INCREASING CONFIDENCE IN GEOTHERMAL HEAT PUMP DESIGN METHODS

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1. INTRODUCTION

Sizing the ground heat exchanger is one of the most important tasks in the design of a geothermal heat pump (GHP) system. Undersizing the heat exchanger can result in poor operating efficiency, reduced comfort, and nuisance heat pump lockouts on safety controls, while an oversized heat exchanger increases the installation cost of the system. The cost of ground loop installation may mean the difference between a feasible and an unfeasible project. Thus there are strong incentives to select heat exchanger lengths which allow satisfactory performance under all operating conditions within a feasible project budget.

Sizing a ground heat exchanger is not a simple calculation. In the first place, there is usually some uncertainty in the peak block and annual space conditioning loads for the building to be served by the GHPs. The thermal properties of the soil formation may be unknown as well. Drilling logs and core samples can identify the soil type, but handbook values for the thermal properties of soils vary widely. Properly-done short-term on-site tests and data analysis to obtain thermal properties provide more accurate information, but since these tests are expensive they are usually only feasible in large projects.

Given the uncertainties inherent in the process, if designers were truly working “close to the edge” – selecting the absolute minimum heat exchanger length required to meet the predicted loads – one would expect to see more examples of undersized heat exchangers. Indeed there have been a few. However, over the past twenty years GHPs have been installed and successfully operated at thousands of locations all over the world. Conversations with customers and facility managers reveal a high degree of satisfaction with the technology, but studies of projects reveal far more cases of generously sized ground heat exchangers than undersized ones. This indicates that the uncertainties in space conditioning loads and soil properties are covered by a factor of safety. These conservative designs increase the installed cost of GHP systems, limiting their use and applicability.

Moreover, as ground heat exchanger sizing methods have improved, they have suggested (and field tests are beginning to verify) that standard bore backfill practices lead to unnecessarily large ground heat exchangers. Growing evidence suggests that in many applications use of sand backfill with a grout plug at the surface, or use of bottom-to-top thermally enhanced grout, may provide groundwater protection equal to current practice at far less cost. Site tests of thermal properties provides more accurate information, but since these tests are expensive they are usually only performed in large projects. Even so, because soil properties can vary over a distance as small as a few feet, the value of these tests is limited.

One objective of ongoing research at the Oak Ridge National Laboratory (ORNL) is to increase designers' confidence in available ground heat exchanger sizing methods that lead to reliable yet cost-effective designs. To this end we have developed research-grade models that address the interactions between buildings, geothermal heat pump systems and ground heat exchangers The first application of these models was at Fort Polk, Louisiana, where the space conditioning systems of over 4,000 homes were replaced with geothermal heat pumps (Shonder and Hughes, 1997; Hughes et. al., 1997).

At Fort Polk, the models were calibrated to detailed data from one of the residences. Data on the energy use of the heat pump, combined with inlet and outlet water temperature and flow rate in the ground heat exchangers, allowed us to determine the thermal properties of the soil formation being experienced by the operating GHP system. Outputs from the models provide all the data required by the various commercially-available ground loop sizing programs. Accurate knowledge of both the building loads and the soil properties eliminated the uncertainty normally associated with the design process, and allowed us to compare the predictions of the commercially-available methods.

2. MODELED BUILDING AND EQUIPMENT

The residence selected for the study was a lower floor apartment in a two-story 5-plex building. It has a conditioned floor area of 1052 ft^2 and sits on a slab floor. The GHP is a nominal 1.5 ton unit with a total cooling capacity of 17,300 BTU/hr and 15.4 EER at ARI 330 rating conditions. Heating capacity is 11,800 Btu/hr with a 3.5 COP at ARI 330 rating conditions. The unit does not include supplementary resistance heat.

Two vertical U-tube ground heat exchangers connected in a parallel arrangement are used to reject/absorb heat to/from the earth. Each of the vertical U-tube ground heat exchangers is placed in a 4.125 inch vertical borehole 258 feet in depth. The boreholes are spaced 16 feet apart, 25 feet from the exterior wall of the building. The bores were backfilled with a bentonite-based grout after the installation of the U-tubes. The U-tubes themselves consist of 1 inch nominal polyethylene pipe with a nominal center-to-center spacing of 2.565 inches. The center-to-center u-tube spacing exists at the bottom of the u-tube heat exchanger (the bottom of the bore). Figure 1 is a diagram of the ground loop in relation to the building; figure 2 illustrates the details of the borehole.

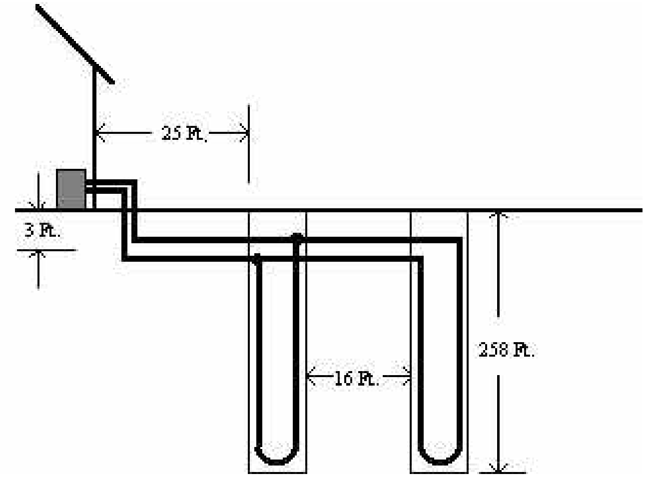


Figure 1: Ground Heat Exchanger Configuration

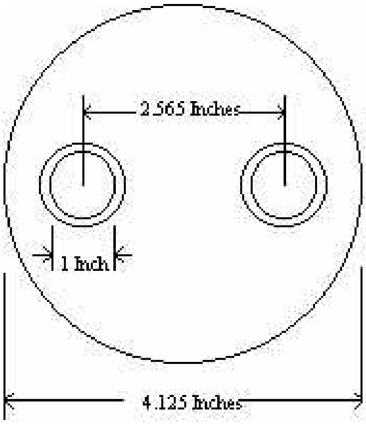


Figure 2: Borehole details

3. MODELING THE SYSTEM

The TRNSYS software package (Klein, 1996) was chosen as the tool for the detailed simulations of the geothermal heat pump system and housing unit. TRNSYS is a modular system simulation package in which the user describes the components that comprise the system and the manner in which these components are interconnected. Components may be typical pieces of equipment like a pump or thermostat, or utility modules like occupancy forcing functions, weather data readers, integrators and printers. Because the program is modular, new component models for the heat pump and vertical ground heat exchangers were easily added to the existing component libraries to expand the capabilities of the program. The program was also chosen for its relative ease in driving the simulation models with measured data for the performance comparisons.

Individual component models were developed for the building and its associated forcing functions, the heat pump, the ground heat exchanger, the thermostat, the ground loop pump, and the heat pump's blower. Details of these models have been presented by Thornton et al. (1997). The heat pump model (heating and cooling capacity, power draw, etc.) was a look-up table based on data obtained from the manufacturer.

For a GHP system, the most important component model is the ground heat exchanger. Although several ground heat exchanger models were available for the study, the duct ground heat storage model (DST) was chosen because it is well documented, validated, and considers multi-bore interactions and long-term (multi-year) effects.

The duct ground heat storage model (DST) was developed at Lund University (Sweden) and chosen in 1981 by the participants of the International Energy Agency, Solar R&D Task VII (Central Solar Heating Plant with Seasonal Storage) for the simulation of duct ground heat storage. A simpler but faster version was implemented by Hellstrom (1983) in the MINSUN program (Mazzarella, 1991), a simulation tool for the optimization of a central solar heating plant with a seasonal storage (CSHPSS). A TRNSYS version based on this faster DST version was implemented by Mazzarella in 1993. A more recent version (Hellstrom et al., 1996) combined the easy utilization of the simple version with the additional features of the more detailed original DST program (Hellstrom, 1989). In addition, a detailed computation of the local heat transfer along the flow path within the storage region was also possible (Pahud and Hellstrom, 1996). The latest version (Pahud et al., 1996) offers the possibility of having several ground layers that cross the storage region, each having their own thermal properties.

The TRNSYS model described in this paper has also been used to model the pre- and post-retrofit electrical consumption of an entire neighborhood at Fort Polk containing 200 residences (Shonder et. al., 1997). Since the model was able to predict the savings due to the GHP retrofit to within 0.1 percent of the savings actually achieved, we have a great deal of confidence in its operation.

4. MODELING CALIBRATION

One-time power measurements allowed calibration of component models for the heat pump controls, blower, thermostat and ground loop pump. To calibrate the building model, parameters such as outdoor air infiltration, occupancy and occupancy schedule were varied until the model's predicted hourly loads matched the energy use data collected from the site. Figure 3 compares the average heating and cooling loads vs. ambient temperature as predicted by the model, and the average hourly loads from the site-collected data.

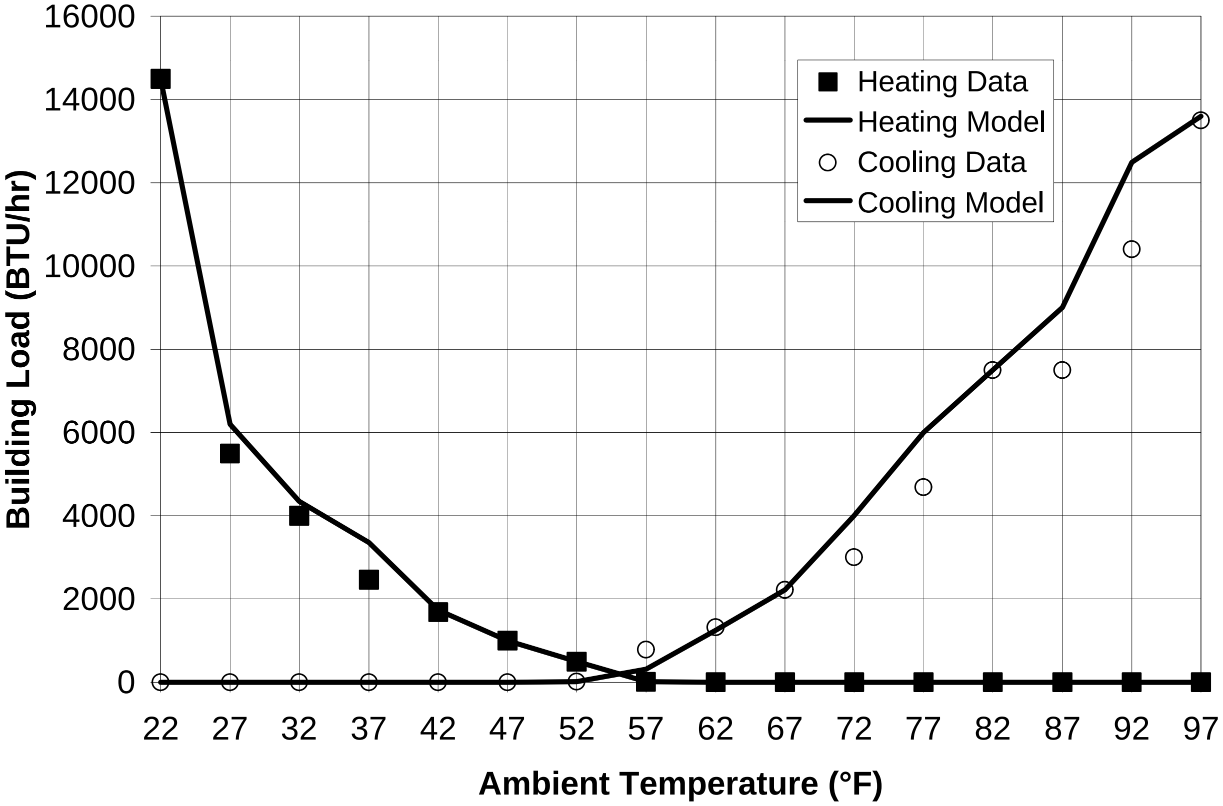


Figure 3: Average heating and cooling load, data and model.

Energy use by the heat pump was collected at 15-minute intervals during all heat pump on-cycles. Along with one-time measurements of power draw by the fan and controls, this data allowed us to determine heat rejection/absorbtion to the ground loop. Heat pump entering water temperature and the temperature difference between inlet and outlet were also measured at 15-minute intervals. This data allowed us to calibrate the ground loop model. Given the heat rejection/absorbtion to the loop and the inlet water temperature, the ground loop model predicts an outlet water temperature depending on the values assumed for deep earth temperature, soil thermal conductivity and soil thermal diffusivity. The soil properties were adjusted until the predicted outlet water temperature matched the measured outlet water temperature in a least-squares sense. As shown in Figure 4, the model does quite well at predicting the maximum entering water temperature to the heat pump in each month.

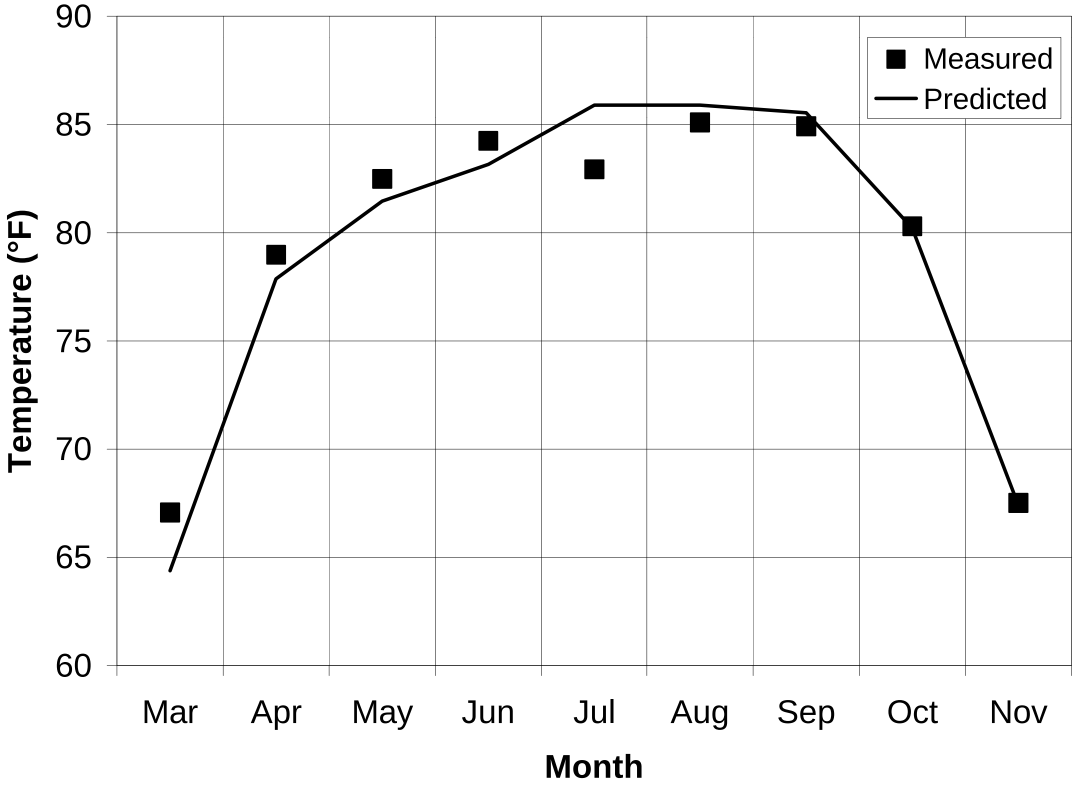


Figure 4: Maximum monthly heat pump entering water temperature

5. GROUND LOOP SIZING SOFTWARE

The general factors which influence the design of a vertical ground heat exchanger are the building design loads, the monthly and annual loads, weather conditions, soil properties, ground loop properties (i.e., pipe sizes and materials, u-tube separation, grout properties, etc.), the working fluid, and the operating characteristics of the heat pump. Authors differ on the degree and manner in which each of these factors affect the final design, but the basic philosophy of ground loop sizing software is to select a heat exchanger length which limits the water temperature exiting the loop (and entering the heat pump) to some user-specified minimum or maximum value. In cooling-dominated climates a common maximum is 95°F, since the efficiency of the heat pump begins to fall substantially above this limit. In heating-dominated climates the minimum temperature limit may depend on the freezing point of the working fluid.

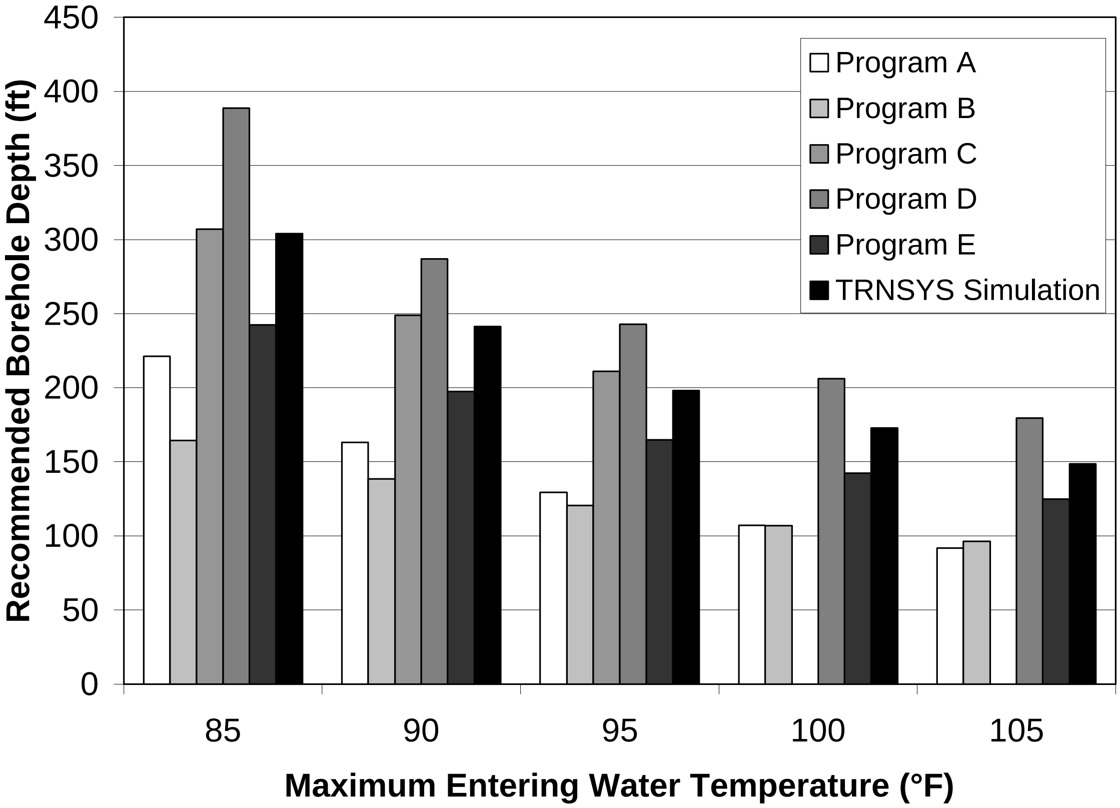
At the heart of all loop sizing software is a model of the heat transfer process between the working fluid and the surrounding soil. Since in general this process is quite complicated – involving a small-scale, rapid convection process coupled to much slower, large-scale conduction in a non-homogeneous material – all design programs make some simplifying assumptions. The heat exchanger may be modeled as a line heat source in an infinite medium, or as a finite-diameter cylindrical heat source. Other models are possible as well.

Available sizing programs also differ in the way they use building load information. Some require heating and cooling design loads; others use monthly or annual loads in addition to the design loads. One program requires monthly heat rejection/absorbtion from the ground loop, while another determines this from the equivalent full-load run hours of the heat pump. The latter program also requires average building design loads during four six-hour periods on the design day. Programs also differ in the level of detail required for the borehole, soil, and weather conditions. The benefit of using the calibrated TRNSYS model is that it was flexible enough to generate the inputs required for all of the commercially-available ground-loop design programs. This allowed us to compare the sizing recommendations of five different design programs with the ground loop that was actually installed at the site.

6. COMPARISON OF FIVE DESIGN METHODS

Figure 5 shows the recommended heat exchanger lengths from the five design programs for various values of maximum entering water temperature (Program C would not allow selection of entering water temperatures of 100 and 105 °F). The wide variation in recommended sizes highlights the problem facing GHP system designers. To take one example, if entering water temperature is to be limited to 95°F, program A recommends a bore depth of 120.4 ft and program D recommends 242.8 ft. In effect, the confidence interval is so large that it includes the entire bore depth.

It is clear that the wide variation in recommended size is a result of the different simplifying assumptions made by each author. However these results hold for this case only - a residential application with a 1.5 ton heat pump in a cooling-dominated climate - and it would be premature to conclude that one design algorithm is more accurate than the others. It should also be noted that this study was performed with versions of the software that were available in 1996. New versions of several of the sizing programs have been released, and it is planned to repeat this study with the current versions.



7. CONCLUSIONS

Five practical vertical ground heat exchanger design programs were exercised with inputs taken from a detailed simulation model calibrated to measured data. Even with consistent (to the extent possible) inputs, these five practical methods calculate very different required borehole depths necessary to keep the heat pump entering water temperature below a user-specified maximum. Since this comparison next-generation versions of several of the practical design methods have become available. We plan to repeat this comparison using the current versions of the software packages. In addition, similar comparisons will be performed based on monitored GHP applications in different building types, and with different heat pump sizes. We are also expanding our work to include building confidence in commercially-available short-term tests and analysis to determine soil formation properties, and building confidence in the use of bore backfill approaches that protect groundwater and enable cost-effective GHP systems.

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