DUAL-SET POINT CONTROL OF OPEN-LOOP HEAT PUMP SYSTEMS

Kevin Rafferty
Geo-Heat Center

ABSTRACT

Control of well pumps in open-loop heat pump systems is a topic which has been largely overlooked in the literature. Three primary methods are in use: dual-set point, variable speed and multiple well (normally employed when multiple wells are required for hydrologic or redundancy). This paper explores the issues involved in the dual-set point method. Establishing the system operating set points requires consideration of peak loop loads, loop thermal mass, well pump motor cycling limitations and heat exchanger performance. Guidelines for pump controller operating range are presented along with the method of establishing the optimum loop temperatures at peak load conditions.

INTRODUCTION

The design of open-loop heat pump systems and the procedure for identifying the optimum groundwater flow for maximum system performance (EER or COP) is discussed in detail in existing references (Kavanaugh and Rafferty, 1997; ASHRAE, 1999). Basically, this procedure consists of calculating the power requirements of both the well pump and the heat pumps over a series of groundwater flows to determine the system optimum groundwater flow at the dominant peak load (normally the cooling mode in large commercial buildings). Above this flow, system performance degrades due to increasing well pump power consumption. Below this flow, system performance degrades due to increasing heat pump power consumption. The issue left largely undefined in the existing literature is the control of the well pump at conditions other than peak load. A variety of strategies have been used and the three most common are dual-set point, multiple well and variable-speed. Multiple well control is normally a strategy chosen when more than one production well is required for hydrologic or redundancy purposes.

The dual-set point method is somewhat similar to the temperature control scheme used in water-loop heat pump systems. The well pump is enabled above a given temperature in the cooling mode and below a given temperature in the heating mode. The multiple well approach is similar in terms of the temperature initiated response of the well pumps; however, the use of multiple wells provides the ability to stage

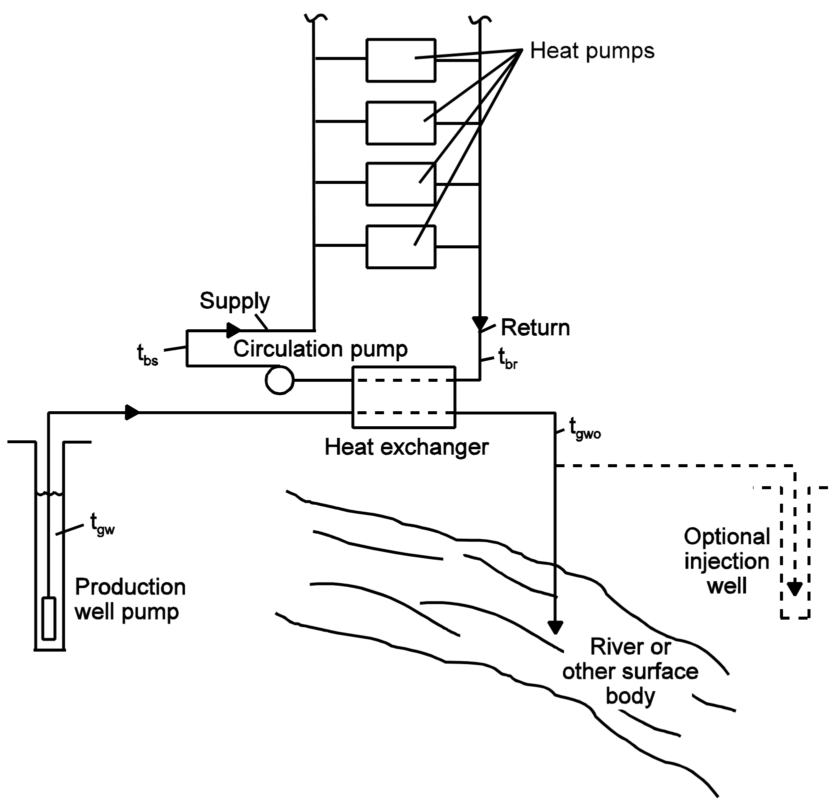

Figure 1.

the groundwater flow and sometimes, better match the different heating and cooling mode flow requirements. Variable-speed control of well pumps permits an infinitely variable groundwater flow for any system load or mode provided sophisticated enough controls are available.

There is no "best" among the methods listed above. The strategy is selected based on the system size, well design parameters specific to the site and the capabilities of the owners operating personnel. Discussion of well pump control from this point will focus on the dual-set point approach and assume a system configured as indicated in Figure 1.

DUAL-SET POINT CONTROL

As indicated above, dual-set point control is similar to the cooling tower/boiler control employed on water-loop heat pump systems--in which the cooling tower is employed above a specific loop temperature in the cooling mode and a boiler is used below a specific temperature in the heating mode with the loop "floating" between these two set points. In this case, it is the well pump that is used to temper the loop in both cases. Ideally, at the peak condition, the pump runs continuously. At less than peak loads, the well pump is cycled in response to the size of the load. In fact, there are four rather than two set points as the name implies: pump on temperature and pump off temperature in the cooling mode, and pump on and pump off temperatures in the heating mode. Each of these pairs of set points are normally arranged symmetrically about the optimum building loop return temperature for that mode.

Properly done, the design process for an open-loop system identifies a groundwater flow rate, which results in the highest system performance (system EER or COP) at peak load. Once this flow has been determined and the heat exchanger selected, the operating temperatures at the peak conditions are fixed. Based on the thermal mass of the system and the loop thermal load, the well pump operating range around the optimum temperature in the dominant mode (usually cooling) is established. System performance is determined in the peak secondary load (usually heating) and the operating range around the loop return temperature at the secondary load peak is established based on the loop thermal load and the system thermal mass. This general procedure establishes an optimum relationship between the well pump power, heat pump power and building load. Maintaining this optimum relationship at off peak conditions is accomplished by cycling the well pump.

Consider the following example system: peak cooling block load 85 tons (299 kW), groundwater temperature 60ºF (15.6ºC), production well static water level 75 ft (23 m), aquifer specific capacity 2 gpm/ft (0.04 L/s-m), building loop flow 213 gpm (13.4 l/s), surface groundwater head losses of 37 ft (11.3 m) and a heat exchanger selected for a 4ºF (2.2ºC) approach temperature (between the building loop return [to the heat exchanger] temperature and the groundwater leaving temperature). Under these conditions, the optimum groundwater flow would be approximately 1.75 gpm per ton (0.031 l/s-kW) or 150 gpm (9.5 l/s). System performance in the peak cooling mode vs. groundwater flow is illustrated in Figure 2.

Figure 2. Example system performance.

At the design load and the flow of 150 gpm (9.5 l/s), the groundwater would enter the exchanger at 60ºF (15.6ºC) and leave at 76.6ºF (24.8ºC). The building loop side would enter at 80.6ºF (27ºC) and leave at 69ºF (20.6ºC). The building loop return temperature is most commonly used for control of the well pump. In this case, since the return temperature under optimum conditions is approximately 81ºF (27.2ºC), this would be the value around which the well pump would be controlled. In order to limit the cycling of the well pump, some range around this temperature must be established such that pump operation is initiated at a temperature above the optimum value (pump on temperature) and operation terminated at a temperature below the optimum (pump off temperature). The size of the range between these two values is a function of the thermal mass of the system (gallons of water per peak block ton [liters of water per peak block kW])and the allowable time between starts for the well pump motor.

SUBMERSIBLE PUMP MOTOR CYCLING

Submersible motors, like any other motors, are limited in terms of the starts to which they can be subjected over a given interval of time. Due to the thermal spike imposed on the motor windings at start up, sufficient time must be permitted to dissipate this heat between starts to avoid damage to the insulation and other thermal cycling damage to the motor. The recommended limitations are a function of the motor size and electrical characteristics (primarily whether it is single or 3 phase). This information is summarized in Table 1

Table 1. Recommended Limitations for Number of Starts per Day for Submersible Motors (Franklin, 1999)

Motor hp	Single Phase	3-Phase
<5	100	300
7 ½ to 30	50	100
>30	–	100

Most larger commercial open loop system pumps will fall into the 100 starts per day imitation category. In the context of the heat pump system, a more useful unit would be 15 minutes between starts.

BUILDING LOOP THERMAL MASS

The nature of the dual-set point approach is such that the building loop is drafted over some temperature interval (difference between the pump on temperature and the pump off temperature). The range between these two temperatures must be sufficient, given the thermal mass of the loop and the load imposed on it to accommodate the 15-minute limitation between starts. In the example system above, the pump might be started when the loop reaches 84ºF (28.9ºC) and operated until the loop is reduced to 78ºF (25.6ºC), a 6ºF (3.3ºC) range. The time required for the loop to be reduced from 84ºF (28.9 ºC) to 78ºF (25.6ºC) (while the pump is running), combined with the time required for the loop to rise from 78ºF (25.6ºC) to 84ºF (28.9ºC)(pump off), is the time between starts and must be no less than 15 minutes.

Obviously, the thermal mass of the building loop is constant as is the capacity of the groundwater (via the heat exchanger) to remove heat from the loop. As a result, the primary variable in terms of the time between pump starts is the building thermal load imposed on the loop. Figure 3 expresses the relationship between this parameter (in units of gallons of water per ton of peak block load) and the number of minutes between pump starts per ºF of difference between pump on and pump off temperature. This plot is based on space load (1 ton = 12,000 Btu/hr [3.52kW]) and incorporates an assumed heat pump unit EER of 14.6, resulting in a loop load of 14,800 Btu/hr (4.34 kW) per ton.

Figure 4 provides the same information for the heating mode of operation. The heating mode plot is also based on space load (1 ton = 12,000 Btu/h [3.52 kW]) and incorporates a heat pump unit COP of 3.5 which results in a loop load of 8,600 Btu/hr (2.52 kW) per ton. Due to the impact of compressor heat, the thermal mass/controller range requirements needed to avoid short cycling in cooling load dominant applications are substantially larger than in heating dominant applications.

Although the phenomenon of short cycling in system components is normally considered to be a problem at minimum load, it is apparent that in open loop systems, the well pump cycling issue is of most concern at 50 % load. This arises from the fact that it is the time between starts (the time for one off-cycle plus one on-cycle) that is of interest. At high-loop thermal load, the pump on-cycle will be long. At low-loop load, the pump off-cycle will be long. Either of these two situations lengthens the time between starts. Thus, it is at the mid point that the time between starts for the well pump is minimized. It is at this 50% load point that the range for the pump control is established. For the example system in the cooling mode, assuming a loop thermal mass of 8 gal/ton (1.1 min/ºF from Fig 3)(106 l/kW(1.98 min/ºC), a range of 15/1.1 or 13.6 ºF (7.6 ºC) would be required. This would result, in the cooling mode of a pump-on temperature of 81 + (13.6/2) = 87.8ºF (31ºC) and a pump-off temperature of 81 - (13.6/2) = 74.2 ºF (23.4 ºC). At a loop thermal mass of 14 gal/ton (186 l/kW), the necessary range would be reduced to 15/1.9 = 7.9º F (4.3 ºC).

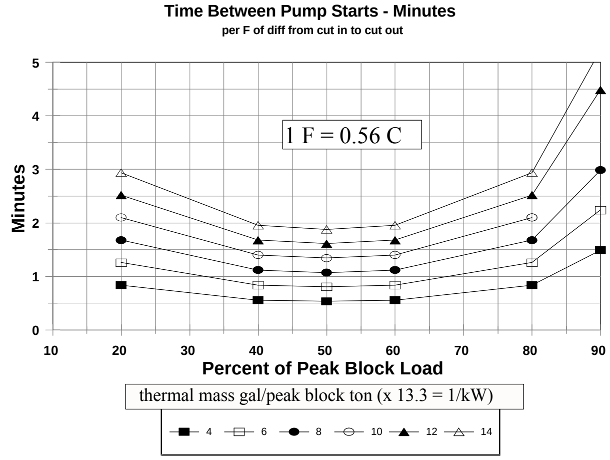

Figure 3.

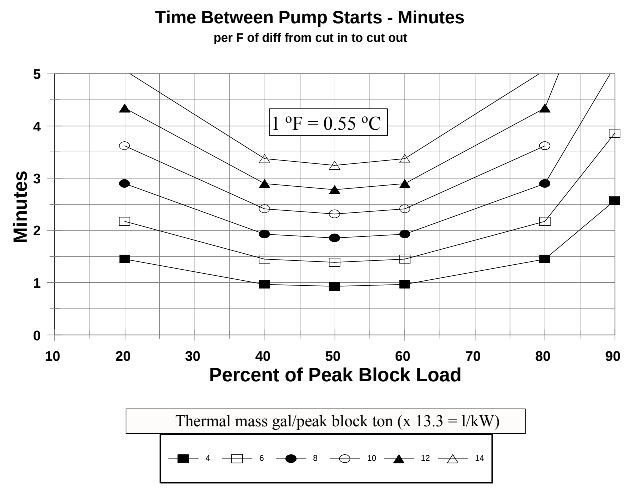

Figure 4.

Values for building loop thermal mass of between 4 and 14 gal per peak block ton (53.2 to 186 l/kW) are considered in the plot; since, these represent the extremes which the author has witnessed in these systems. Generally, small multistory office type buildings with a small foot print tend toward the lower end of the spectrum and large single story large footprint (schools) tend toward the upper end of the range.

GUIDELINES FOR WELL PUMP CONTROLLER TEMPERATURE RANGE

To simplify the process of range selection, Table 2 was developed. The table offers guidelines for minimum well pump controller range in ºF (ºC) with examples for large (>5 hp [3.7 kW]) and small (5hp [3.7 kW] and less, 3 phase) pumps and both cooling load and heating load dominant applications. The values in the table are the minimum temperature ranges necessary to assure adequate time between starts for the system well pump in a single production well application.

Table 2. Minimum Controller Range Requirements ºF(ºC)

Motor hp(kW)	System Thermal Mass - gal/block ton (l/kW)						
	2(27)	4(53)	6(80)	8(106)	10(133)	12(160)	14(213)
	COOLING MODE - ºF (ºC) RANGE						
<5hp(3.7kW)	28(16)	14(8)	9(5)	7(4)	6(3.3)	5(3)	4(2)
>5hp(3.7kW)	56(31)	28(16)	19(11)	14(8)	11(6)	9(5)	8(4)
	HEATING MODE - ºF (ºC) RANGE						
<5hp(3.7kW)	16(9)	8(4)	5(3)	4(2)	3(2)	3(2)	2(1)
>5hp(3.7kW)	32(18)	16(9)	11(6)	8(4)	6(3)	5(3)	5(3)

It is apparent that at system thermal mass values of less than 8 gal/ton (106 l/kW)(cooling mode dominant), the required range on the well pump controller becomes very large. Although it is reasonable to assume that a system operating over a small temperature range about an optimum point will, on average achieve the optimum performance, as the range becomes larger system performance suffers. As a result for systems with very low mass, it may be worth considering an alternate method of well pump control or the addition of some mass to the system. For small systems, the addition of sufficient storage to reach the 10 gal/ton(133 l/kW) threshold is achievable for reasonable capital cost. Otherwise, use of the variable-speed or multiple well approach should be considered.

SECONDARY LOAD SET POINTS

The discussion, to this point, has focused on the dominant system load using the cooling load as the example since this is normally the dominant load in most large building applications. A similar approach is used for establishing the well pump controller range at the secondary load peak condition. The difference is that since the groundwater flow rate and the heat exchanger are sized for the dominant load peak, some calculation is necessary to determine the building loop operating temperatures in the secondary load peak condition. Once this value is determined, the appropriate minimum range can be selected from Table 2 to arrive at the pump-on and pump-off temperatures.

To determine the operating temperatures at the secondary load peak, it is necessary to evaluate the performance of the heat exchanger at the reduced thermal load imposed by the secondary peak. This can be done by manual calculation or with analysis provided by the heat exchanger vendor. Using the example 85 ton (299 kW) system established above and assuming a peak heating load of 900,000 Btu/hr (264 kW), it can be calculated that the building loop return temperature at peak heating conditions would be 49ºF (9.4ºC). From the previous calculations, it was established that the system has a building loop thermal mass of 8 gal/ton (106 l/kW) based on the cooling load. As a result, for the heating mode, the value would be (85 tons * 8 gal/ton)/(900,000/12,000) = 9.1 gal/ton (121 l/kW). From Table 2, this would result in the selection of a minimum well pump controller range of approximately 4ºF (2.2ºC). As a result, in the heating mode, the well pump for this system would be started at 49 - (4/2) = 47ºF (8.3 ºC) and stopped at 49 + (4/2) = 51ºF (10.6ºC).

ADDITIONAL CONSIDERATIONS

The issue of thermal mass is an important one in the context of range size determinations. Since the critical point for pump cycle time occurs at 50% load, a more useful term might be effective thermal mass for systems with variable-speed. In systems with variable-speed control of the building loop pump, at 50% load by definition, 50% of the heat pump capacity will be idle. The water in the branch piping to the idle heat pumps is not available to contribute to the thermal mass of the system as far as calculations for well pump cycling are concerned. This influence is a complicated one and more amenable to adjustment after the system is in operation rather than calculation at the design stage. Again, this is an issue more in small compact buildings than extensive, large footprint buildings.

The system thermal mass used in the development of the guidelines sited in this paper considers only the water volume. No credit has been taken for the heat pump refrigerant-to-water heat exchangers or the building loop piping itself. The building loop piping increases the loop thermal mass by approximately 25% for steel and 10% for copper and PVC materials relative to the water only thermal mass. As a result of this impact, the temperature ranges sited in Table 2 can be decreased accordingly. The exact impact is influenced by the pipe sizes involved. In smaller diameter pipe, the relative contribution of the pipe material to the total thermal mass (pipe plus water) on a per foot basis, is much higher than it is in larger diameter pipe. For example, in 1-1/4" (32mm) schedule 40 steel pipe, the pipe material constitutes 28% of the total thermal mass on a per foot basis and at the 6"(152mm) size the pipe material constitutes only 15%. The variation with pipe size is less for copper and PVC materials.

CONCLUSIONS

The dual-set point method of well pump control for open loop heat pump systems is a simple, efficient and widely used strategy. To properly apply it, it is necessary to fully consider the issues of dominant and secondary loads, building loop thermal mass, submersible motor cycling limitations, and heat exchanger performance. For cooling load dominated buildings, it may be necessary to consider another method of control or the addition of volume to the building loop in applications with less than approximately 8 gal/ton (106 l/kW) thermal mass.

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