E0	9.0202E-1	7.81833E0	2.878E-2	6.669E-2
$Q_{c,ref}$	$Q_{h,ref}$	$W_{c,ref}$	$W_{h,ref}$	C_{hp}
70kW	70kW	15kW	15kW	5.08245E-5
T_{ref}	$T_{S,in}$	$T_{L,in}$	V_{ref}	V_S
273K	288K	313K	284LPM	250LPM

Head loss occurred in the piping of the groundwater loop is approximated by Equation (10), and head loss coefficient in the piping is found as 3.25E-5.

The submersible pumps installed in the wells supply the groundwater with the head to cover the system head of the groundwater loop, which includes the pumping water level and the head losses in heat exchanger and the pping. The system head equation is shown Equation (15).

$$H_{SYS} = H_{GW} + H_{hp} + H_{hx} + H_{piping} \tag{15}$$

The head of the submersible pump and the system head vary as the groundwater flow rate varies. The residual head of the groundwater loop is defined as the difference between the groundwater loop system head and the submersible pump head. At the operating flow rate, the submersible pump head and the system head of the groundwater loop coincide, meaning that the residual head becomes zero.

$$H_{res} = H_{SYS} - H_p \tag{11}$$

The Newton-Raphson method is used to find the operating flow rate. Iterations on the groundwater loop system head in terms of the groundwater flow rate are performed until the residual head vanishes.

In the secondary loop, the circulation pump in the secondary loop is chosen with Grundfos CR 15 single stage model. The operating circulation water flow rate of the circulation pump is 300LPM with the head of 17.4m. The power consumption of the pump is 1.17kW based on the product data.

5. RESULTS

The performance of the GwHP system can be expressed in terms of system coefficients of performance (COPs), which are the ratio of the heating or cooling capacities to the corresponding electricity consumptions of the GwHP system. Meanwhile, the COPs of heat pump unit are the ratio of the heating and cooling capacities to the corresponding electricity consumption for only the heat pump unit, excluding the pumps. System COPs are always lower than the heat pump unit COPs since the denominators of the ratios always become larger with the added pump power consumptions. In calculating the GwHP system performance, the power consumption of the air handling units/fan coil units and the pump in the load side loop are not included. The performance and characteristics of components in the load side loop varies greatly in various types of building uses and designs. To evaluate the system performance of GwHP without the effects caused by load side designs, the load side loop is assumed as unchanged in the analysis.

5.1 Groundwater Level

The pumping groundwater levels are assumed to be obtained from a series of pumping tests. The drawdown is a function of various parameters including pumping flow rate, transmissivity, time and the distance from the well. (Banks 2012) But the water levels in the well during pumping tests include the drawdown effects, not being treated separately in this study.

System COP values of GwHP systems are presented for the for three different constant pumping groundwater levels 15m, 25m, and 35m. At each groundwater level, groundwater flow rates for the selected submersible pumps are found, and performance results of GwHP system are calculated for the flow rates. Submersible pumps of eleven different stages are considered at each groundwater level. Performance results include heat pump COP and GwHP system COP.

System heating and cooling COPs are shown in Figures 2 and 3, respectively. (Kim and Nam 2014) In Figure 2, as the groundwater level drops, the optimum flow rate for the GwHP heating system COP becomes more recognizable.

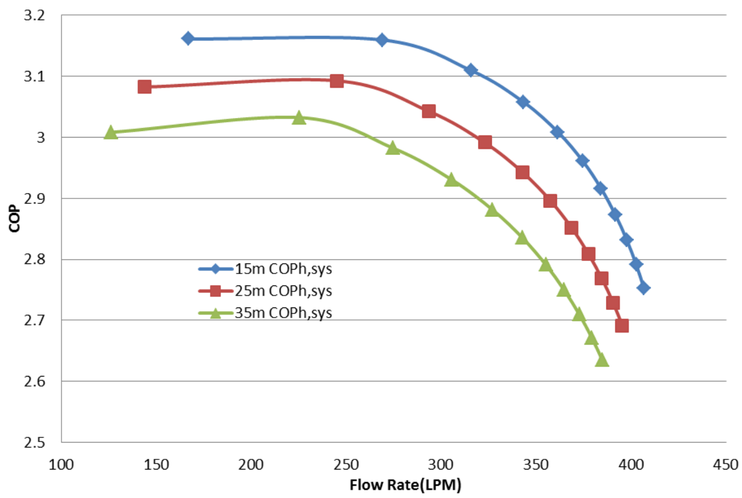

Figure 2: Heating System COP Variation with the Flow Rate (Kim and Nam 2014)

In Figure 3, as the groundwater level drops, the slope of the curve in the low flow rate region becomes the smaller in magnitude. However, in the high flow rate region, the system heating and cooling COPs drop rapidly as the flow rate increases.

The percentage of reduction of the COP of groundwater heat pump system as compared with that of heat pump unit increases, as the flow rate increases and as the groundwater level drops. Figure 4 shows that the system heating COP value variation with flow rates and groundwater levels. The 10 to 15% reduction is shown for the 250LPM groundwater flow rate. When the groundwater level is 35m below the ground, the system heating COP shows the largest 15% reduction as compared to heat pump COP. At the higher flow rate of around 350LPM, the system heating COP is reduced by 15 to 22% from the heat pump unit COP.

Figure 5 shows that the reduction percentage of system cooling COP values as compared to the heat pump unit COP is larger than that of the heating system COP value reduction. The similar trend is found with the variation of flow rate and groundwater level. The 15 to 22% reduction is observed for the 250LPM groundwater flow rate. When the groundwater level is 15m below the ground, the system heating COP shows the lowest 15% reduction as compared to heat pump COP. At the flow rate of around 350LPM, the system heating COP shows 22 to 29% reduction from the heat pump unit COP.

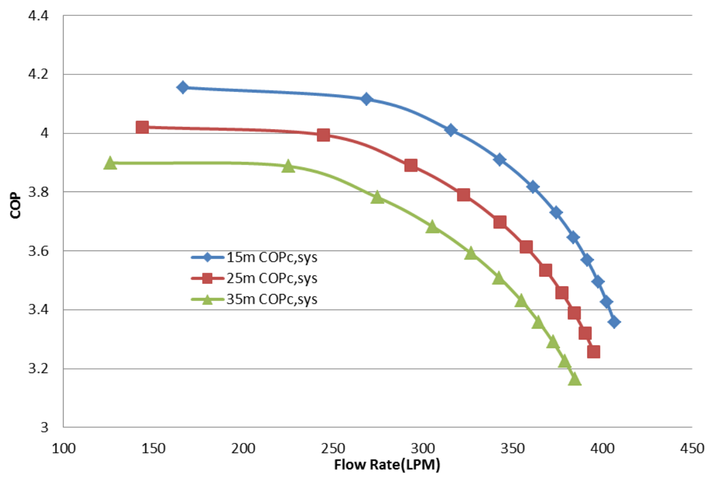

Figure 3: Cooling System COP Variation with the Flow Rate (Kim and Nam 2014)

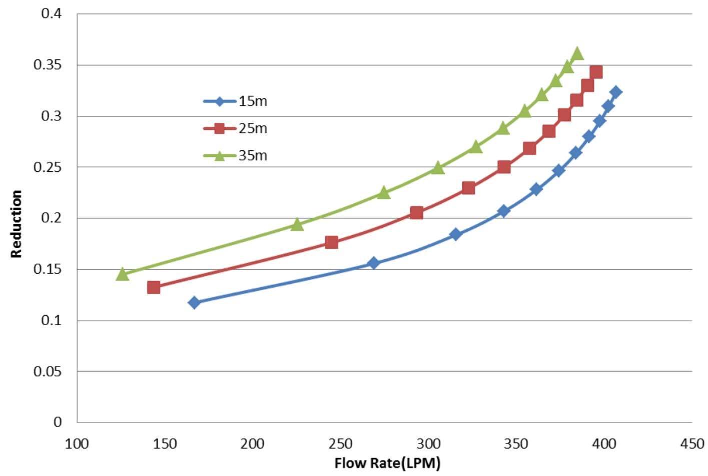

Figure 4: System Heating COP Reduction compared to Heat Pump Unit COP

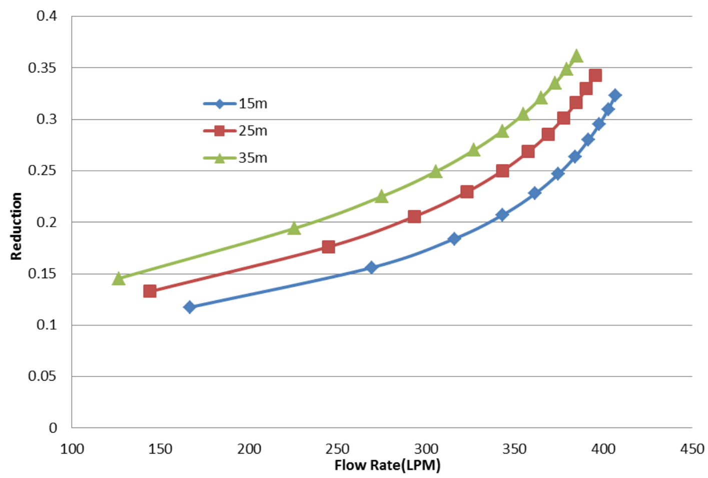

Figure 5: System Cooling COP Reduction compared to Heat Pump Unit COP

5.2 Groundwater Temperature

Groundwater temperature gives influence on system COPs of GwHP system, since the heat pump capacities and COPs are dependent on the groundwater temperature. As the groundwater temperature increases, the heating COPs also increase, however, the cooling COPs decrease. On the contrary, as the groundwater temperature decreases, the heating COPs decrease, however, the cooling COPs increase. In studying the effect of groundwater temperature on system COPs of GwHP, the groundwater level is set to constant 25m. The system COPs are calculated and shown in Figure 6 for the groundwater temperatures of 12ºC, 15ºC, and 18ºC.

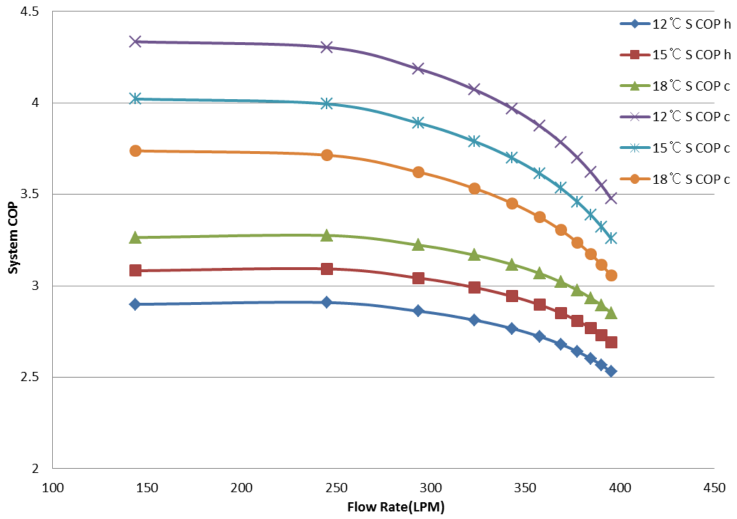

Figure 6: System Cooling and Heating COP variation to Groundwater Temperature

The graph for the system cooling COPs for 12ºC groundwater shows the highest values, however the system heating COPs show the lowest values. The system COPs for 18ºC groundwater show the opposite trend as compared to the case for 12ºC. The graphs for 15ºC groundwater lie between the graphs of 12ºC and 18ºC. As the flow rate varies from 144.0LPM to 395.3LPM, the system cooling COPs drop by approximately 19.0% (19.8% for 12ºC, 19.0% for 15ºC , and 18.3% for 18ºC, respectively), the system heating COPs drop by approximately 12.7% (12.7% for 12ºC, 12.7% for 15ºC , and 12.6% for 18ºC, respectively).

At the flow rate of 245LPM, the system heating COP drops 11.2% when the COP values, for groundwater temperatures of 12ºC and 18ºC, are compared. The system cooling COP drops 13.7%. At a higher flow rate of 343LPM, the system heating COP drops 11.2%, and the system cooling COP drops 13.1%

5.3 Heat Exchanger UA Value

Heat exchanger installed between the groundwater pump and the heat pump unit gives influence on the system COP of GwHP system. The temperature of the water circulated between the heat exchanger and the heat pump unit influence the capacity and power consumption of the heat pump unit.

The UA value of heat exchanger determines the temperature differences between the hot and cold streams. So far in this study, UA value of 12 W/K has been used. The positive and negative 25% variation from 12W/K is considered, and three UA values of 9 W/K, 12W/K, and 15W/K are used to study its effect of UA values on the system COPs.

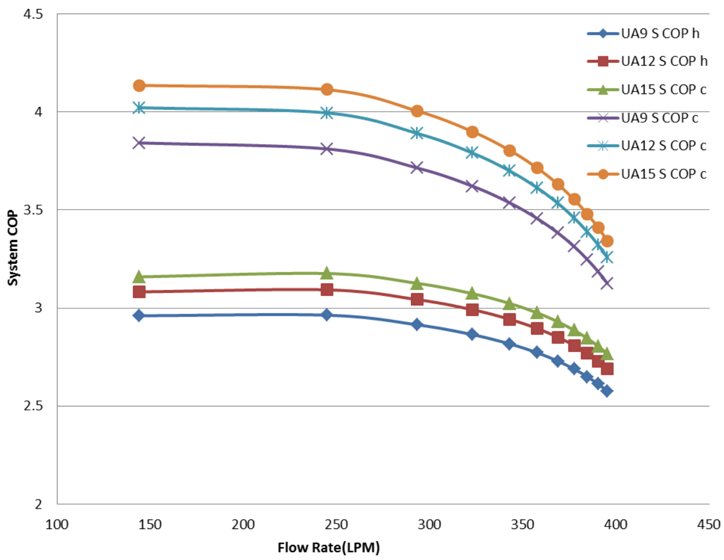

Figure 7: System Cooling and Heating COP variation to Heat Exchanger UA Values

In comparing UA value of 9W/K to 12W/K, the system heating COP drops by 4.2% and the system cooling COP drops by 4.6%. When UA value of 15W/K is compared to 12W/K, the system heating COP rises by 2.7% and the system cooling COP rises by 3.0%. It is expected that the low UA values of the small heat exchanger may deteriorate the system COP values by the large amount.

6. CONCLUSION

The system COPs as measures of performance for GwHP systems are obtained by integrating the component mathematical models. The system heating and cooling COPs are calculated at the three different groundwater levels, i.e., 15m, 25m, and 35m. The system COPs remain almost unchanged or gradually changed at the low flow rate range as the flow rate increases. However, at the higher flow rate region, the system COPs decrease rapidly as the flow rate increases.

The system heating COPs are reduced 10~15% at around 250LPM and 15~22% at around 350LPM when compared to heat pump unit COPs. The system cooling COPs are reduced by a larger rate, 15~22% at around 250LPM and 22~29% at around 350LPM.

At the flow rate of 245LPM, the system heating COP drops by 11.2% when 12°C groundwater temperatures are compared to 18°C, and the system cooling COP rises by 13.7%. At a higher flow rate of 343LPM, the system heating COP drops by 11.2%, and the system cooling COP rises by 13.1%. The influence of groundwater temperature on the system performance of GwHP systems depends on the dominance of annual heating or cooling usage.

The system heating COP drops by 4.2% and the system cooling COP drops by 4.6% in comparing UA value of 9W/K to 12W/K. When UA value of 15W/K is compared to 12W/K, the system heating COP rises by 2.7% and the system cooling COP rises by 3.0%. Selection of proper UA values of the heat exchanger may ensure proper system COP values.

The GwHP system design engineers need to find the groundwater flow rates at which the GwHP systems maintain high system COPs with a proper selection of heat exchanger. The GwHP systems need to be modeled with detailed information for components such as submersible pumps, heat pump units and heat exchangers. In order to accurately predict system performance, the proper GwHP system model along with the building heating and cooling load variation need to be used.

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