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ABSTRACT

One of world's largest uses of energy is the heating and cooling of buildings. Ground Source Heat Pumps (GSHP) provide a more energy efficient way to meet building energy needs than conventional alternatives. At a relatively shallow depth, the ground temperature is nearly constant year round providing a reliable heat source or sink for the operation of a heat pump. The design of such systems is complicated by the short and long term behavior of the ground as well as various options for system configuration and control. The stochastic nature of year-to-year weather variation also influences the design. In this paper the GSHP system is introduced and the system model developed at the UW-Madison is discussed. The impact of weather variation on the optimal design of such a system is examined. Initial validation of the key component in the model, the ground heat exchanger, against experimental data is presented.

1. INTRODUCTION

Air source heat pumps use the outdoor air as a heat source or sink to supply heating and cooling to a building. In most locations, the air temperature varies significantly throughout the year leading to a reduction in system efficiency; the efficiency of a heat pump decreases as the difference between the indoor and outdoor temperatures increases. However, at a relatively shallow depth, the ground temperature essentially remains constant at a moderate temperature (e.g., 5-10°C) throughout the year. The ground, therefore, can provide consistently high system efficiency when it is used as the heat source or sink for a ground source heat pump (GSHP).

There are a variety of ways to implement a GSHP, but this work is focused on the vertical heat exchanger (VHE) design. A VHE consists of a borehole (0.15 m diameter typical) that is drilled into the ground to a depth that is dependent on the local geography; depths of 45 to 90 m are common. A high density polyethylene pipe (2.5 to 5 cm typical) is placed in the hole. This pipe has a u-bend at the bottom so that the working fluid flows down one leg of the pipe and up the other leg. The number of boreholes is based on the expected load of the building (or buildings) and they are typically spaced 4.6 to 6 m apart. The entire array of boreholes is referred to hereafter as the ground heat exchanger (GHX). The boreholes are tied together in a header and that is connected to the building. The working fluid in this system is a water or water-antifreeze mixture (in cold regions; propylene glycol is most common); the working fluid is used to transfer energy between the heat pump and the ground. This system is typically used with water-to-air or water-to-water heat pumps in the building.

Figure 1 is an illustration of this system as applied to a house (based on Kavanaugh, 2009), showing the heat flow that occurs during summer and winter. Heat is removed from the house and rejected to the ground in the summer and removed from the ground and rejected to the house in the winter. The figure also points out an advantage of the GSHP; the ground can provide long-term storage so that the heat rejected to the ground during the summer can balance the heat absorbed in the winter, thereby leaving the ground temperature relatively unchanged over time. These systems have been applied to single family homes, multi-unit buildings, office buildings and schools.

In addition to the advantages of GSHPs already presented, there are some difficulties. Although GSHPs typically have lower maintenance and operating costs than conventional systems, they also often have higher first costs due to the expense of drilling the boreholes. When implemented in cooler regions, where there are high heating loads, antifreeze must be included in the working fluid to prevent freezing during operation. This system also requires a separate outdoor air system, which can be an advantage in some situations, but can also be viewed as an extra piece of equipment. One of the primary disadvantages of GSHPs that this work hopes to address is a lack of familiarity by designers, building owners, and sub-contractors with how to best implement and construct the system.

The performance characteristics of a GSHP system make it an attractive option for reducing building energy use and carbon footprint as documented in a study sponsored by the US DOE EERE (Energy Efficiency and Renewable Energy) Geothermal Technologies Program (Hughes, 2008). In the United States, according to the report, buildings account for 40% of energy consumption and green house gas (GHG) emissions as well as 72% of the electricity and 55% of the natural gas consumption. GSHPs have higher efficiency than conventional air source heat pump systems, so they generally use less electricity and have lower carbon footprints than comparable conventional heating and cooling systems. A DOE funding opportunity program was partially based on the findings of this study. The topics available for request for proposals included the collection of validation data from existing systems and the development of software tools for the design of GSHP systems, which will help those unfamiliar with GSHP design.

This paper will discuss three investigations involving GSHPs. The first section will review the work performed by Hackel et al. (2009) to develop a distributable design tool. The second section will discuss the influence that weather variation has on the design of a GSHP and the third section will discuss validation work in progress. Additional planned work is included in the conclusions.

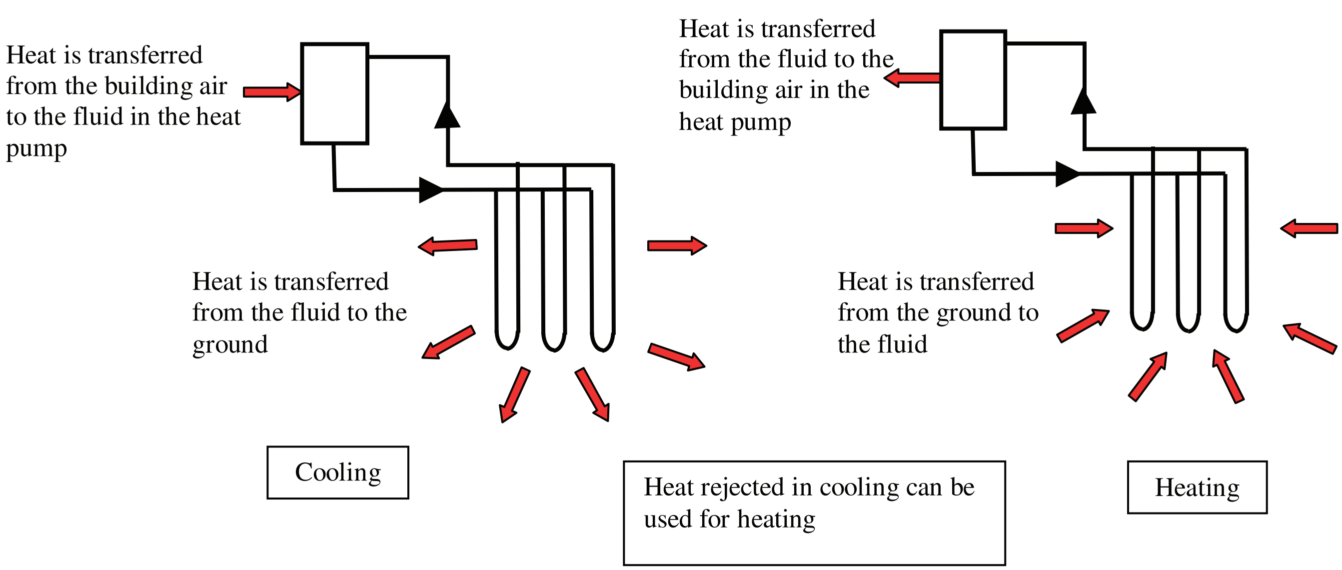

Figure 1. Example of a VHE ground source heat pump system (based on Kavanaugh, 2009).

2. Hybrid Ground Source Heat Pumps

GSHP systems offer the advantages of higher efficiency and reliability as compared to conventional systems, but they have several disadvantages, including potentially higher installation costs and a lack of familiarity for many designers. One of the primary causes of higher costs is the expense of drilling the boreholes for the GHX. The number of boreholes is often based on the requirement that the GHX meet 100% of the design load of the building. In most of the United States, the heating and cooling loads are not balanced. Therefore, the ground temperature will change over time, which will negatively impact the long term system efficiency; in order to meet the building load during the life of the system even as the efficiency decreases, a larger GHX (more boreholes) must be used in an unbalanced climate, leading to even greater installation costs. One alternative is to use a hybrid ground source (or ground coupled) heat pump (HyGCHP) system. In this situation, a conventional component such as a boiler or cooling tower is used to supplement the GSHP. The supplemental source provides some of the building load which reduces the required size of the GHX and also tends to balance the heat rejection and extraction associated with the ground so that the ground temperature can be maintained at a reasonable level.

2.1 Model Description

Hackel et al. (2009) developed a distributable model of the HyGCHP system integrated with an optimization engine that could be used to determine the optimal size of the GHX and the supplemental component as well as the various control setpoints for the system. This model was developed in TRNSYS (TRaNsient SYstem Simulation), which is a flexible, powerful tool for simulating energy systems, especially as related to buildings (Klein et al., 2006). This program calculates the hourly variation in the ground temperature and the resulting change in the efficiency of the total system over the life of the system, which is usually ten to thirty years. As the ground temperature changes, the system efficiency is degraded and a larger GHX is required unless there is a supplemental source. HyGCHP sizes the GHX and supplemental component based on minimizing the life cycle cost (LCC) of the design subject to the constraint that the system be capable of meeting the peak load experienced by the building over its entire life. Because LCC is the optimization parameter, the optimal design is not necessarily one where the cooling and heating loads to the GHX are balanced (i.e., where the ground temperature remains constant), but rather one in which the temperature of the ground may increase or decrease over time in a controlled manner. In this way, the ground is "used up" at the end of life and, as a result, the supplemental component bears more of the load over time.

Figure 2 shows a basic schematic of the cooling tower hybrid configuration modeled by the HyGCHP simulation. The program implements a control algorithm that turns the cooling tower and GHX on or off based on temperature setpoints. The simulation is allowed to run for the system's operational lifespan in order to compute a LCC. The control setpoints and size of the equipment are varied in order to minimize the LCC.

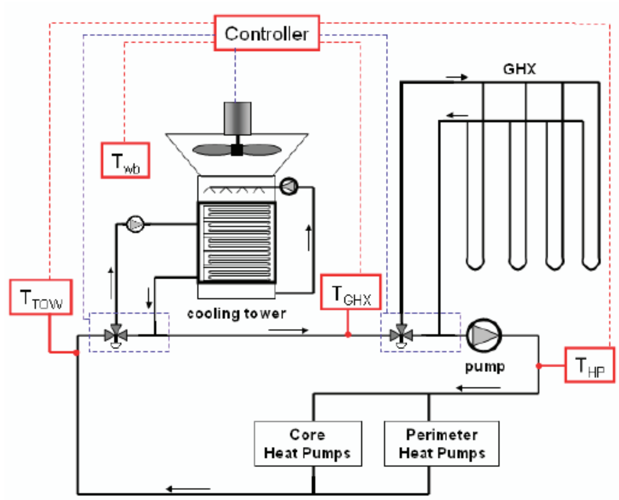

Figure 2. Schematic of a cooling tower hybrid GSHP system.

2.2 Model Limitations

The existing HyGCHP program has two primary limitations; it is slow and it has not been completely validated. The optimization is a slow process because the entire life of the system must be modeled for each set of potential optimization parameters. Because the system is characterized by important time scales ranging from minutes (for control decisions) to months (for seasonal variations) to years (for long term variations in the ground temperature) it is necessary to simulate several decades with sub-hourly time steps. The optimization process requires carrying out many of these simulations, which is computationally time consuming. The second limitation, validation, is being addressed as discussed later in this report.

3. Weather Variation

The performance of the GSHP is dependent on how much energy is transferred between the working fluid and the ground. As energy is rejected or extracted from the ground, the ground temperature changes; this variation can occur over both a short time period and a long time period. The HyGCHP program calculates the ground temperature based on the building loads for each hour of, in this study, the 20 year simulation. In the standard methodology, the building loads are calculated using a weather file that is based on a Typical Meteorological Year (TMY) which is obtained by constructing an average year based on observations over a 30 year period (NREL, 2009a). This representation of the weather cannot incorporate the year-to-year variation in weather. The design obtained using TMY weather data will therefore be over-sized for particularly mild years and under-sized for severe weather years. Therefore, an optimal GSHP design that is based on weather data that includes year-to-year variations and therefore the impact of unusually severe weather years will be different from a design based on a TMY weather file. The evaluation of the significance of year-to-year weather variation on the optimal design is briefly presented in this section.

3.1 Description of Investigation

Building loads were calculated for a 455 m^2 heating-dominated (i.e., the heating load is larger than the cooling load on an annual basis) building located in Madison, WI. Only 15 years of data were available (NREL, 2009b); therefore, five of the fifteen years were repeated in order to bring the total simulation time to 20 years. The building was modeled as a small office building. Due to its size, the building loads should reflect the variation in the weather conditions.

3.2 Results

The optimal design for this building using annual weather data has been normalized by the optimal design using TMY weather data; the results are presented in Figure 3 normalized by the TMY results, with the optimal value of each of the parameters based on the TMY model shown above each bar. The key parameters are:

- LCC – Life Cycle Cost
- L_{GHX} – Length of the Ground Heat Exchanger
- Q_{boiler} – Capacity of the boiler
- T_g – Change in ground temperature over 20 years
- Q_{rej} – Heat rejected to the ground over 20 years
- Q_{abs} – Heat removed from the ground over 20 years

The optimal size of the GHX is the same for both designs, but the boiler size increases by 11% when 15 years of actual weather data are used. In this heating dominated case, the ground temperature decreases over time due to the large imbalance between the amount of energy removed from the ground during the heating season and added to the ground during the cooling season. When 15 years of actual data are used, the ground temperature still decreases over time, but the decrease is 5.6% less than when TMY data are used. This effect is not due to lower heating demand for the annual data, but rather the use of a larger boiler meeting more of the load than in the nominal case. The LCC decreases slightly when 15 years of actual data are used for design. This decrease occurs because the average peak heating load for the 15 years of actual data is less than the peak heating load for the TMY data; although the heating load is more severe in at least one year of the 15 years of actual data, overall the heating load is less severe. The consequence of using the TMY weather file for design is that the system is undersized and therefore unable to meet the heating load associated with an unusually cold year. When the optimizer is provided with actual yearly weather data, it elects to increase the size of the supplemental heating system (the boiler) in order to accommodate severe weather years. Similar results are seen for a cooling dominated design.

4. Validation

One of the limitations of the HyGCHP model is a lack of both component and system validation. Thanks to the receipt of a DOE grant, data from operational HyGCHP systems are being obtained and will be used to validate the model. The initial effort has focused on validating individual components. This section describes preliminary short time-scale validation of the ground heat exchanger model using a residential building in Madison, WI.

4.1 Description of the Investigation

The DST (Duct STorage Model) is implemented in TRNSYS as Type 557 in order to model a vertical ground heat exchanger. The DST model incorporates the effects of the entire storage volume and the interaction between the vertical bores on the performance of the heat exchanger. The temperature of the working fluid entering the GHX and the estimated flow rate, based on experimental data, are inputs to the model. The primary output from Type 557 is the temperature of the working fluid exiting the GHX. This value is compared to the measured value. Figure 4 is a schematic system being modeled. The pump for the GHX is labeled *G* and the pumps for the building loop are labeled *A* and *B*. The inlet and outlet temperature of the GHX are labeled G_{in} and G_{out}.

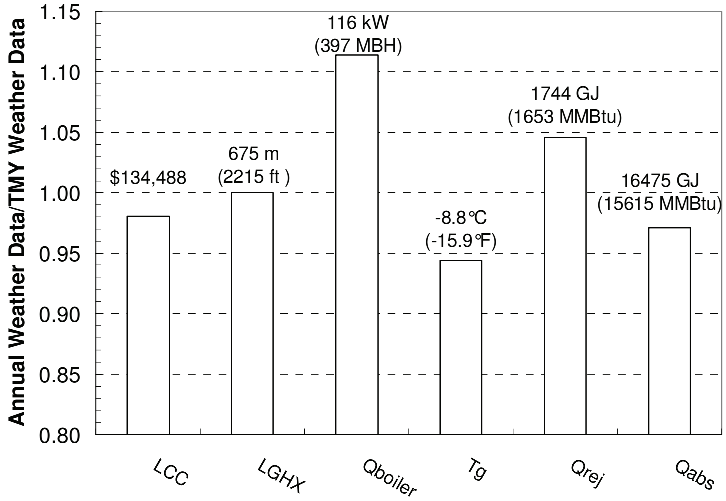

Figure 3. Characteristics of a boiler hybrid designed for the building in Madison using 15 years of actual annual weather data.

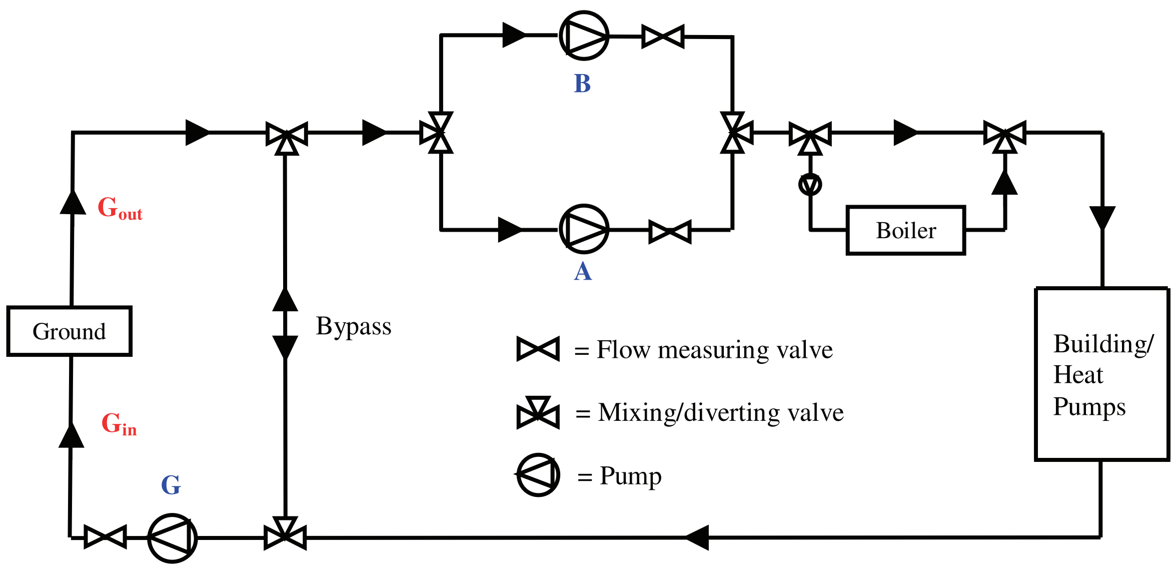

Figure 4. Schematic of the GHX and building loops.

4.2 Results

The top plot in Figure 5 shows the output temperature of the ground loop calculated by using the DST overlaid onto the measured outlet temperature as a function of time. The temperature output from the DST follows the measured results, but initially it is slightly higher. Over time, the magnitudes of the temperatures become nearly identical. This behavior is also displayed in the bottom plot, which shows the difference between the DST temperature results and the measurements. Initially this difference is on the order of 1°C, but over time it decreases to within 0.5°C. This comparison may be improved by adding an initial development period to establish the correct initial temperature distribution in the ground for the DST model. Figure 6 is a histogram of the difference between the model and the measurement. A difference of 0.5°C is considered to be within measurement error, so these results need to be further examined and more data need to be used for comparison before any final conclusion can be drawn. It is known that the results are highly sensitive to the ground thermal conductivity, which is difficult to know precisely, so this is a parameter that may need to be tuned. Based on this preliminary study, the DST model can be an accurate approximation to reality, but it may require some tuning.

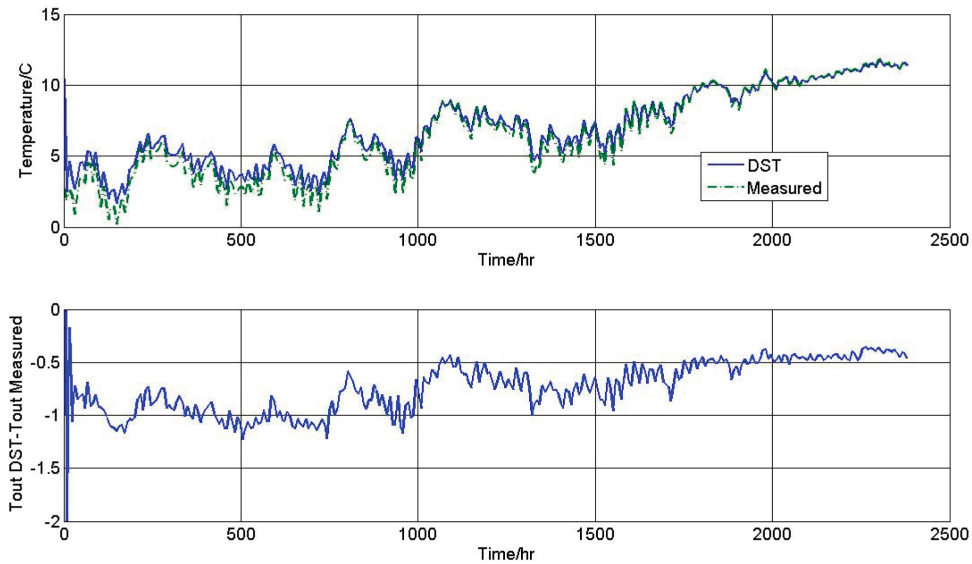

Figure 5. Top: Temperature calculated using the DST model and measurements. Bottom: Difference between the outlet temperature from the DST model and measurements.

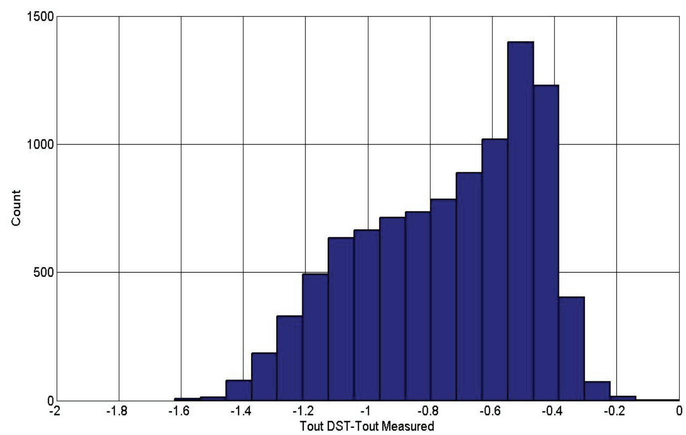

Figure 6. Histogram of the difference between the model and the measurement.

5. CONCLUSIONS

An overview of the work being conducted on GSHPs at the University of Wisconsin – Madison has been presented. The work to date has found that designs based on TMY weather data may under-predict the required component sizes because the actual year-to-year weather variation is ignored. Initial validation of the component used to simulate the GHX (the DST model) has shown that the model can predict the outlet temperature of the GHX for short term simulations, but additional validation is required.

Additional validation of the DST model will be performed as data is collected from the site in Madison as well as from additional sites in Las Vegas, NV. The heat pump component model will also be validated. This validation is limited to "short term" simulations because data are not available for the full life of the system (which is several decades). Once the key components have been validated, models of the existing buildings and integrated systems will be validated. These models will be used as baseline test models for evaluating the accuracy of the generic HyGCHP models.

NOMENCLATURE

A	pump in the building schematic
B	pump in the building schematic
DOE	Department of Energy
DST	duct storage model
G	GHX pump in the building schematic
G_{in}	temperature at the GHX inlet in the building schematic [°C]
G_{out}	temperature at the GHX outlet in the building schematic [°C]
GHX	ground heat exchanger
GSHP	ground source heat pump
HyGCHP	hybrid ground coupled heat pump
LCC	life cycle cost over 20 year simulation [$]
L_{GHX}	ground heat exchanger length [m]
NREL	national renewable energy laboratory
Q_{abs}	heat removed from the ground over 20 years [GJ]
Q_{boiler}	boiler capacity [kW]
Q_{rej}	heat rejected to the ground over 20 years [GJ]
T_g	change in ground temperature after 20 years [°C]
TMY	typical meteorological year
TRNSYS	transient systems simulation

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