DESIGN ASPECTS OF COMMERCIAL OPEN-LOOP HEAT PUMP SYSTEMS

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ABSTRACT

Open loop (or groundwater heat pump systems are the oldest of the ground-source systems. Common design variations include direct (groundwater used directly in the heat pump units), indirect (building loop isolated with a plate heat exchanger), and standing column (water produced and returned to the same well). Direct systems are typically limited to the smallest applications. Standing column systems are employed in hard rock geology sites where it is not possible to produce sufficient water for a conventional system. Due to its greater potential application, this paper reviews key design aspects of the indirect approach. The general design procedure is reviewed, identification of optimum groundwater flow, heat exchanger selection guidelines, well pump control, disposal options, well spacing, piping connections and related issues.

INTRODUCTION

Open-loop or Groundwater Heat Pump (GWHP) systems are the oldest and most well established of the ground-source heat pump systems. Despite this, little formal design information has been available for them until recently. Although seemingly simple in nature, these systems require careful consideration of well design, groundwater flow, heat exchanger selection and disposal in order that an efficient and reliable system results.

Several variations on the open loop system are in use. The most common of these are illustrated in Figure 1. The direct use of the groundwater in the heat pump units is largely an extension of residential design and is sometimes used in very small commercial applications. It is very susceptible to water quality induced problems, the most common of which is scaling of the refrigerant-to-water heat exchangers. This design is recommended in only the smallest applications in which practicality or economics precludes the use of an isolation heat exchanger and/or groundwater quality is excellent (the determination of which requires extensive testing). The standing column system has been installed in many locations in the northeast portion of the U.S. Like the direct groundwater system, it too is subject to water quality induced problems. In general, water quality in the area where most of the installations have been made (New England) is extremely good with low pH and hardness (little scaling potential). Standing column systems are used in locations underlain by hard rock geology; where, wells do not produce sufficient water for conventional open loop systems and where water quality is excellent. Well depths are often in the 1000 to 1500 ft range and the systems operate at temperatures between those of open and closed loop systems. In colder climates, this sometimes precludes the use of a heat exchanger to isolate the groundwater.

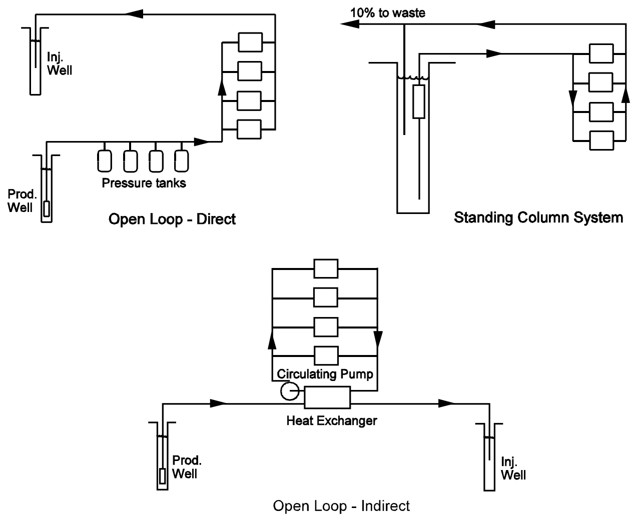


Figure 1. Open-loop systems.

Indirect open loop systems employ a heat exchanger between the building loop and the ground water. This eliminates exposure of any building components to the ground water and allows the building loop and ground water loops to be operated at different flows for optimum system performance. Water can be disposed of in an injection well or to a surface body if one is available. These systems offer energy efficiency comparable to closed loop systems at substantially reduced capital cost. Due to the elimination of water quality and geology limitations this system type is the most widely applicable of the three and will be the focus of the balance of this paper

The design of an open loop system is one in which the performance of the system is optimized based on the power requirements of the well pump, loop pump and heat pumps. In a system of this configuration, it is apparent that the greater the ground water flow, the more favorable will be the temperatures at which the heat pumps will operate. As the ground water flow is increased, the improvement in heat pump performance is increasingly compromised by rising well pump power. At some point, increasing well pump power overshadows the improvement in heat pump performance and the total system performance begins to decline. The task in open loop design is to gather enough information about the well pump, loop pump and heat pumps to permit the identification of these trends and to select the optimum system performance point. It is the SYSTEM EER or COP that is the focus of the design not simply the performance of the heat pumps. The general procedure is to evaluate the well pump power required to produce a range of groundwater flows and combine that with the heat pump performance at those same groundwater flows. The optimum relationship between pumping power and heat pump performance is established at the design condition and system performance at off peak conditions is maintained by accurate well pump control. A spreadsheet used to make these calculations will be described at the end of this paper. Prior to that, however, it is useful to review some in the individual design issues of these systems.

WATER WELL TERMINOLOGY

Wells are the foundation of open loop systems and as such it is useful to review certain key terms prior to a detailed discussion of system design. Figure 2 provides a generalized diagram of a water well. In any well there will be a water level at which the water stands in the well under non-pumping conditions. This level is indicative of the water table level in unconfined (or water table aquifers) or the piezometric level in a confined (or artesian) aquifer and is known as the static water level (SWL). When the pump is started, water level will normally drop to a new, lower level referred to as the pumping level. The pumping level is a function of the rate at which the well is being pumped, the greater the rate the lower the pumping level. The difference between the SWL and the pumping level is referred to as the drawdown. Drawdown at a given pumping rate, divided by the rate results in a value known as specific capacity with units of gpm/ft (L/s·m). Specific capacity is a useful value for indicating the ease with which the aquifer produces water. A high value (2.1 L/s·m [10 gpm/ft]) would indicate a “good” well; whereas, a value of 0.1 L/s·m (0.5 gpm/ft) would be a “poor” well. For artesian aquifers, specific capacity will be a constant value over a broad range of flows. In water table aquifers, specific capacity will diminish as pumping rate increases.

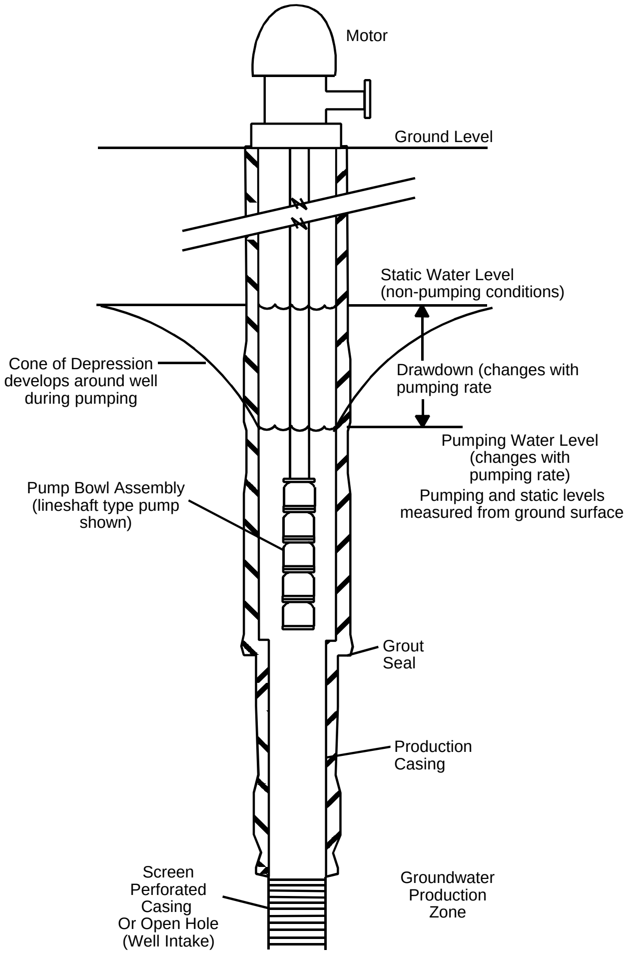


Figure 2. Water Well Terminology.

The drawdown at a given rate is the manifestation, at the well, of the cone of depression that forms in the aquifer around the well during pumping. The size and shape of the cone and the depth of the drawdown are a function of the aquifer and it’s ability to deliver water.

The construction of a well is also a function of the aquifer as. In “competent” rock formations, often the bottom of the well is uncased. This is referred to as open hole completion. In formations in which there is a tendency to cave, a slotted casing or possibly screen may be placed. In very fine sands and in thinly stratified formations, it may be necessary to place a “gravel pack” around the screen to provide additional filtering and to increase the permeability of the near well materials.

PRODUCTION WELL INFORMATION

A key part of the design process is the determination of the well pump power required for a range of ground water flow rates. To calculate these values it is necessary to know something about the performance of the production well in terms of the head (static water level plus drawdown) it imposes on the pump to produce the water. The best source of information are the results of a pump test of the well. This data normally includes pumping water level at three different flow rates and the pre-test static water level. Form this it is possible to calculate the pumping level at a wide range of flows and to incorporate this data into the design calculations.

Pump tests for GWHP systems are normally carried out in a period of from 2 to 12 hours. Water level and flow rate are monitored and readings are taken at frequent (5 min) intervals initially and less frequently (30 min) later in the test. Instrumentation is typically an orifice plate discharging to atmosphere and a manometer type differential pressure gage. Well water level is measured with an electronic continuity device with depth graduations on the wire. The length of the test determined to a large extent by the time required to reach apparent water level equilibrium at each flow rate. Once the level has stabilized, the rate can be increased to the next step. The result of the test is a table on which the flow rate, water level and time of each reading are recorded.

A second method of determining the performance of the wells at the site is to base it upon the performance of nearby wells in the same aquifer. Results from these wells may also provide information useful for the design of the new well. Construction details and sometimes pump test results are included in the well completion reports submitted by the driller upon completion of the well. They are normally kept on file (in some cases available on the internet) by the state water resources regulatory agency and are public information.

It is important that the well be completed in such a way as to minimize the production of sand. This is especially true if an injection well is to be used for disposal of the water. A well producing just 10 ppm of sand, operating a total of 1000 hr per year at 19 l/s (300 gpm) will produce 680 kg (1500 lbs) of sand. Sand production is best controlled by the careful specification of the well completion. Water well construction specifications are available from several sources (Roscoe Moss Co, 1985; EPA, 1975; Rafferty, 1999) and should be incorporated into the construction documents for the project. Key portions of the specifications related to sand are the screen slot size and gravel pack gradation. Both should be based upon a sieve analysis of the cuttings from the production zone. Allowable sand content is normally incorporated into the development portion of the specification.

If it is not possible to complete the well in such a way as to limit sand production, some form of surface separator will be necessary. Open tanks are not acceptable for this purpose. These tanks allow oxygen to enter the water and CO_2 to evolve from the water. If ferrous iron is present in the water, the addition of oxygen will alter it to a ferric state having much lower solubility. The result will be fouling of the heat exchanger. Evolution of CO_2 will raise the water pH thus making calcium carbonate scale more likely. The most effective surface sand removal device is a strainer. Strainers assure that effective removal will be accomplished at any flow rate or condition. Centrifugal devices are generally not designed to achieve the very low sand contents required for this type of application and they are subject to poor performance at pump start up and shut down.

WELL PUMPS

Open loop systems typically use submersible type pumps equipped for the most part with nominal 3,600 rpm motors. As a result, they are able to produce a higher flow per unit diameter than line shaft pumps which typically operate at speeds of 1800 rpm or less. The higher speed of the submersible also results in a greater susceptibility to erosion if significant sand is produced from the well. Submersibles are somewhat more sensitive to voltage variation than surface motors and adequate voltage (allowing for any drop in wiring to the well and down well) should be verified.

Calculating the head for a well pump involves some different issues than a similar calculation for a circulating pump. There are three main components to the total head: lift, surface losses and injection head. Lift is composed off the static water level plus the drawdown at the design rate. Its name derives from the fact that this is the vertical distance the water must be "lifted" by the pump to get it to the surface. Data to determine these values comes from the flow test of the well serving the system (preferred) or from information on nearby wells. Also included in the lift is the friction loss in the pump column (between the pump and the ground surface) which is usually on the order of 0.3 to 0.9 m (1 to 3 ft). Surface losses are those associated with the piping from the well to the building, mechanical room piping and equipment (heat exchanger, etc.) and piping from the building to the disposal point. Unless there are significant elevation considerations or distances involved, surface losses normally amount to less than 15 m (40 ft) assuming a 35 kPa (5 psi) loss in the heat exchanger. The type of disposal can have an impact on the total pump head. In surface discharge applications, often a pressure sustaining valve is used to maintain a small (less than 35 kPa [5 psi]) back pressure on the system to keep it full of water. For injection, the impact may result in added pump head (if a positive pressure is required at the surface) or reduced pump head (if the water level in the well remains below ground surface). A short discussion of injection well head considerations is presented in Kavanaugh and Rafferty, 1997. Table 1 provides an idea of the variation of pump head with flow for a system.

Table 1. Well Pump Head Example

Flow(L/s)	Lift(m)	Surface Losses(m)	Injection(m)	Total(m)
7.9	36.6	10.7	-7.0	40.3
9.5	39.0	12.8	-3.8	48.0
11.0	42.4	14.4	-0.6	56.2
12.6	43.6	7.9	2.5	54.0
14.2	46.1	8.2	5.7	60.0
15.8	48.8	8.5	8.9	66.2
17.4	51.9	9.2	12.1	73.2
18.9	54.3	9.5	15.3	79.1

This example is based upon a confined aquifer with a 23 m (75 ft) static level, specific capacity of 0.62 L/s·m (3.0 gpm/ft) a heat exchanger head loss of 70 kPa (10 psi) and 240 m (800 ft) total equivalent length of pipe and fittings. It is apparent that the lift is the most significant single component. The drop in the surface losses is due to a pipe size change. Most unusual is the injection head which changes from a negative value (water level in the injection well below the ground surface) to a positive value as the pressure builds with greater injection flow rate. Overall, the total head approximately linear with flow rate in this case. This is characteristic of well pumping applications and results from the heavy influence of the lift component.

Key components in the connection of the production well to the system are illustrated in Figure 3. Not shown in this diagram is a pump column check valve which would be located at the base of the column near the bowl assembly. The check valve maintains the column full of water and in doing so prevents damaging reverse thrust on start up. Submersible motors are equipped with a thrust bearing to resist the down thrust developed in normal operation. When starting with an empty column, a pump can exert a temporary up thrust on the motor which if encountered often enough can result in premature failure of the motor. To prevent this submersibles should be equipped with a column check valve.

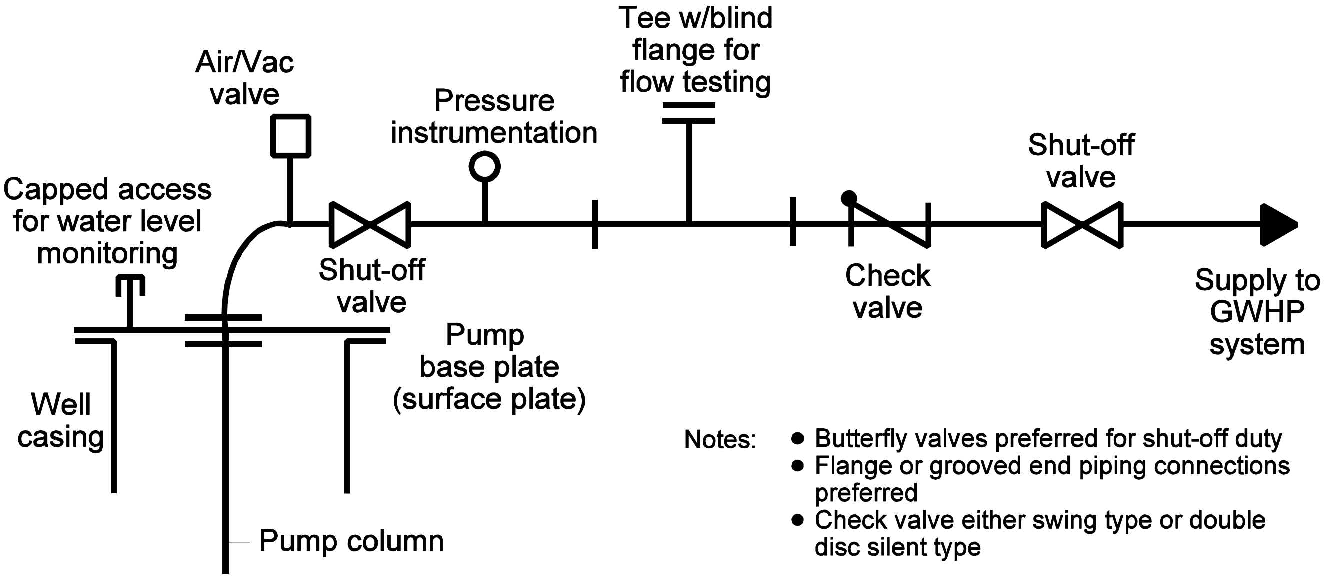


Figure 3. Key connection components for a production well.

Control of the well pump can be accomplished by numerous means. In the smallest systems (typically those without an isolation heat exchanger), the water is pumped to a number of pressure tanks arranged in parallel and the water admitted to the system from the tanks. Due to the extensive tankage required to accommodate this approach it is not normally employed in large systems. In these systems, typically one of three methods is employed: dual set-point, multiple-well (staged pumps), and variable-speed.

The dual set-point approach is fairly common in systems with a single production well and is reminiscent of the control used in water loop heat pump systems. Well pump operation is initiated above a given building loop return temperature in the cooling mode and below a given temperature in the heating mode. Between these two temperatures, the loop "floats." In actuality, the loop operates not between two temperatures but between two temperature ranges in order to adequately control cycling of the pump. For example, if the design indicated an optimum loop return temperature of 26.7 °C (80°F) in the cooling mode, the pump might actually start at a loop temperature of 28.3°C (83°F) and stop at 25°C (77°F). A similar, though smaller, range would exist around the heating mode temperature. The size of the range required around the control temperatures is heavily influenced by cycling limitations on the submersible motor (typically 15 min between starts) and the thermal mass of the building loop. Table 2 presents some guidelines for selection of the ranges based on the building loop thermal mass of the system as measured in gallons of water per peak block ton. This table is based on applications in which the cooling load is the dominant load on the system. This method can result in very large controller range requirements when system thermal mass is less than 8 - 10 l/kW (7 - 9 gal/ton). For such conditions, an alternate control method should be selected or some mass added to the loop. Additional detail on this topic is presented in Rafferty, 2000, and in this Bulletin.

Table 2. Controller Temperature Range for Dual Set Point Control °C (°F)

Motor kW (hp)	System Thermal Mass - l/kW (gal/block ton)						
	2	4	6	8	10	12	14
	COOLING MODE - °C (°F) RANGE						
<3.7kW(5hp)	16(28)	8(14)	5(9)	4(7)	3.3(6)	3(5)	2(4)
>3.7kW(5hp)	31(56)	16(28)	11(19)	8(14)	6(11)	5(9)	4(8)
	HEATING MODE - °C (°F) RANGE						
<3.7kW(5hp)	9(16)	4(8)	3(5)	2(4)	2(3)	2(3)	1(1)
>3.7kW(5hp)	18(32)	9(16)	6(11)	4(8)	3(6)	3(5)	3(5)

In systems in which multiple wells are required due to aquifer hydrology or redundancy, it is possible to employ a staged ground water pumping arrangement. This approach offers somewhat greater control than the single well approach above, but shares the same general approach. Since the pumps are staged, the required controller ranges can be reduced and the issue of system thermal mass is less influential.

Variable-speed control of well pumps is the least common of the three strategies. One of the reasons for this is that the primary purpose for using variable speed control, energy savings, is largely absent in well pump applications. Since a large portion of the well pump head is static head ("lift" described earlier) the nature of the relationship between flow and head is such that savings arising from the use of the drive are substantially less than they would be in a friction head application. Variable-speed control does offer more accurate control, allows optimization of the groundwater flow at any load and eliminates any considerations of system thermal mass. When using variable-speed, it is important to require confirmation from the contractor that the motor manufacturer is aware that his product will be used in a variable-speed application. Issues of conductor length (drive to motor) drive switching frequency, critical speeds and motor cooling must be carefully coordinated with and approved by the motor manufacturer to avoid operational problems.

HEAT EXCHANGERS

Open loop systems employ plate and frame type heat exchangers almost exclusively. These exchangers are key to the reliability of the system since they protect the building loop from exposure to the groundwater. In most cases, the cost of the exchanger is on the order of $7 to $8.50 per kW ($25 to $30 per ton)--a small price for the protection provided. Presence of the exchanger essentially eliminates water quality limitations to the use of open loop. The only common water quality problem which should trigger consideration of alternate design is iron bacteria. Issues of importance to the designer with respect to heat exchangers include pressure drop, approach temperature, materials, and installation issues.

In most commercial applications, the optimum design dictates a flow of 0.045 - 0.054 L/s@kW(2.5 to 3.0 gpm/ton) on the building loop side of the exchanger and 0.018 - 0.045 L/s @kW(1 to 2.5 gpm/ton) on the groundwater side. As a result of this, the approach or minimum temperature difference between the two flows occurs at the building loop return (heat pump leaving water) and groundwater leaving end of the exchanger. Selecting the approach value is a trade off between operating costs (lower at low approach temperature) and heat exchanger capital cost (higher at lower approach). Dropping from an 4.4°C (8°F) to a 1.6°C (3°F) approach will normally gain approximately one full point in system EER. Due to the much flatter performance in the heating mode relative to EWT, the gain in heating mode performance for the added heat exchanger are amounts to approximately 1/3 of this value. As a result, the selection of heat exchanger approach is largely a function of annual system operating hours. The greater the operating time of the system, the easier it is to justify added exchanger area to achieve lower operating cost. For normal occupancy offices and schools, a 2.2°C to 3.3°C (4 to 6°F) approach is often the most economical.

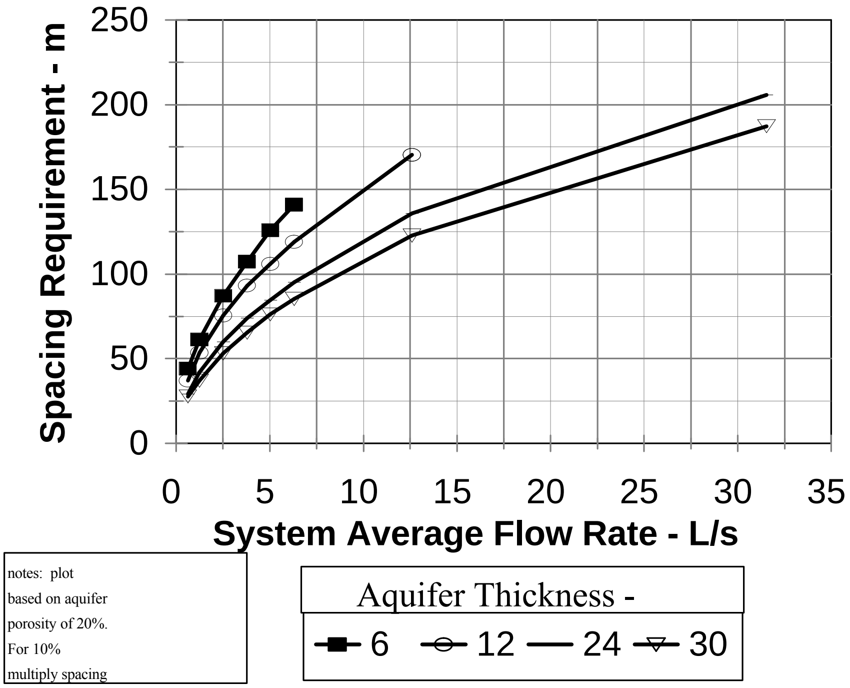
Pressure drop selection is also a trade-of between operating cost and capital cost. Higher pressure drop in a plate exchanger results in higher overall heat transfer coefficient ("U") and lower transfer area (cost) for the same duty. The higher pressure drop however translates into pump head and operating cost. In open loop systems, the higher pressure drop is normally on the building loop side due to the higher flow rate. For systems involving a constant speed pump on the building side, a pressure drop of no greater than 35 kPa (5 psi) on the building side, should be specified. For systems using variable-speed on the building side, a pressure drop of no greater than 70 kPa (10 psi) should be used.

Materials considerations for plate heat exchangers are rarely a major issue. Most manufacturers offer 304 or 316 stainless steel as the base material for the plates and Buna-N (medium nitrile rubber) as the gasket material all of which are generally suitable for groundwater applications. In applications in which the groundwater contains more than 150 ppm chloride, 316 plates should be used in place of 304. For chloride concentrations greater than 375 ppm (a very rare occurrence), titanium plates should be specified. Piping connections and placement of plate exchangers should be configured in such a way as to allow easy access for disassembly and cleaning. If piping connections are required on the movable end plate, the piping should be of flanged or grooved end material to permit easy disassembly. It is generally not necessary to specify a two heat exchanger installation. Exchangers can normally be disassembled, cleaned and reassembled in a single shift. Contractors should be required to furnish at least one spare plate for each type of plate in the exchanger (usually at least two types of plates). Gaskets for the plates should be provided as well and glued in place (if of the "glue in" type).

DISPOSAL

There are two basic options for water disposal from an open loop system: surface and injection. Both options are subject to regulatory oversight and permitting. Surface disposal the most common method used in the past is less expensive, but requires that the receiving body be capable of accepting the water over a long period. Injection is more complex and costly but offers the certainty that the groundwater aquifer will not be adversely affected (aquifer decline) by the operation of the system over the long term since the water is "recycled."

For surface disposal, it may be advisable to place a pressure sustaining valve on the end of the system to maintain the piping full when the pump is not operating. Some designers prefer to simply place a motorized valve at this point in the system and interlock it with the pump (through an end switch). Distance from the building has some influence on the strategy used as the motorized valve requires a control signal and power source and the pilot-operated valve does not.



notes: plot based on aquifer porosity of 20%. For 10% multiply spacing

Figure 4. Well spacing requirements - minimum (from Kazmann and Whitehead data).

Injection is a more mysterious strategy to most mechanical engineers. Key issues are well design and well spacing. In theory, the only difference between an production and an injection well is the direction of flow. In practice, there are some differences in the design depending upon the type of aquifer penetrated. For wells completed in unconsolidated materials, and equipped with a screen, the screen area should be twice that used in the production well. The rule of thumb for injection wells is that the entrance velocity of the water through the screen openings (slots) should be limited to 0.015 m/s (0.05 ft/sec); whereas, production wells are normally based upon 0.030 m/s (0.1 ft/sec). This does not mean that a larger diameter well is required in all cases. The reduced velocity could also be accomplished by screening more of the aquifer, particularly in the case of wells penetrating water table aquifers. For wells completed in fractured rock and completed "open hole," there is often no difference between the injection and production well design. Sealing is an important issue in injection wells. Because it is likely that the water level in the well will be higher than the static water level when in operation, it is important that the seal (grout placed between the borehole and the outside of the casing) be carefully placed and that it extends from the top of the aquifer to the ground surface. This prevents the injected water from finding a path up around the outside of the casing to the surface.

Well spacing, or the distance required between the production and injection wells is an important consideration. It is not necessary that the injection well be sited in such a way as to prevent any flow from the injection to the production well, just that any inter-well flow be sufficiently low that it arrives at the production well at a temperature close to the aquifer temperature. For unconsolidated aquifers, the method developed by Kazmann and Whitehead provides a guideline for minimum spacing. In order to use the method, it is necessary to know the aquifer thickness, porosity, system average flow rate and the period of duration (days) of the dominant load. The method is covered in detail in Kavanaugh and Rafferty, 1997. A summary of spacing information appears in Figure 4.

Connection of the system piping to the injection well is illustrated in Figure 5. Of particular importance is the injection "dip tube" in the well. Injected fluid should always be released below the static water level in the well so as to minimize the formation of air bubbles. Bubbles entering the injection zone can impede water flow just as an accumulation of particulate would. The air release valve also helps to minimize the air in the injection well. This component is especially important in systems which cycle the well pump. A means of diverting the water flow in the event that the well must be removed from service allows the system to continue operation with temporary surface disposal. Finally, the provision for pressure (or water level) monitoring is important in injection wells as a means of monitoring the performance of the well and any accumulation of particulate in the injection interval.

There is a perception that injection wells often fail. This is false. In fact, the failure is normally that of the designer not the well. Poor production well performance in terms of sand content coupled with the lack of a surface removal system inevitably means that this material will be deposited in the injection well. Successful injection requires clean, particle free fluid. The system must be designed with this as the goal.

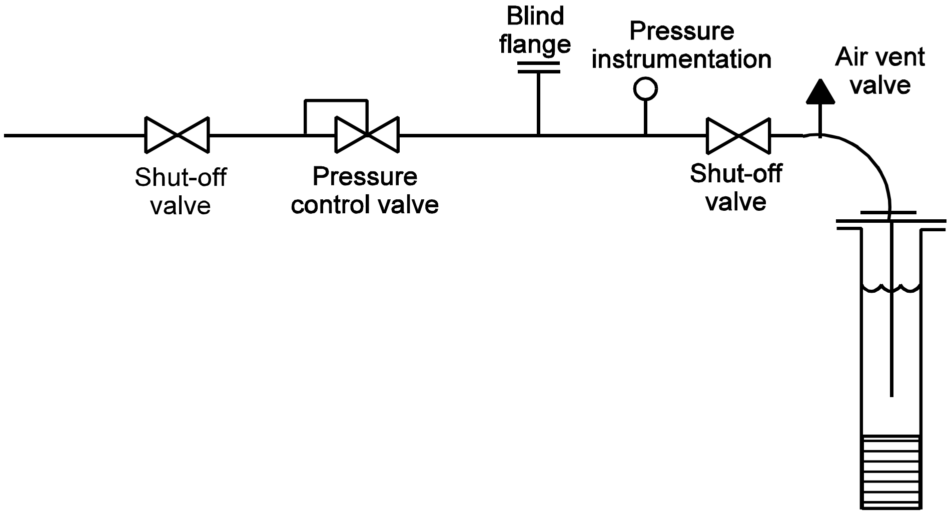


Figure 5. Injection well piping connections.

Wells								
GW temp	60	F	**Syst EER**	13.10		**Syst COP**	3.49	
Static	75	ft	Flow	149	gpm	loop pump	4.76	kW
Spec cap	2	gpm/ft	gpm/ton	1.75	gpm/ton	Unit COP	4.3	
Flow	40	gpm				Loop out	54.2	F
Drawdn	25	ft	**Pump**			Loop in	47.9	F
Aquifer t	150	ft	Flow	149	gpm	GW lvg	50.9	F
Inj Well ?	0	1-Y, 0-N	Head	186	ft			
Inj Eff	0.8		Setting	174	ft	**GCHP**	12.70	EER
			Heat Ex					
Building			GW in	60.0	F			
Load	1020000	Btu/hr	GW out	76.6	F			
Htg Load	900000	Btu/hr	Loop in	80.6	F			
Htx dp	7	psi	Loop out	69.0	F	**Control**		
Hd loss	37	ft	Area C	265.0	sq ft	cool on	86	F
Approach	4	F	Area H	204.6	sq ft	cool off	75	F
Loop flow	213	gpm	Inj Well			heat on	44	F
Loop head	65	ft	Distance	0	ft	heatoff	51	F
HP brand	8		Inj press	0	psi			
Syst vol	1000	gal						

EWT	LWT	h/p EER	LWT GW	GW Flo	gpm/ton	GW head	GW kW	SYS EER
53.00	64.26	19.40	60.26	9192.54	108.1	262.0	157.075	0.00
55.00	66.31	18.90	62.31	1044.50	12.3	262.0	65.693	0.00
57.00	68.34	18.50	64.34	556.32	6.5	262.0	41.684	0.00
59.00	70.38	18.10	66.38	379.88	4.5	301.9	35.108	0.00
61.00	72.43	17.60	68.43	288.77	3.4	256.4	23.664	11.81
63.00	74.47	17.30	70.47	233.35	2.7	228.7	17.509	12.56
65.00	76.51	16.90	72.51	195.97	2.3	210.0	13.742	12.93
67.00	78.56	16.50	74.56	169.10	2.0	196.6	11.409	13.08
69.00	80.61	16.10	76.61	148.87	1.8	186.4	9.722	13.10
71.00	82.66	15.70	78.66	133.09	1.6	178.5	8.452	13.05
73.00	84.71	15.30	80.71	120.45	1.4	172.2	7.468	12.93
75.00	86.74	15.10	82.74	109.97	1.3	167.0	6.676	12.91
77.00	88.77	14.90	84.77	101.21	1.2	162.6	6.032	12.87
79.00	90.82	14.55	86.82	93.88	1.1	158.9	5.506	12.69
81.00	92.88	14.20	88.88	87.61	1.0	155.8	5.065	12.49
83.00	94.94	13.85	90.94	82.18	1.0	153.1	4.691	12.27
85.00	97.00	13.50	93.00	77.44	0.9	150.7	4.370	12.04
87.00	99.03	13.30	95.03	73.16	0.9	148.6	4.085	11.92
89.00	101.07	13.10	97.07	69.35	0.8	146.7	3.835	11.80
91.00	103.13	12.80	99.13	66.02	0.8	145.0	3.620	11.58
93.00	105.19	12.50	101.19	63.04	0.7	143.5	3.429	11.36

Figure 6. Spreadsheet for open-loop system design.

DESIGN PROCEDURE

Figure 6 provides a summary of a spreadsheet developed to design open loop systems. This spreadsheet was developed in English units and no SI version is available. The spreadsheet illustrates the information necessary to accurately design an open loop system. Unshaded values are input and shaded values are output. In general, all of the information concerning the well or wells would be available from the driller's completion report and/or the flow test results. With the exception of the groundwater temperature, all of the values are used primarily for the calculation of well pump power. Such items as the static water level, specific capacity (entered only for confined aquifers), flow and drawdown (entered only for unconfined aquifers) and aquifer thickness (used in the determination of well spacing) are all characteristics of the aquifer itself and although necessary as inputs, they are not "adjustable" by the designer. The final two well related inputs indicate whether or not an injection well will be used and if so, what the injection efficiency is expected to be. Injection efficiency is a value used to adjust the drawdown (from the flow test) to calculate the expected pressure buildup at the injection well for the same flow. It is used in the calculation of the well pump head.

Building loop related inputs include the building block cooling and heating loads (expressed as space loads), the pressure drop for which the heat exchanger will be selected, surface head losses for the groundwater loop (piping, heat exchanger, fittings etc), heat exchanger approach (between groundwater leaving and building loop entering), building loop flow rate and head loss, heat pump brand (to calculate COP, EER), and system water volume (to calculate loop thermal mass and well pump control set points).

The table in the lower portion of the figure indicates the calculations for the cooling mode. The spreadsheet calculates heat pump performance at a series of entering water temperatures (EWT's), and using the performance and EWT, calculates a series of LWT's. Using the LWT value (assumed to be equal to the building loop heat exchanger entering temperature), and the specified heat exchanger approach a ground water heat exchanger LWT is calculated. Using the load information and the groundwater temperature rise, the groundwater flow is calculated. With the input data on the well performance, the head on the well pump at each of the flows is calculated and from this, pump horsepower and kW are determined. Combining the well pump power, loop pump power and heat pump power, the final calculation is the system EER. A similar calculation is made for the heating mode (Figure 7).

The spreadsheet is configured to look at the cooling load as the primary load and it selects the peak EER value from the table and displays it along with the groundwater flow in the output section. This is the flow rate for which the well pump would be selected. Well pump design information is located just below the cooling mode output. Shown are the flow rate and head for which the pump would be selected along with the setting depth for the bowl assembly (depth at which the pump suction should be located). Heat exchanger data includes the cooling mode entering and leaving temperatures at the peak condition along with calculated surface area requirements in the heating and cooling modes. These surface area values are not intended to be specified to the vendor but are used to give the designer an indication of which mode (heating or cooling) is dominant in the system design. If an injection well was specified in the input, the spreadsheet, using the aquifer thickness and flow rate, calculates a separation distance requirement for the production and injection wells. Based on the flow test drawdown or specific capacity and the injection well efficiency specified, the spreadsheet calculates the injection well pressure (at the ground surface) at peak flow.

Peak heating mode performance values are displayed in the next column. All values shown are based on an assumed heat exchanger approach as specified in the input. In most cases, the heat exchanger area required for cooling exceeds that for heating. As a result, the system will operate at more favorable temperature than that which is indicated in

EWT	LWT	h/p COP	LWT GW	GW Flo	GW head	GW kW	SYS COP
35	28.8	3.68	32.8	48.3	136.1	2.20	3.35
37	30.8	3.75	34.8	52.4	138.2	2.42	3.40
39	32.8	3.81	36.8	57.1	140.6	2.69	3.44
41	34.7	3.88	38.7	62.8	143.4	3.02	3.48
43	36.7	3.94	40.7	69.6	146.8	3.42	3.51
45	38.7	4.01	42.7	77.9	151.0	3.94	3.54
47	40.6	4.08	44.6	88.3	156.2	4.62	3.56
49	42.6	4.14	46.6	101.8	162.9	5.56	3.56
51	44.6	4.21	48.6	119.9	172.0	6.91	3.55
53	46.5	4.27	50.5	145.5	184.8	9.01	3.49
55	48.5	4.34	52.5	184.6	204.3	12.64	3.37
57	50.5	4.41	54.5	251.5	237.7	20.03	3.12
59	52.4	4.47	56.4	392.4	308.2	40.53	2.53
61	54.4	4.54	58.4	883.4	262.0	77.55	0.00
63	56.4	4.60	60.4	-3661.6	-1718.8	2108.74	0.00
65	58.4	4.67	62.4	-599.7	-187.8	37.74	0.00

Figure 7. Calculations for the heating mode (from Figure 6).

this column. The spreadsheet includes a heat exchanger analysis module to make this evaluation.

For convenience, the performance of a vertical closed loop system using the same heat pumps and designed for 11 °C (20 °F) above the undisturbed soil temperature is displayed in the output to provide the designer with a comparison system.

Finally, set point temperature for the well pump in the heating and cooling modes are displayed based on the system volume specified in the input. These temperature assume the use of a single production well with a single speed pump.

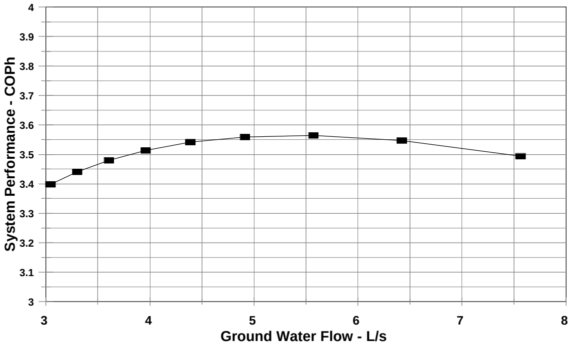


Figure 8. Heating performance.

Graphs of the heating and cooling mode performance are shown in Figures 8 and 9. These provide a clearer indication of the systems performance in the different modes and permits the designer to evaluate the impact at operation at other than the peak performance selected by the spreadsheet.

CONCLUSION

Open loop systems can offer the owner performance comparable or in some cases better than that of closed loop systems. Despite their long history of use and perceived simplicity, care is required in the design and installation in order that the ful potential of the systems be achieved. Some important guidelines along with a useful design tool are illustrated in this paper. The following "10 Commandments" of open loop design will help to keep the designer on track to a reliable and efficient system:

THINK SYSTEM - well pump, heat pumps, loop pumps
PUMP LESS WATER - reasonable loop and groundwater flows
KNOW THE LOAD - design for block load not installed capacity
KNOW THE AQUIFER - static level, specific capacity, drawdown, flow test
KNOW THE RULES - verify groundwater regulatory issues
DO YOUR HOMEWORK - previous groundwater experience in the area, other wells
KNOW THE GROUND WATER - complete chemistry test if used directly
KEEP THE AIR OUT - no open tanks
ISOLATE THE GROUND WATER - use a plate heat exchanger
KNOW YOUR LIMITATIONS - in complex settings use a hydrogeologist

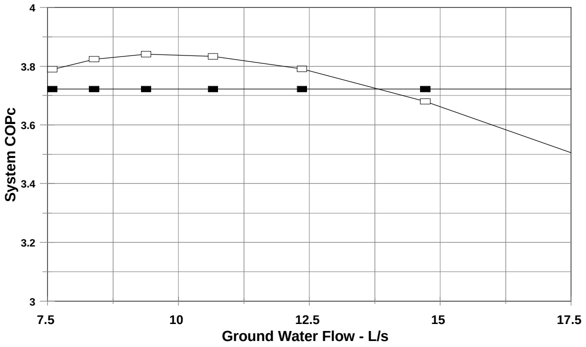


Figure 9. Cooling performance.

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