Study on Groundwater Heat Pump System Performance with Various Groundwater Levels

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Abstract: Groundwater heat pumps have great greenhouse gas mitigation potential where the groundwater resources are sufficient. System coefficients of performance of groundwater heat pump systems vary with groundwater level in the well. Each component of groundwater heat pump systems has different capacities and power consumption for its flow rates and temperatures. Head and power consumption values of components are expressed in the polynomial equations, and theses equations are solved numerically by using regression coefficients obtained from product data. The system cooling COP of 4.16 and the system heating COP of 3.16 are achieved at the groundwater level of 15m. The system heating COP drops 2.3% and 4.3% as the groundwater levels are lowered to 25m and 35m, and the system cooling COP drops 3.3% and 6.1% at the groundwater flow rate of 200LPM. At the higher groundwater flow rate, the system COP reduction decrease more rapidly.

Key Words: heat pumps, groundwater, groundwater level, system performance, coefficient of performance, head, power consumption, submersible pumps

1 INTRODUCTION

With an estimate of global energy consumption, the operation of buildings is reported to contribute more to energy use and climate change than either transportation or industry. (Mendler 2012) The building sector is reported to offer the largest low-cost greenhouse gas mitigation potential in all world regions. (IPCC 2007) Significant portion of energy consumption in buildings are in space heating and cooling. Geothermal heat pumps can greatly reduce the energy consumption needed in building heating, cooling and producing hot water.

Groundwater heat pumps use groundwater as the heat source to the heat pumps, and groundwater temperature remains stable throughout the year. Groundwater heat pump systems are among the oldest geothermal heat pump and among the oldest commercial heat pump system. Equitable Building in Portland was recorded as a National Mechanical Engineering Landmark by American Society of Mechanical Engineers (ASME). The first commercial heat pump installation in USA initiated heating and cooling in 1948 and used groundwater as heat source.

Both the low installation cost and low operation cost for groundwater heat pump systems can be achieved through proper design, installation, and operation. (Kavanaugh and Rafferty, 1997) As contrary to ground source heat pumps which can be installed almost anywhere, groundwater heat pump systems can be constructed only where the aquifer can provide the groundwater sustainably to heat pump units. Proper site characterization and system design can provide stable operation and efficiency.

Groundwater heat pump system performance can vary greatly by design of pumping systems and selection of operating conditions. Groundwater usually has favorable temperature conditions as compared to ground source heat exchanger, but open-loop groundwater pumping can consume more energy than closed-loop circulation pumping of ground source heat exchanger. Groundwater level variations give significant impact on groundwater heat pump system performance.

In this study, the effect of groundwater level to the system efficiency of groundwater heat pumps is analyzed by using the system heating and cooling coefficients of performance (COPs). The system COPs are calculated by employing polynomial models for heat pump units and pumps, and their coefficients in the models are found by using regression analysis for manufacturers' data. Performance data calculated at the three different pumping levels are presented, and the effect of groundwater level on the system performance is analyzed for two groundwater flow rates.

2 GROUNDWATER HEAT PUMP SYSTEM

Groundwater heat pump (GwHP) systems consume a smaller amount of energy in operating heat pump units than ground source heat pump (GSHP) systems, since their heat pumps units operate under more favorable conditions due to groundwater temperature which remains stable throughout the year. However, GwHP systems can consume more energy in pumping the groundwater since the groundwater circuit is open. The pumping energy consumption increase greatly as the groundwater level becomes low from the ground.

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, and the distance bet the static water level and the pumping water level is drawdown. The pumped water level is used in calculating the GwHP system performance. (Banks 2012, Sachs 2002)

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 system, 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 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 water 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 by 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.

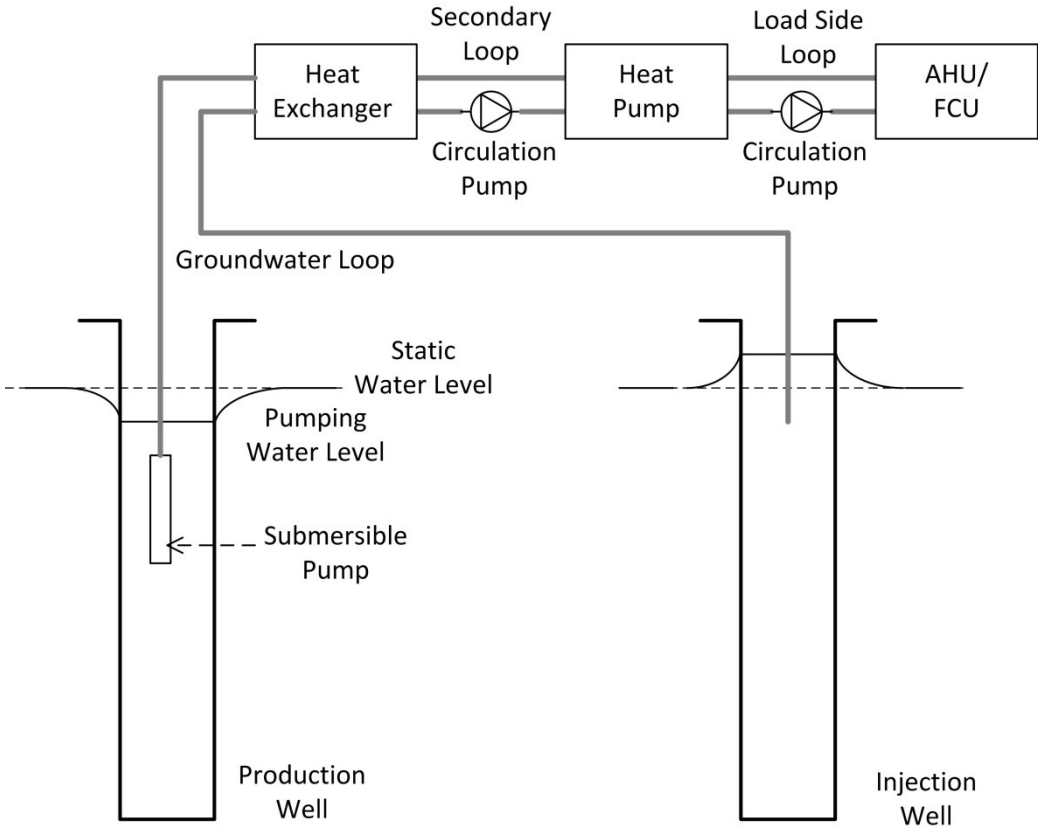


Figure 1 GwHP System Layout

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 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. 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.

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 each component need to be modeled in the mathematical forms in terms of flow rate and temperature 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 value for the single stage.

$$H_p = \mathrm{n} \cdot h_p \quad (1)$$

$$W_p = \mathrm{n} \cdot w_p \quad (2)$$

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).

$$h_p = A_0 + A_1 \cdot V + A_2 \cdot V^2 + A_3 \cdot V^3 \quad (3)$$

$$w_p = B_0 + B_1 \cdot V + B_2 \cdot V^2 + B_3 \cdot V^3 \quad (4)$$

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 equations for the head and power consumption are used.

3.2 Heat Pump Unit Model

When the circulation water 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 water. 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.

$$H_{hp} = \mathrm{C}_{hp} \cdot \mathrm{V}^2 \quad (5)$$

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*).

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

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

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

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

Subscripts *S* and *L* indicate the secondary loop and the load side loop, and subscript *ref* is the reference value for the corresponding variable. Product data of a water to water heat pump unit can be used to find coefficients by using regression analysis. Performance table include 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.

$$H_{pipe} = \mathrm{C}_{pipe} \cdot \mathrm{V}^2 \tag{10}$$

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 rates of either groundwater or circulation fluid or both change, the output temperatures vary in the following way.

$$H_{hx} = \mathrm{C}_{hx} \cdot \mathrm{V}^2 \tag{11}$$

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

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

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

Subscript *hx* indicates the heat exchanger. *UA* is the 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 MODEL

The GwHP system 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. Indirect GwHP system with single production well is considered.

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 1 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 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) and the system head variation with flow rate is shown in Figure 2.

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

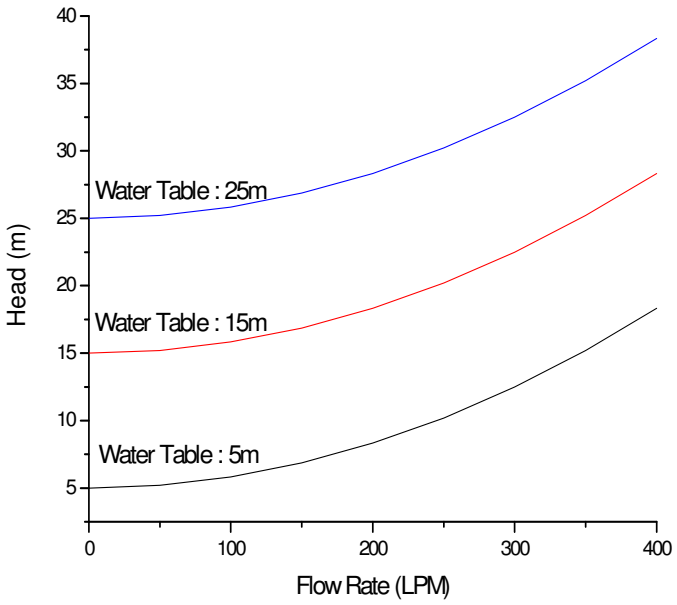


Figure 2 Groundwater Loop System Head Variation

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.

$$H_{res} = H_{SYS} - H_p \quad (16)$$

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. Detailed calculation results of operating flow rate and head are not given in this publication.

5 GWHP SYSTEM PERFORMANCE

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 included 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.

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

At the 15m groundwater level, results for eleven different submersible pumps of two stages through twelve stages are shown in Figure 3, each submersible pump is represented as points with the corresponding groundwater flow rate. The data of pump with two stages (166.8LPM) are shown in the leftmost side and those of pump with twelve stages (406.7LPM) are shown in the rightmost side. The GwHP heating system COP varies from 3.16(166.8LPM) to 2.75(406.7LPM), and cooling system COP varies from 4.16(166.8LPM) to 3.36(406.7LPM). The GwHP system COP curve drops as the groundwater flow rate increases, indicating that the pump power consumption increase due to groundwater flow rate increase outweighs the heat pump performance increase due to favorable conditions. The heat pump unit heating COP varies from 3.44(166.8LPM) to 3.58(406.7LPM), and the cooling COP varies from 4.71(166.8LPM) to 4.96(406.7LPM), since the heat pump unit operates under more favorable working conditions as the ground flow rate increases.

The optimum operating condition with the highest system COPs is at the point with the lowest groundwater flow rate, which is 166.8LPM. However, the system COP with the higher flow rate of 269.1LPM shows almost the same system COPs, meaning that the groundwater flow rate effect on the optimum system COP is small in the low flow regime. (heating 0.05% higher and cooling 0.96% higher)

At the 25m groundwater level, Figure 4 includes performance data for eleven submersible pumps of three stages through thirteen stages. The two stage submersible pump is not included since it does not provide enough head for the current GwHP system at this groundwater level. The GwHP heating system COP varies from 3.08(144.0LPM) to 2.69(395.3LPM), and cooling system COP varies from 4.02(144.0LPM) to 3.26(395.3LPM). The heat pump unit heating COP varies from 3.40(144.0LPM) to 3.58(395.3LPM), and the cooling COP varies from 4.64(144.0LPM) to 4.96(395.3LPM).

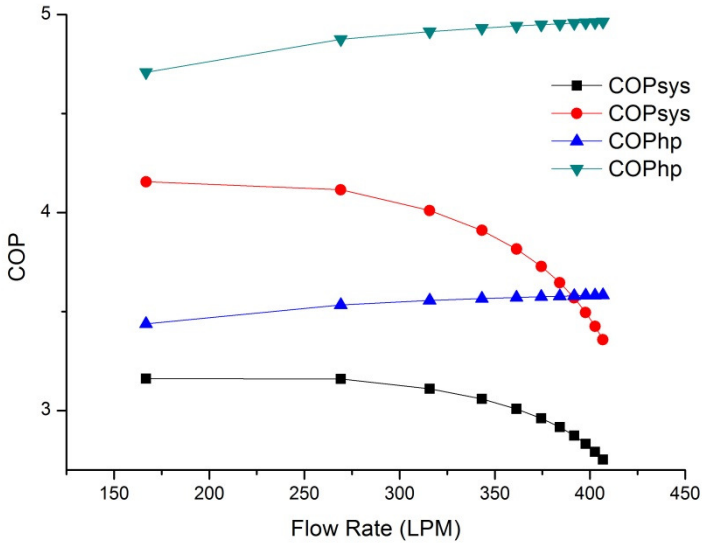


Figure 3 System COP Variation with Flow Rate (15m)

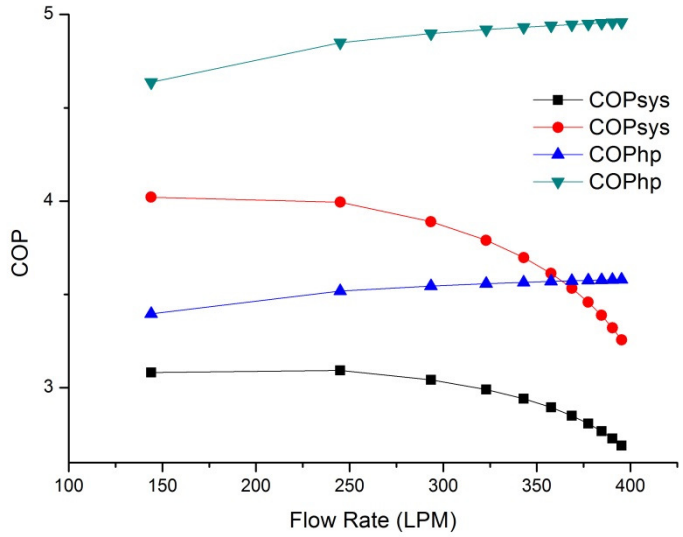


Figure 4 System COP Variation with Flow Rate (25m)

Optimum operating point for the highest system COPs is different for heating and cooling respectively. Heating system COP is the highest at the flow rate of 144.0LPM, and cooling system COP is the highest at the flow rate of 245.0LPM. (heating 0.34% higher and cooling 0.67% higher)

At the 35m groundwater level, performance data for eleven submersible pumps of four stages through fourteen stages are shown Figure 5. The three stage submersible pump is not included since it does not provide enough head for the current GwHP system at this groundwater level. The GwHP heating system COP varies from 3.01(126.4LPM) to 2.63(384.8LPM), and cooling system COP varies from 3.90(126.4LPM) to 3.16(384.8LPM). The heat pump unit heating COP varies from 3.35(126.4LPM) to 3.58(384.8LPM), and the cooling COP varies from 4.56(126.4LPM) to 4.95(384.8LPM).

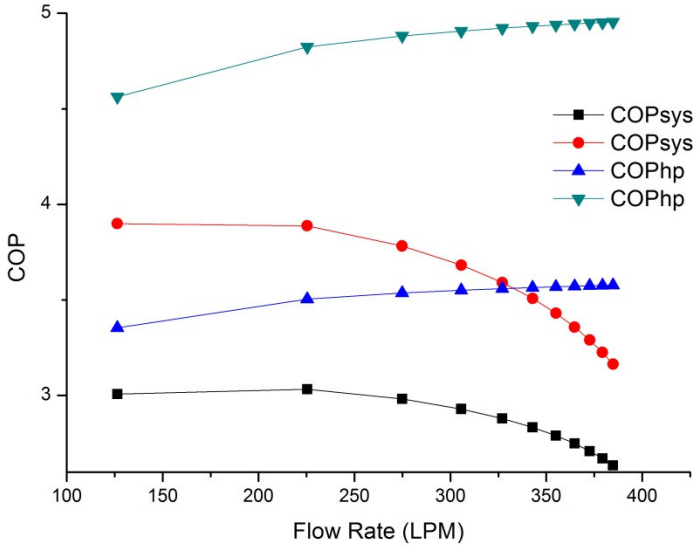


Figure 5 System COP Variation with Flow Rate (35m)

Optimum operatimg point for the highest system COPs is also different for heating and cooling respectively. Heating system COP is the highest at the flow rate of 126.4LPM, and cooling system COP is the highest at the flow rate of 225.4LPM. (heating 0.80% higher and cooling 0.29% higher)

System heating and cooling COPs are shown in Figures 6 and 7, respectively. In Figure 6, as the groundwater level drops, the optimum flow rate becomes more easily recognizable.

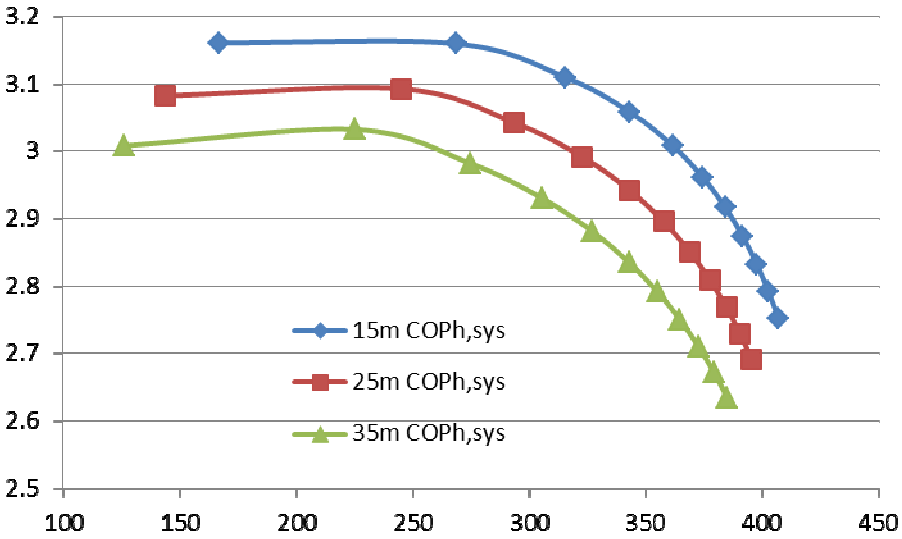


Figure 6 System Heating COP with Flow Rate Comparison

In Figure 7, as the groundwater level drops, the slope of the curve becomes the smaller in magnitude. However, in the high flow rate areas, the system heating and cooling COPs drop rapidly as the flow rate increases. Care must be taken the groundwater flow rate be in the high system COP area.

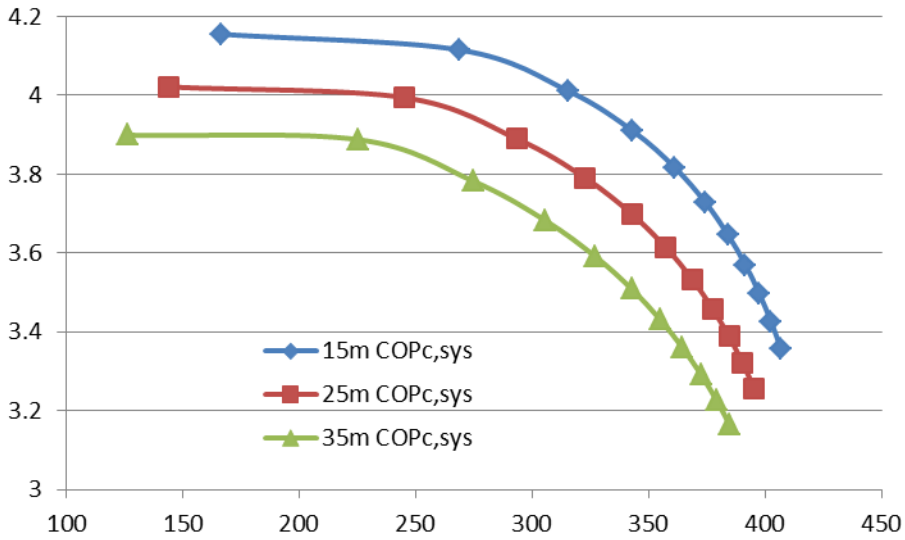


Figure 7 System Cooling COP with Flow Rate Comparison

In order to evaluate the effect of groundwater level on the GwHP system performance, the system COPs need to be compared with the fixed groundwater flow rates for each groundwater level. Two flow rates are selected, 200LPM and 300LPM.

System COP values at the defined flow rate are obtained by interpolating linearly two adjacent data sets. At the flow rate of 200LPM, the GwHP system heating COPs are 3.16(15m), 3.09(25m), and 3.03(35m). The system heating COP reductions in percentage as compared to the groundwater level of 15m are 2.3% and 4.3% for the groundwater levels of 25m and 35m respectively. The cooling system COP reductions are 3.3% and 6.1% for the groundwater levels of 25m and 35m as compared to 15m.

When the groundwater flow rate is 300LPM, the GwHP system heating COP reductions are 3.0% and 6.0% for the groundwater levels of 25m and 35m as compared to 15m. The system cooling COP reduces 4.4% and 8.5% respectively. Interpolated values of system heating and cooling COPs at the selected flow rates are given in Table 3.

Table 3 System COP Comparison for Groundwater Flow Rates 200 and 300LPM

Flow Rate (LPM)	15m		25m		35m	
	Heating	Cooling	Heating	Cooling	Heating	Cooling
200	3.16	4.14	3.09	4.01	3.03	3.89
300	3.13	4.04	3.03	3.87	2.94	3.70

6 CONCLUSION

The system COPs as measures of performance for GwHP systems are obtained by summing the values calculated from 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.

At the groundwater flow rate of 200LPM, the heating system COP reductions in percentage as compared to the groundwater level of 15m are 2.3% and 4.3% for the groundwater levels of 25m and 35m respectively. The cooling system COP reductions are 3.3% and 6.1% for the groundwater levels of 25m and 35m as compared to 15m.
When the groundwater flow rate is 300LPM, the heating GwHP system COP reductions are 3.0% and 6.0% for the groundwater levels of 25m and 35m as compared to 15m. The cooling system COP reduces 4.4% and 8.5% respectively.

The GwHP system design engineers need to find the groundwater flow rates at which the GwHP systems maintain the low system COPs. 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, groundwater temperature and heat exchanger characteristic need to be incorporated in the GwHP system model along with the building heating and cooling load variation.

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