AN EVALUATION OF THE EFFECTIVENESS OF PRE-COOLING IN A HYBRID GROUND SOURCE HEAT PUMP

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ABSTRACT

Hybrid ground source heat pump (HyGSHP) systems for building heating and cooling are gaining popularity as a means of decreasing long term energy and maintenance costs while maintaining manageable first costs. In these systems there is a potential to use the ground not only as an immediate heat source or sink, but as an energy store. On a scale of hours, the ground store could be cooled by a hybrid component, such as a cooling tower, during the night in order to improve the heat rejection efficiency in cooling during the following day. This paper presents the results of a study of the ground as a thermal energy store on a short term basis.

INTRODUCTION

In a cooling dominated environment a Hybrid Ground Source Heat Pump (HyGSHP) incorporates a supplemental heat rejection device, such as a cooling tower (CT), with a ground heat exchanger, GHX, to meet heating and cooling loads. The addition of a CT allows for the use of a smaller GHX by balancing the load on the ground. The first cost of the system is reduced but the higher energy efficiency of a GSHP versus a more conventional system (e.g. boiler and chiller) is still maintained.

One of the key design questions for a HyGSHP is how to control the CT to maximize energy and/or cost savings. One particularly influential paper studied five different control methods (Yavuzturk & Spitler, 2000), including set point temperature control and differential temperature control. With set point control the CT operates when the temperature of the fluid exceeds a specified set point; the method was evaluated with the fluid temperature measured at either the inlet or outlet of the HP. Differential temperature control showed the best results; in this method the CT operates when the fluid temperature entering the CT exceeds the wet bulb temperature by a specified setpoint. This strategy ensures that the CT is only used if it is beneficial. Another strategy was to pre-cool (PC) the ground in anticipation of high cooling loads. This strategy was also effective at lowering energy cost, but not as effective as the differential control strategy.

Numerous other authors have reached the same conclusion (Fan, Jiang, Yao, & Ma, 2008; Jinggang, Xiaoxia, Zhenjiang, & Fang, 2009; Man, Yang, & Wang, 2008; Xu, 2007); PC is effective at reducing operational costs, but differential temperature control results in greater savings.

These studies focused on comparing the effectiveness of several different control strategies, but none optimized the strategies or used them in combination. For example, pre-cooling could be used in combination with differential temperature control, which would be the dominant control scheme. Additionally, the economic and energy analyses often did not include the cost of water or additional sources of energy consumption resulting from pre-cooling operation. The current work details the preliminary investigation of the pre-cooling control strategy with the GHX as a thermal store. The goal of this work is to obtain an understanding of how the PC control strategy affects the GHX, which in turn modifies the performance of the HP. A thorough economic and energy analysis are conducted to evaluate how the potential improvement in HP performance is offset by the increased cost and power consumption of the CT and circulating pump. The change in operational and life cycle costs are presented as a metric for measuring the effectiveness of PC as a control strategy.

DEFINITION OF PRE-COOLING

The concept of pre-cooling as explored in this work is to operate equipment at night, when off-peak electric rates apply and building loads are low, to produce a source of cooling for the next day. This can be accomplished by, for example, storing chilled water in a thermal storage tank. A cooling tower HyGSHP has a

CT which could be used to produce chilled water and a GHX which could be used for thermal storage. In this case the chilled water flows through the GHX and heat is removed from the ground. The ground is not an ideal thermal store, but it is very expensive, so if it can be used more extensively the economics may be more appealing.

In the present work, pre-cooling is studied as a control strategy in which the CT cools the ground during the night so that the ground temperature is lower the next day. This leads to a reduction in the entering water temperature (EWT) to the heat pump (HP), which leads to a reduction in HP power consumption. Operating the CT at night takes advantage of off-peak electric rates. The reduction in HP power consumption during the day occurs during times of peak electric rates, so the economic savings may be significant. The benefit of pre-cooling is a reduction in operating costs.

SOFTWARE

The model, described below, is implemented as an executable FORTRAN program. The CT model is based on TRNSYS type 510, a closed circuit cooling tower (Klein et al., 2004; TESS, 2004; Zweifel, Dorer, Koschenz, & Weber, 1995). The GHX model is based on TRNSYS type 557, the DST (duct storage) model (Hellström, 1989). The heat pump model is based on a model developed for the software HyGCHP, a program for optimizing HyGSHP design (Energy Center of Wisconsin, 2011; Hackel, Nellis, & Klein, 2009). In this case individual HPs are modeled as one large HP which meets the building load; additional details on this gang-of-heat-pumps model can be found in the references (Hackel et al., 2009; Xu, 2007). The fraction of the time step that the heat pump actually operates is calculated by dividing the load by the capacity of the heat pump. The power consumption is then scaled by this run time fraction. If both heating and cooling loads exist then two HPs are included in the model, one for heating loads and one for cooling loads. The building heating or cooling load and entering water temperature are input to the HP model. The power consumption and flow rate are calculated based on manufacturer's data.

ECONOMIC ANALYSIS

The economic analysis uses the P1-P2 method to calculate Life Cycle Cost (LCC) (J.A. Duffie & Beckman, 2006). Some of the key economic parameters are given in Table 1. The same values were used in both Las Vegas and Chicago.

Table 1 Value of key economic parameters.

Effective income tax rate	35%
Property tax rate	3%
Duration of the economic analysis	20 years
Fuel inflation rate	1.33%
Discount rate	8.5%
Down payment	100%
Minimum time frame in the analysis	20 years
Depreciation life	5 years
First cost of GHX	39 \$/m
Cost of water	1.41 $\$/m^3$
Peak rate (11:00 to 20:00)	0.104 \$/kWh
Off-peak rate	0.057 \$/kWh

MODEL

The layout of the system modeled in this study is shown in Figure 1. In order to isolate the effects of PC, this system is modeled as a more traditional GSHP. When there are loads, the GSHP is used to meet those loads; the CT is used only at night in order to cool the GHX. When there is a load, the HP is plumbed in series with the GHX; if the flow rate through the HP is especially low due to a small load, then the HP can be bypassed such that the circulating pump is always operating with at least 30% of the maximum flow. During pre-cooling, the HP is not used. The CT and GHX operate in series such that the CT directly cools the ground. The flow rate through the cooling tower is the design flow rate; if the flow through the CT is too low then the CT is bypassed such that the flow into the GHX is always at least 30% of the maximum flow rate. Only cooling loads are present in this study, so only one HP is required.

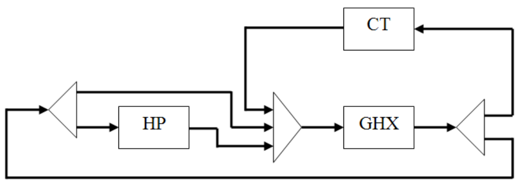

Figure 1 System schematic.

SINGLE DAY SIMULATIONS

A synthetic cooling load for a single day is shown in Figure 2. It was developed with the constraints that the peak load occurs in the afternoon and there is no load during the night, when the CT operates in PC. This model allows for the evaluation of how PC affects the ground temperature over night without confounding factors, such as night loads or CT operation during the day.

The single cooling day was repeated for a year long simulation (365 days) and for a 20 year simulation (7300 days). Two locations were selected for the simulation, Las Vegas and Chicago. Las Vegas has a favorable environment for PC while Chicago is less favorable due to higher wet bulb temperature and lower ground temperature. The wet and dry bulb temperatures for July 2 (TMY data, (NREL, 2009)) are shown in Figure 3 and Figure 4.

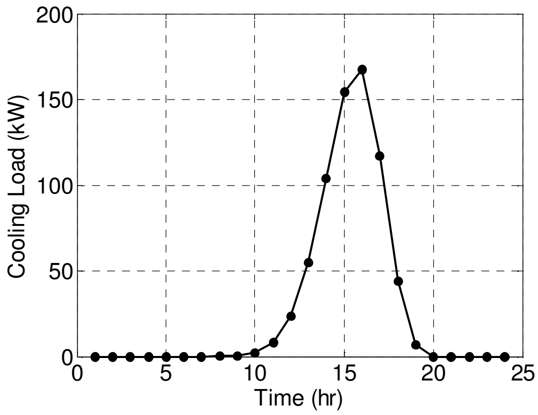

Figure 2 Single day cooling load profile.

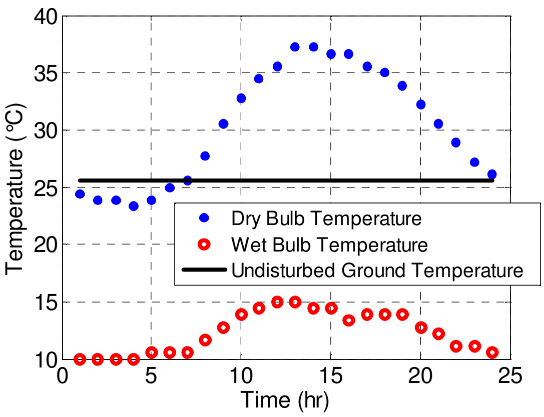

Figure 3 Temperatures in Las Vegas.

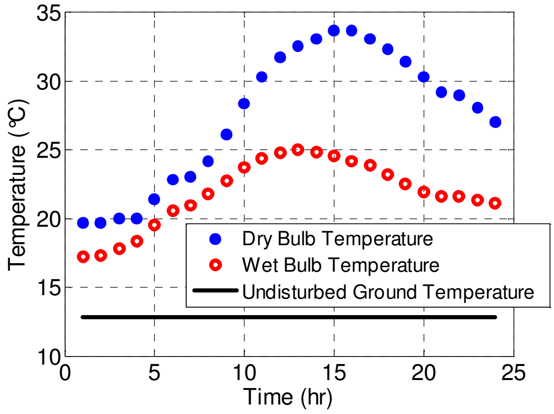

Figure 4 Temperatures in Chicago.

Five cases were simulated:

1. No PC, GHX size optimized
2. PC is added with a 100 kW CT
3. PC is added with a 250 kW CT
4. PC is added with a 1000 kW CT
5. PC, GHX and CT size are optimized

The subplex scheme was used to determine the optimal system design in order to minimize LCC (Rowan, 1990) with the constraint that the EWT was never below 1.7°C or above 35°C. Cases 3 and 4 use a CT size which exceeds the peak cooling load; these cases were simulated in order to better illustrate the trend in PC performance as a function of CT size.

Results for a Single Year Simulation

The optimal GHX length for a single year simulation in Las Vegas is 4059 m; when PC is included in the design the optimal GHX length is 2854 m and the optimal CT size is 130 kW. The addition of a CT balances the heating and cooling load on the ground, so a smaller GHX can be used. Table 2 shows some of the results; “HP Power” is the total HP power consumption and “Additional Power” is the total circulating pump and CT power.

When PC is added there is a reduction in HP power consumption, indicating that PC is effective in reducing EWT. However, the additional power consumption due to the circulating pump and CT exceeds the reduction in HP power. In the optimal case, Case 5, the reduction in HP power consumption is small. When the GHX length is reduced, heat is rejected to a smaller volume and therefore the ground temperature increases more during the day, leading to a greater EWT and a reduction in the amount of HP power saved.

Table 2 Key power results.

	HP POWER (KWH)	ADDITIONAL POWER (KWH)
Case 1	84,662	4,024
Case 2	80,497	13,410
Case 3	77,280	35,487
Case 4	72,890	311,572
Case 5	84,301	17,021

Economic results are shown in Table 3. When PC is added, operational costs increase, so the overall LCC increases. In the optimal PC case, Case 5, the first cost of the system is much lower than in the case without PC. The reduction in GHX length leads to a large savings in first cost. In this case, the LCC decreases because the first cost of the GHX decreases.

Table 3 Economic results.

	FIRST COST ($)	ELECTRICAL COST ($)	WATER COST ($)	LCC ($)
Case 1	223,967	8,149	0	374,588
Case 2	233,673	8,277	880	386,323
Case 3	241,627	9,218	1607	403,505
Case 4	276,249	24,483	2783	590,767
Case 5	188,297	8,856	1023	355,841

In Chicago the optimal GHX length for a single year is 1949 m. For a single year, PC is never optimal. As can be seen in Figure 4, the wet bulb temperature is greater than the ground temperature, so the CT heats the ground rather than cooling it. However, as more and more heat is rejected to the ground the temperature increases as shown in Figure 5. It eventually becomes high enough for the CT to start cooling the ground.

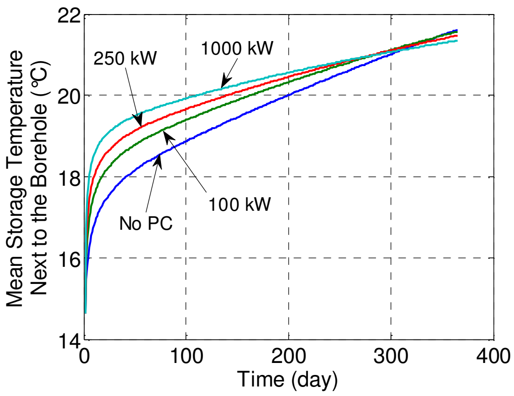

Figure 5 Mean GHX temperature next to the borehole.

For a single year, PC is optimal in Las Vegas not because of a reduction in operating cost, but because of a reduction in the first cost of the GHX. PC, as implemented here, is never optimal in Chicago for a single year because during this time the ground temperature is lower than the wet bulb temperature. This study was repeated for a 20 year simulation in order to more fully understand PC.

Results for a 20 Year Simulation

The optimal GHX length for a 20 year simulation in Las Vegas is 10,700 m. This is substantially larger than for a single year because in order to mitigate the increase in ground temperature the GHX volume must be increased. When PC is added the optimal length is 2854 m and the CT size is 157 kW. This length is the same as for a single year and the CT is just 27 kW larger. The CT is effective at balancing the ground load and only a slight increase is required to keep up with the additional heat rejection which occurs over 20 years. The increase in GHX length for the case without PC means the savings in first cost when PC is added will be more significant than they were for the single year simulation. This result is shown in Table 4.

As in the single year simulation, the power consumption and operating costs increase for Cases 3 through 5; see Table 5. In Case 2 there is a decrease in electrical cost despite an overall increase in power consumption because the additional power consumption occurs when off-peak electric rates apply while the savings occur during peak rates. However, the savings in electrical costs are more than offset by the increased first cost of the system as well as the cost of water.

Table 4 Economic results.

	FIRST COST ($)	ELECTRICAL COST ($)	WATER COST ($)	LCC ($)
Case 1	482,966	88,974	0	609,038
Case 2	492,672	88,491	10,500	618,993
Case 3	500,626	97,546	19,579	634,170
Case 4	535,248	266,959	34,408	829,557
Case 5	189,715	100,637	12,892	358,094

Table 5 Key power results.

	HP POWER (KWH)	ADDITIONAL POWER (KWH)
Case 1	1,681,914	79,861
Case 2	1,537,799	266,780
Case 3	1,433,950	708,432
Case 4	1,303,388	6,243,217
Case 5	1,670,460	412,756

For a 20 year simulation in Chicago, a system that can pre-cool is optimal. Without PC the optimal GHX length is 4650 m, but with PC the optimal GHX length is 2910 m with a 166 kW CT. With a longer system life the ground temperature eventually increases to a point where PC cools rather than heats the ground and the behavior is the same as in Las Vegas. Figure 6 demonstrates this behavior. For the first several years PC leads to an increase in the temperature of the GHX next to the borehole relative to the case with no PC, but in later years the temperature increases less relative to the case without PC. The overall temperature increase is lower for the larger CT's, which actually lead to a net removal of heat from the ground.

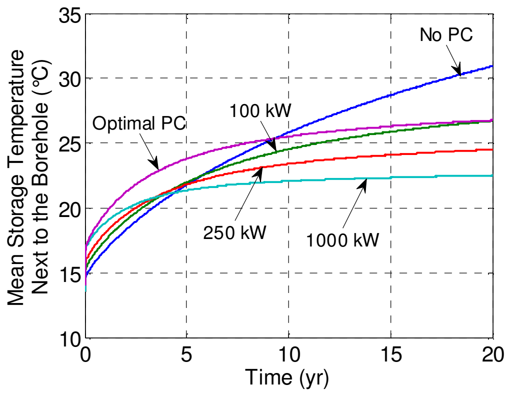

Figure 6 Mean GHX temperature next to the borehole.

Table 6 shows the power consumption for each of the cases; for the optimal case, Case 5, the heat pump power increases. In this case the GHX length was reduced, so in the early years PC leads to greater heat rejection to the ground for a given volume and therefore more heat pump power consumption. In addition, the smaller volume also leads to a greater increase in ground temperature during the day. As shown in Figure 6, the optimal design does not lead to lower ground temperature relative to the case with no PC until the ninth year. When pre-cooling cools the ground in later years, the reduction in heat pump power does not offset the initial increase or the increase that occurs during the day due to the smaller volume.

Table 6 Key power results.

	HP POWER (KWH)	ADDITIONAL POWER (KWH)
Case 1	1,529,328	76,694
Case 2	1,485,636	265,726
Case 3	1,455,907	709,169
Case 4	1,426,477	6,246,654
Case 5	1,604,850	436,020

Table 7 Economic results.

	FIRST COST ($)	ELECTRICAL COST ($)	WATER COST ($)	LCC ($)
Case 1	247,016	79,271	0	361,802
Case 2	256,722	84,012	2,125	374,231
Case 3	264,676	97,112	3,681	390,584
Case 4	299,298	272,365	6,419	580,792
Case 5	192,404	96,032	4,053	332,151

ANNUAL LOAD SIMULATION

A more realistic case was studied by running a 20 year simulation in Las Vegas using a typical annual cooling load profile. Building heating loads were assumed to be supplied by a boiler rather than the heat pump so that the ground load could be balanced only by adding a CT; see Figure 7. As in the prior studies, the CT operated every night, meaning that PC was used even when it was winter or a shoulder season. At times cooling loads occured during the night, so the CT acted to both cool the ground and meet the building load.

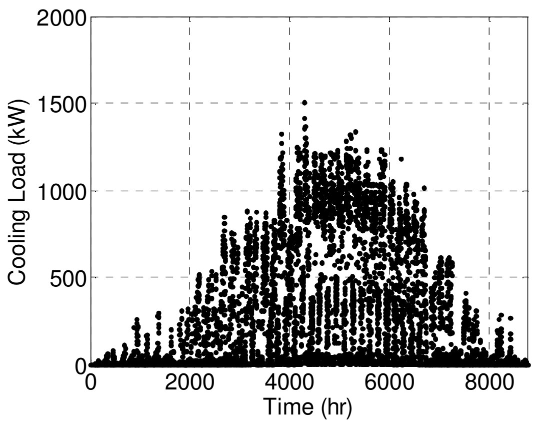

Figure 7 Annual cooling load.

Without PC, the optimal GHX length is 106,650 m; with nightly PC the optimal length is 29,223 m and the CT size is 2243 kW. Despite an increase in power consumption (see Table 8) and operational costs (see

Table 9) with pre-cooling, the economic savings are significant. As in the prior simulations, these savings are due to the decrease in first cost.

Table 8 Key power results.

	HP POWER (KWH)	ADDITIONAL POWER (KWH)
Case 1	12,318,844	614,385
Case 2	12,316,814	720,767
Case 3	12,313,774	857,567
Case 4	12,298,682	1,547,823
Case 5	11,528,958	4,649,357

Table 9 Economic results.

	FIRST COST ($)	ELECTRICAL COST ($)	WATER COST ($)	LCC ($)
Case 1	4,749,172	500,585	0	5,297,267
Case 2	4,758,878	504,012	193	5,310,913
Case 3	4,766,832	508,396	482	5,321,725
Case 4	4,801,454	530,523	1,922	5,371,109
Case 5	1,821,028	612,744	78,673	2,715,021

One particularly interesting result from the annual study is that the CT is noticeably larger than the peak load. Typically, a CT is sized to meet the peak load; the over-sizing in this case is due to several factors. The CT is being used in an atypical way; it is not directly meeting the cooling load most of the time and never meets the peak cooling load, which occurs during the day. When there are loads during the night that coincide with CT operation, the CT meets those loads in addition to cooling the ground, so the effective load is higher than the building load. The CT helps meet the cooling load during the day by cooling the ground, which is an imperfect thermal store. Some of the heat rejection capability of the CT is lost due to the inefficiency of the storage in the ground.

One objective of additional studies is to evaluate the difference between operating the CT at night and operating the CT during the day, with the constraint that a GHX meets some of the load. The ground load is balanced by the CT in either case, so the advantage of night operation is to shift electrical usage to a time with off-peak electric rates. It is questionable that there would be sufficient economic savings in electricity costs to offset the increased cost of using a larger CT at night or to make up for the inefficiency in thermal storage in the GHX. In addition, during the day the CT would meet some of the building load directly, likely lowering heat pump power consumption more than PC.

Another objective is to evaluate the use of combined day/night CT operation, again with the constraint that a GHX is present. In this type of operation the CT could be sized based on day time operation, leading to a smaller CT, but also operated at night to provide additional ground cooling. The concern in this operation is that the additional cooling of the ground will not lead to sufficient performance gains to offset the cost of operating the CT and circulating pump at night.

DISCUSSION

Based on the single year simulation, a location such as Las Vegas is more favorable for pre-cooling than a location such as Chicago because the wet bulb temperature is significantly lower than the ground temperature. However, over 20 years a location such as Chicago can become favorable as the ground temperature increases. The implementation of pre-cooling should include a consideration of when in the system life it should be used; in Chicago it would not be implemented for the first several years.

Based on the economic analysis pre-cooling can lead to economic savings by allowing a reduction in the size of the GHX and, therefore, a reduction in the first cost of the system. CT operation balances the load on the ground, so a smaller GHX can be used to meet the same load. However, this same conclusion holds true if a CT is used during the day in order to directly meet the load (Energy Center of Wisconsin, 2011; Jinggang et al., 2009; Man et al., 2008; Yavuzturk & Spitler, 2000), so it is unclear if pre-cooling is beneficial when compared to a different control strategy in a more standard HyGSHP design.

Based on both the economic and energy analyses even in an optimal pre-cooling design, the operational cost and energy consumption of pre-cooling is greater than when it is not used. There is a reduction in heat pump power consumption, but this reduction is offset by an increase in circulating pump power consumption and the addition of the cooling tower power consumption. The lower, off-peak cost of operating the CT at night is insufficient to offset the higher peak cost of operating the heat pump during the day. Case 2 of Table 4 is the lone exception to this statement; there is a reduction in electrical cost, but the addition of water cost and the first cost of the CT leads to an overall increase in LCC. The cost of water and the first cost of the CT can be significant and should be accounted for in any analysis.

In addition to supporting the conclusions about pre-cooling from the single cooling day simulations, the annual simulation illustrated several other important considerations. In this simulation PC was used every night, so it provided not only short term cooling of the ground, but also long term or seasonal cooling. Additional work will be required to determine the potential benefit of cooling the ground during winter and/or shoulder seasons. It is possible that cooling during this period may not significantly increase the efficiency of the HP, but only a detailed study can answer this question.

The coincidence of PC and a cooling load also needs to be further assessed to determine if this is a beneficial situation. It is also possible that a smaller CT could be used if it operated with a combined strategy of differential temperature control and PC. In this situation the CT could be used to meet more of the building load directly. The economic difference between using a larger CT at night and a smaller CT during the day needs to be considered as well.

CONCLUSION

This work has provided an understanding of how pre-cooling using the GHX as a thermal store performs. However, due to the simplifications in this study it is difficult to make a broad statement about pre-cooling as a control strategy. Even the simulation with an annual cooling load was limited in that heating loads were not included. In addition, the use of the CT during winter and the shoulder seasons rather than just during times of peak loading confuses how best to implement PC.

When PC was optimal it did not reduce operational costs and in all but one case the cost of electricity increased. This indicates that in general the potential economic savings of operating the CT at night when off-peak electric rates apply is unrealized. Economic savings can be significant when PC is implemented at the design stage because the GHX can be smaller. However, this result indicates not that PC is beneficial, but that adding a supplemental heat rejector in order to balance the ground load is beneficial. One key question to answer is if pre-cooling is effective as compared to other control strategies, such as differential temperature control, or in combination with such control strategies.

Although the GHX can be more fully utilized by employing it as a thermal store, it is not an ideal thermal store because the ground is never cooled to the temperature of the fluid. It is likely that a control strategy which incorporates PC with a more ideal thermal storage device, such as a thermal storage tank, will be more energy efficient than the current design. Whether or not the incorporation of a thermal storage tank will make PC economically viable requires further study.

ACKNOWLEDGMENT

The authors recognize Scott Hackel at the Energy Center of Wisconsin for his guidance in selecting some of the model inputs.

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