

ENHANCED DESIGN AND ENERGY ANALYSIS TOOL FOR GEOTHERMAL WATER LOOP HEAT PUMP SYSTEMS

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Abstract: Because of the outstanding energy saving potential and flexible control capability, geothermal water loop heat pump system (GWLHP) has attracted more and more attention. In order to mostly realize the energy saving potential of the GWLHP system, proper system design is essential. In addition, to get the deserved energy efficiency incentives or LEED points for applying GWLHP system, it is usually required to compare the performance and energy consumption between GWLHP system and a standard HVAC system. It is thus highly desired to have a tool that is able to calculate the building heating and cooling loads, design ground heat exchanger, and predict the performance and energy consumption of the GWLHP system. For this purpose, an integrated building and HVAC system simulation tool has been enhanced recently to facilitate the design and energy analysis of the GWLHP systems. This paper gives an overview of the enhancements, verification of the new enhancements, and example applications of the enhanced design and simulation tool.

Key Words: *design, energy analysis, geothermal, heat pump*

1 INTRODUCTION

Due to the increasing demand for energy efficiency, indoor air quality, and thermal comfort control, the geothermal water loop heat pump (GWLHP) system is becoming a favourable choice in more and more projects. In a typical GWLHP system, multiple small water-to-air heat pump units, which serve each conditioned zone, are connected hydronically with a common two-pipe system (the water loop). The supply temperature of the water loop is maintained within certain range by a ground heat exchanger (GHX) or a combination of various type of GHX, which could be either vertical or horizontal ground loop heat exchanger, surface water body (i.e. lake, river) heat exchanger, or ground water wells. Since it uses the natural thermal properties of the earth to maintain the temperature of the water loop, GWLHP system can completely eliminate the boiler and heat rejecter required in a conventional water loop system.

GWLHP system combines the merits of the superior energy efficiency of geothermal heat pump (GHP) technology and the flexible individual zone control and heat recovery capability of the water loop heat pump (WLHP) system. In addition, GWLHP systems do not have any outdoor equipment. It thus eliminates the related concerns over architectural aesthetics, radiated sound, freeze protection, legionella, or vandalism.

However, compared with other conventional HVAC systems, GWLHP system demands more effort in the design. First, it requires both peak and cumulative heating and cooling loads to account for the possible heat/cool built-up in the ground. Second, the performance of various types of GHX is affected by many factors and their design heavily relies on computerized calculation. Third, the designer needs to collect and analyse extensive geology information at the project site and be aware of the construction technologies of various types of GHX.

Currently, as a typical practice for designing GWLHP system, the whole system is separated into two parts: one is the WLHP system (inside the building) and the other is the GHX (outside the building). The building heating and cooling loads are calculated with certain tool/software, and then they are transferred to other special programs, or just using “rule of thumb”, to size the GHX. This is a one-way process and the interaction between systems inside and outside the building is neglected. In addition, the inconvenience of transferring data among different programs could prevent the design of GHX being updated with the change of the building and the HVAC system inside. More importantly, the separation of GHX from other part of the whole system makes it difficult, if not impossible, to predict the performance (i.e. the temperature of each conditioned space) and energy consumption of the GWLHP. However, to get the deserved energy efficiency incentives or LEED points for applying GWLHP system, it is usually required to compare the performance and energy consumption between GWLHP system and standard HVAC systems. It is thus highly desirable to have a tool that is able to calculate the building heating and cooling loads, design the GHX, and predict the performance and energy consumption of the GWLHP system.

To provide such a tool to the professionals in the HVAC industry, a building energy analysis program, eQUEST and its simulation engine DOE-2.2, which is most widely used in the U.S., have been enhanced recently. The major enhancements include implementing a g-function based model for simulating the vertical ground loop heat exchanger (VGLHE) and integrating a dedicated interface for specifying VGLHE related parameters. In addition, the program is also enhanced to be capable of simulating the advanced features of newly developed water-to-air heat pumps, which include variable airflow and staged heating and cooling. To facilitate the equipment selection, a water-to-air heat pump library has been created and it can be integrated into the simulation tool as an add-on feature.

In the following sections, the new features of the GWLHP simulation of eQUEST/DOE-2.2 will be overviewed and examples of applying this enhanced tool in GWLHP system design and HVAC systems comparison will be presented at the end.

2 ENHANCEMENTS IN GWLHP SIMULATION CAPABILITY

The simulation capability of previous versions of eQUEST/DOE-2.2 is limited to model heat pumps with only single stage compressor and constant volume fan. In addition, it can only model 19 pre-defined VGLHE configurations with maximum borehole number of 32, which is usually not sufficient for commercial buildings. Besides, this model does not account for the effects of grouting material and anti-freeze solutions on the heat transfer performance of VGLHE. A preliminary evaluation of this model shows that it tends to over-predict the temperature swing of the fluid circulated through the VGLHE (McLain and Martin 1999).

To keep up-to-date with the development of water-to-air heat pumps and provide more flexible and accurate simulation of VGLHE, which is the most popularly used GHX in the U.S., eQUEST and its simulation engine DOE-2.2 have recently been enhanced in two aspects. The first enhancement is modeling the water-to-air heat pump with an existing model for packaged variable temperature and variable airflow system. It is thus able to take advantage the existing modeling capability to model water-to-air heat pumps with advanced features including staged heating/cooling capacity and airflow, and energy recovery. The second enhancement includes modeling the VGLHE with the most widely accepted g-function algorithm and integrating a dedicated interface for specifying VGLHE into the wizard system of eQUEST. In the following sections, modeling algorithms for heat pumps with staged capacity and airflow will be covered as well as the modeling algorithms for VGLHE.

2.1 Modeling heat pumps with staged capacity and airflow

Water-to-air heat pumps with staged heating/cooling capacity and airflow have become more popular in the market because of their higher energy efficiency and better moisture control capability due to the longer running time at part load condition (Shirey et. al. 2006).

This type of heat pump may utilize a single multi-stage compressor, equally/unequally sized compressors, or a combination of both. The compressors share a common refrigerant circuit so that the low-stage cooling and heating utilize the entire heat exchanger area. As a result, higher energy efficiency can be achieved at low-stage cooling and heating even with reduced airflow. Variable speed fans with electronically commutated motor (ECM) are usually used in this kind of heat pump. The ECM motor can be controlled to provide specified airflows associated with the staged heating/cooling capacities¹. A typical two-stage water-to air heat pump can have two stages of cooling and heating. If the indoor fan of the heat pump runs continuously (to deliver necessary ventilation in the conditioned space), a floating stage is added in addition to the mechanical heating and cooling stages. At the floating stage, the compressor is turned off and the indoor fan runs at the minimum flow rate. If the heat pump has supplemental heat, an additional heating stage will be added after the highest mechanical heating stage. At part load conditions, if the heating/cooling loads cannot be satisfied at lower stage of heating/cooling, the heat pump will cycle between the two successive stages, of which the higher stage has larger heating/cooling capacity than the heating/cooling loads while the lower stage has smaller heating/cooling capacity than the heating/cooling loads.

In order to model a heat pump with staged capacity/airflow, we need not only an algorithm to mimic the staging sequence of the heat pump but also the knowledge of the heat pump performance at various stages and conditions. In the DOE-2.2 simulation, the heat pump operating stage is determined based upon the hourly heating/cooling loads and the heating/cooling capacity that the heat pump can provide during the same hour.

To simulate the performance of a water-to-air heat pump with DOE-2.2, at least eight performance curves have to be provided. A description of these curves is given in Table 1. The first six curves, which are functions of entering fluid temperature and entering wet/dry bulb temperature, are used to correct the performance data (i.e. capacity and efficiency) at rated condition when the heat pump runs at off-rated conditions. The correction factors determined with these curves are applied to the performance data at rated conditions. For a two-stage heat pump, since these performance curves at the low and high stages are very close to each other, the average of the curves at these two stages is used to represent the characteristics of the heat pump and does not distinguish whether the compressor runs at low or high stage. The last two performance curves determine correction factors for the Electric Input Ratio (EIR) when the heat pump runs at part load condition (switching between off and low stage cooling/heating, or between low and high stages cooling/heating). EIR is the ratio of electricity consumption of the compressor to the cooling/heating capacity of the heat pump. For two-stage heat pumps, these curves have to be determined through a relatively complicated procedure since both the cycling loss and the difference of efficiency at various stages have to be accounted for.

The electric consumption of the compressor is determined as the product of the high stage heating/cooling capacity and the EIR of the heat pump. The heating/cooling capacity is corrected by the performance curves for off-rated conditions. The EIR is not only corrected by the performance curves for off-rated conditions but also corrected for part load conditions.

¹ As an alternative, the ECM motor can also be controlled to maintained specified supply air temperature, but this is not commonly done for water-to-air heat pump.

Following the procedure designed by (Addison et. al. 2003), performance curves for EIR at part load conditions have been generated for water-to-air heat pumps with two stages of heating and cooling. The calculation procedure is described in the following.

Table 1; List of performance curves required by DOE-2.2 for water-to-air heat pump simulation

Curve Name	Description	Note
TC = f(EWB, EFT)	Correction factor for Total Cooling (TC) capacity as a function of the Entering Wet Bulb temperature (EWB) and the Entering Fluid Temperature (EFT).	For cooling
SC = f(EWB, EFT)	Correction factor for Sensible Cooling (SC) capacity as a function of the Entering Wet Bulb temperature (EWB) and the Entering Fluid Temperature (EFT).	For cooling
EIR_C = f(EWB, EFT)	Correction factor for Electric Input Ratio (EIR) as a function of the Entering Wet Bulb temperature (EWB) and the Entering Fluid Temperature (EFT).	For cooling
BPF = f(EWB, EFT)	Correction factor for Bypass Factor (BPF) as a function of the Entering Wet Bulb temperature (EWB) and the Entering Fluid Temperature (EFT).	For cooling
HC = f(EDB, EFT)	Correction factor for Heating Capacity (HC) as a function of the Entering Dry Bulb temperature (EDB) and the Entering Fluid Temperature (EFT).	For heating
EIR_H = f(EDB, EFT)	Correction factor for Electric Input Ratio (EIR) as a function of the Entering Dry Bulb temperature (EDB) and the Entering Fluid Temperature (EFT).	For heating
EIR_C = f(PLR)	Correction factor for Electric Input Ratio (EIR) as a function of Part Load Ratio (PLR).	For cooling
EIR_H = f(PLR)	Correction factor for Electric Input Ratio (EIR) as a function of Part Load Ratio (PLR).	For heating

When the compressor cycles between off and the low stage heating/cooling, the correction factor of EIR at part load condition $EIR_f(PLR)$ is calculated as:

$$EIR_f(PLR) = LSR \cdot [f_{on} + (1 - f_{on}) \cdot P_{off}] \cdot \frac{EIR_{low}}{EIR_{high}} \quad (1)$$

In above equation, PLR is the ratio of heating/cooling load at current hour to the high stage heating/cooling capacity of the heat pump at the same hour; LSR is the ratio of the low stage to the high stage heating/cooling capacity of the heat pump; f_{on} is the fractional run time of the compressor at low stage; P_{off} is the percentage of off-cycle power consumption to that when the heat pump runs at high stage cooling/heating. It is typically negligible for small water-to-air heat pumps; EIR_{low} and EIR_{high} are the EIR at rated condition when the heat pump runs continuously at low or high stage; respectively.

The fractional run time f_{on} can be calculated using following equation:

$$f_{on} = \frac{-(1 - X) + \sqrt{(1 - X)^2 + 4 \cdot X \cdot PLR^*}}{2X} \quad (2)$$

where, PLR^* is the ratio of heating/cooling load at current hour to the low stage heating/cooling capacity of the heat pump at the same hour; $X = 4N_{max}\tau/3600$, where N_{max} is the thermostat maximum cycling rate in cycles/hour and τ is the system time constant, which can be related to the degradation factor C_D as $\tau = 288C_D/(1 - 0.2C_D)$.

When the compressor cycles between the low and high stages of heating/cooling, the correction factor of EIR at part load condition $EIR_f(PLR)$ is calculated as:

$$EIR_f(PLR) = PLR[r_{high}EIR_{high} + (1 - r_{high})EIR_{low}] \quad (3)$$

where, $r_{high} = (PLR - LSR)/(1 - LSR)$ is fractional time when the compressor runs at high stage.

Figure 1 shows an example of the correction factor of EIR at part load conditions of a two-stage water-to-air heat pump. In addition, a diagonal line is also plotted in this figure, which represents the EIR at part load conditions of an ideal single-stage heat pump that does not have any cycling loss when the compressor cycles on and off to satisfy the cooling/heating loads. As shown in Figure 1, EIR of the two-stage heat pump is below the diagonal line, which indicates that the two-stage heat pump consumes less electricity than the ideal single-stage heat pump when providing same amount of cooling/heating. The two-stage compressor is most efficient when running at low-stage continuously ($PLR=LSR=0.767$), and then becomes less efficient at lower loads as cycling losses come into play and also at the higher loads due to the lower efficiency at high stage.

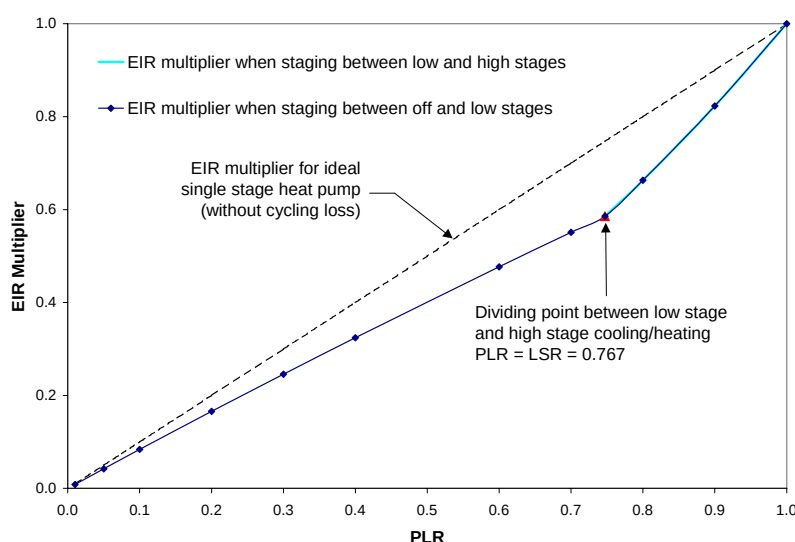


Figure 1: Example of performance curves for EIR as a function of PLR

The control of the ECM fan of the two-stage heat pump is linked with the staging of the compressor. When the compressor switches from high stage to low stage, the supply airflow rate is reduced correspondingly. Since, according to the fan law, the reduction in fan power consumption is the cubic of the reduction in the flow rate, the reduced flow rate at low stage heating/cooling operation will save significant amount of energy. A comparison of energy consumption between GWLHP systems using single-stage and two-stage heat pumps are presented in section 4.2. It shows that the two-stage heat pump reduces electric consumption in space cooling, space heating, and fan significantly compared with the single-stage heat pump.

2.2 Enhancements in VGLHE modeling

A new vertical ground loop heat exchanger (VGLHE) model, based upon the widely accepted g-function algorithm, has been implemented. In addition, an interface and associated database for specifying VGLHE related parameters have also been created and integrated into the Building Creation Wizard of eQUEST.

2.2.1 Hourly simulation of vertical VGLHE

A g-function based model has been implemented into DOE-2.2 for hourly simulation of VGLHE. In this model, a sophisticated method is adopted to calculate the borehole thermal resistance. Thermal properties of various antifreeze aqueous solutions are calculated and used in the calculation of borehole thermal resistance.

Extended G-function

G-function is an algorithm proposed by Eskilson (1987) at Lund University of Sweden for fast calculation of the borehole wall temperature. Eskilson calculated the temperature distribution around a borehole using two-dimensional transient finite-difference equations on a radial-axial coordinate system for a single borehole in homogeneous ground with constant initial and boundary conditions. The temperature fields from a single borehole were superimposed in space to obtain the response from a borehole field of several boreholes in certain arrangement². The temperature response of the borehole field was converted to a set of non-dimensional temperature response factors, called g-functions. A g-function represents temperature change at the borehole wall over certain time duration in response to a step heat pulse. Once the response of the borehole wall temperature to a single step heat pulse is represented with a g-function, devolving the heat rejection/extraction profile into a series of step heat pulses, and superimposing the response to each step heat pulse can determine the response to any arbitrary heat rejection/extraction profile.

The detailed numerical model used by Eskilson for developing the g-function approximates the borehole as a cylinder with finite length (so that the borehole end effects can be considered). This approximation is only valid for times greater than a few hours since the transient process in the borehole must be considered for shorter period. For this reason, Eskilson's g-function is usually referred as the long-time g-function. To extend it down to shorter time scale (hour or less), Yavuzturk and Spitler (1999) calculated the fluid temperature of a single borehole VGLHE in response to short duration of heat rejection/extraction pulses using a two-dimensional, radial-angular, finite volume model.

With the pre-calculated g-function data, the average fluid temperature at the end of n^{th} hour ($\overline{T}_{f_n}$) from the beginning of the operation of the VGLHE can be calculated with Equation (4).

$$\overline{T}_{f_n} = \overline{T}_g - \sum_{i=1}^n \frac{(Q_i - Q_{i-1})}{2\pi\lambda} g\left(\frac{t_n - t_{i-1}}{t_s}, \frac{r_b}{H}\right) - Q_n \cdot R_{eff} \quad (4)$$

where,

$g\left(\frac{t}{t_s}, \frac{r_b}{H}\right)$ is g-function;

t is time from the beginning of a step heat pulse, hour.

t_s is defined as $t_s = \frac{H^2}{9\alpha}$ (α is the thermal diffusivity of the ground), hour;

r_b and H are borehole radius and depth, m;

λ is thermal conductivity of the ground, W/m-C;

$\overline{T}_f$ is average temperature of heat carrier fluid, °C;

R_{eff} is effective steady-state borehole thermal resistance, K/ (W/m);

² The heat flux to each borehole in the borehole field of interest was adjusted at each incremental time-step in the numerical calculation so that a common borehole wall temperature was applied to all the boreholes.

Q is step heat pulse imposed on a VGLHE, W/m;

$\overline{T}_g$ is mean undisturbed ground temperature along the depth of a borehole, °C.

Figure 2 shows the short-time g-function calculated by Yavuzturk and Spitler (1999) for a specific borehole and Eskilson's long-time g-functions for borehole fields with various configurations. As shown in Figure 2, the short-time g-function curve matches well at the boundaries of the long-time g-functions where the associated non-dimensional time is -8.5 . It can also be observed in Figure 2 that the relationship between $\ln(t/t_s)$ and the corresponding value of the g-function is almost linear when $\ln(t/t_s)$ is between -8 and -12 . For a typical borehole, it implies time duration less than 1 hour. As a result, instead of using complicated numerical calculation, linear extrapolation from Eskilson's long-time g-function is used to approximate the short-time g-function for hourly VGLHE simulation.

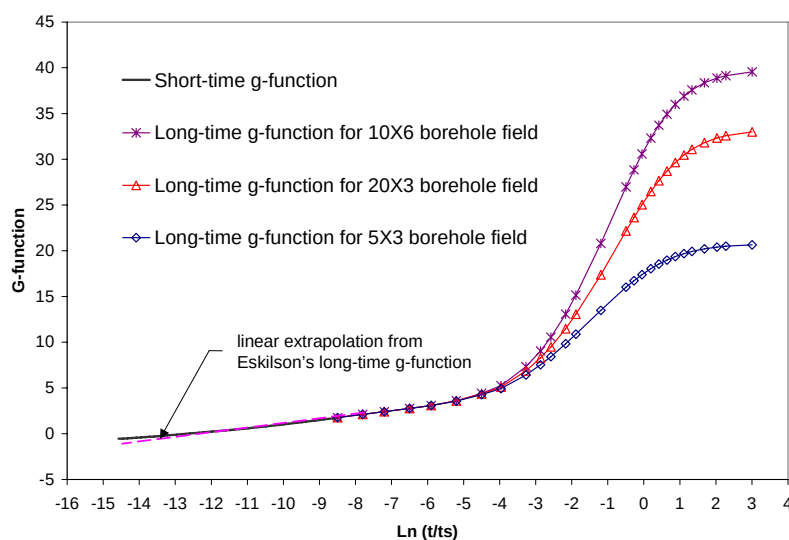


Figure 2: Short-time and long-time g-functions for borehole fields with various configurations

Effective borehole thermal resistance

Bennet et al. (1987) proposed a so-called multi-pole method to calculate the effective steady-state thermal resistance between the heat carrier fluid in the U-tube and the borehole wall. For the case of single U-tube in a borehole, a set of simplified formulae has been derived from the complicated multi-pole method to calculate the effective steady-state borehole thermal resistance R_{eff} (Hellstrom 1991). Hellstrom derived two equations for calculating the steady-state borehole thermal resistance: one is for the case of uniform borehole wall temperature and the other is for the case of uniform heat flux on borehole wall. The arithmetic mean of the two steady-state borehole thermal resistances is used in the simulation to approximate the actual steady-state borehole thermal resistances.

To account for the effect of antifreeze on the steady-state borehole thermal resistance, subroutines of antifreeze thermal properties have been added into DOE-2.2. Given fluid temperature and concentration of antifreeze, these subroutines calculate thermal conductivity, specific heat capacity, viscosity, density, and freezing point of aqueous solutions of the four most commonly used antifreezes in geothermal heat pump systems - propylene glycol, ethylene glycol, methanol, and ethanol. These subroutines are based upon the data and formulae suggested by Khan (2004).

2.2.2 Wizard interface for creating GSHP simulation

A user-friendly and informative interface for specifying VGLHE has been developed and integrated into the wizard systems of eQUEST. Figure 3 is a snapshot of this dedicated wizard interface. Parameters associated with VGLHE are categorized into four sections in this interface. The first section is for specifying parameters of the fluid circulation loop connected to VGLHE, including pump configuration, flow control, design loop temperature, etc. The second section is for specifying ground and grout thermal properties as well as years of previous operation of the VGLHE. Thermal conductivity and diffusivity of various type of soil/rock and thermal conductivity of various commonly used grouting materials are provided in build-in databases. Users can either select rock/soil and grout type from the databases or input the thermal properties directly. The third section is for specifying parameters of boreholes, including VGLHE type, configuration, geometry, pipe material and size. Various vertical VGLHE configurations are available, including boreholes in a straight line, in the form of L- or U-shaped lines, and as open or filled rectangles. The fourth section is for specifying properties of the fluid circulating through VGLHE. In addition to pure water, aqueous solutions with different concentration of antifreezes can be selected. Detailed on-line help, databases, and design tips for each of the required parameters can be accessed directly in this interface.

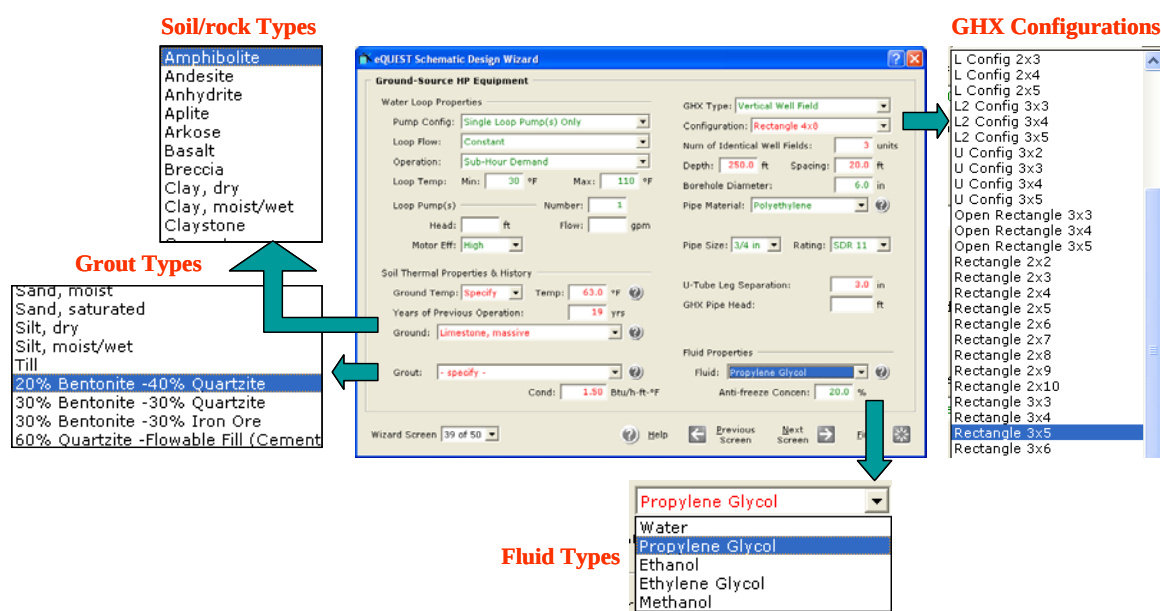


Figure 3: Snapshot of the dedicated wizard interface for specifying VGLHE

3 VERIFICATION OF VGLHE MODEL IMPLEMENTATION

A series of tests have been conducted to verify/validate the enhanced GWLHP simulation of eQUEST. There are three phases in the verification/validation process. The first phase is comparing the enhanced VGLHE simulation results with that of an experimentally validated VGLHE model. This test is to verify the implementation of the VGLHE model newly integrated into eQUEST/DOE-2.2. The second phase is conducting a series of parametric studies to examine whether the enhanced GWLHP simulation responds correctly to changes of various VGLHE design parameters. The third phase is to validate the enhanced GWLHP simulation with monitored data. Due to the space limitation, only the comparison between the predictions of the enhanced VGLHE model and that of an experimentally validated model is presented in the following. Results of other validation/verification exercises are available in (Liu, 2006 and 2007).

An office building conditioned by a GWLHP system has been simulated with the enhanced eQUEST. The exact same VGLHE is then simulated with HVACSIM+ (Clark, 1985), which has an experimentally validated VGLHE model (Liu 2005), using the annual hourly VGLHE loads calculated by eQUEST as inputs. Both the short and long-time g-functions used by HVACSIM+ are calculated with a research version of GLHEPRO, a VGLHE sizing program developed by Spitler (1999). The VGLHE leaving fluid temperatures predicted by the two simulations are plotted in Figure 4. As shown in Figure 4, the two temperature profiles match fairly well except during a few peak load hours where the eQUEST results are slightly lower. This discrepancy is usually less than 1 °C and thought to be a result of the approximated short-time g-functions described earlier.

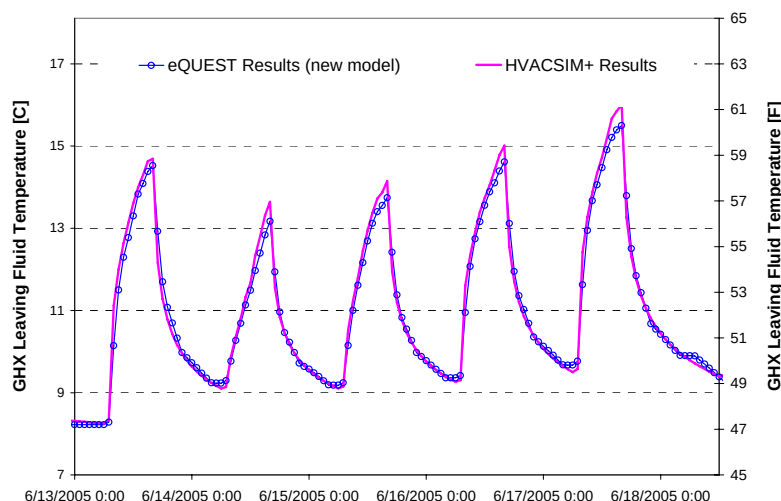


Figure 4: Comparison of VGLHE leaving fluid temperatures: enhanced eQUEST vs. HVACSIM+

4 APPLICATION OF ENHANCED EQUEST/DOE-2.2

The enhanced eQUEST/DOE-2.2 can be used to size the heat pump and the VGLHE of a GWLHP system. It can also be used to predict the energy consumption of the GWLHP system and other HVAC systems so that the energy savings from using GWLHP systems can be estimated. In the following, examples of using eQUEST in GWLHP system design and HVAC systems comparison are presented.

4.1 GWLHP System Design

The enhanced eQUEST has been used to size the heat pump and VGLHE for many real GWLHP projects. Because both the building and the entire GWLHP system are simulated within one program, there is no hassle any more in transferring data among different programs and the building design and GWLHP system's performance are dynamically linked internally. Based on the predicted performance, the VGLHE design can be adjusted manually until satisfactory performance is obtained. With this simulation-based integrated design approach, the impact of the building design on the size of heat pump and VGLHE can be clearly illustrated. As an example, the simulation model of a townhouse building at Oklahoma City of the U.S. and the heat pump size and VGLHE design are presented in the following.

Figure 5 shows a 3-D illustration of the townhouse building modeled with eQUEST. This building has 7 dwelling units. As shown in Figure 5, unit 1 has three floors and has a west facing exterior wall; unit 2 also has three floors but is attached to units 1 and 3 and therefore only has an east facing exterior wall at the third floor; unit 3 has two floors and no west or

east facing exterior walls; unit 4 has three floors and an east facing exterior wall. Except for differences in number of floors and exterior wall area, these dwelling units are almost identical. Each of these dwelling units is conditioned with an individual GWLHP system (with its own heat pump, water loop, and VGLHE) and the VGLHE is only allowed underneath the garage of each unit.

As shown in Table 2, the individual heat pump sizes determined with eQUEST reflect the differences among the four dwelling units. Correspondingly, the design of the VGLHE for each of the four dwelling units is different. The interesting thing is that the ratio of the installed heat pump cooling capacity to the total length of borehole (product of borehole depth and the number of boreholes) varies from 44.6 to 58.5 W/m. It indicates that the typically used "Rule of Thumb" in the U.S. for sizing VGLHE (60 W/m) tends to undersize the VGLHE for this building, which has multiple boreholes and thus the long-term thermal interaction among boreholes has to be accounted for.

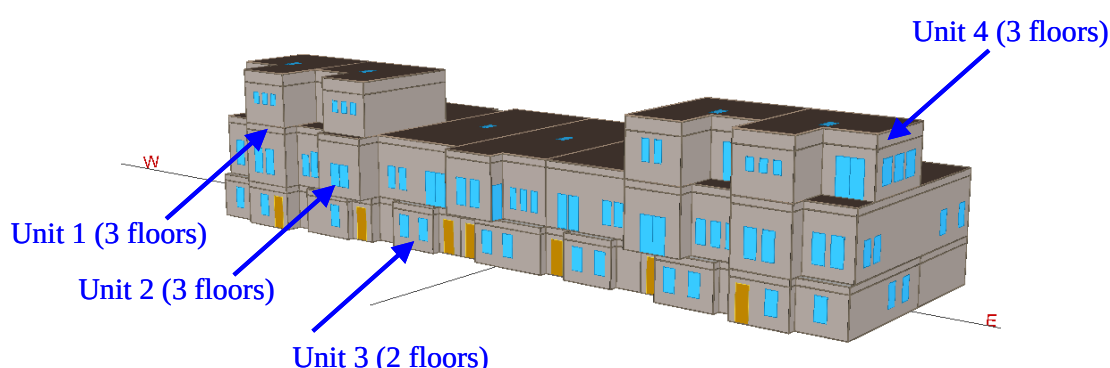


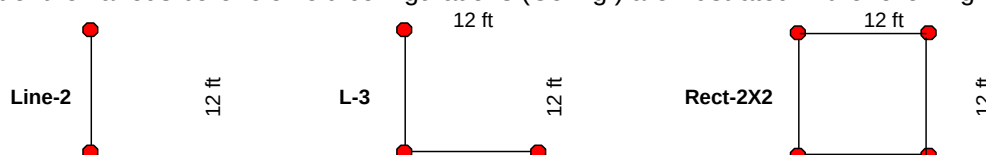
Figure 5: 3-D illustration of the townhouse building modeled with eQUEST

Table 2; Summary of the heat pump and VGLHE design determined with the enhanced eQUEST

Dwelling Unit		Heat Pump	VGLHE				
Index	Area [m ²]	Cool cap. [kW]	Config.	Depth [m]	Cool cap/Total length [W/m]	Min LFT [C]	Max LFT [C]
1	270	19.25	Rect-2X2	108	44.6	11.1	35.8
2	270	15.75	L-3	90	58.5	10.2	35.5
3	200	10.5	Line-2	96	54.6	10.8	35.8
4	270	17.5	Rect-2X2	96	45.6	10.6	35.4

Note:

1. Layout of the various borehole field configurations (Config.) are illustrated in the following



2. The minimum and maximum leaving fluid temperatures of the VGLHE (Min LFT and Max LFT) are obtained from simulations of 30 years operation of the GWLHP system.

4.2 HVAC Systems Comparison

Comparison of energy consumption of various HVAC systems including the GWLHP system can be conducted with the enhanced eQUEST conveniently. Examples of comparing GWLHP with other HVAC systems have been presented in other literature (Liu, 2007). In this

paper, a comparison of annual energy consumption of GWLHP systems using single-stage and two-stage heat pumps will be presented.

An office building in Cincinnati, OH has been simulated with the enhanced eQUEST. The building is conditioned with GWLHP system. Two simulations have been conducted. The first simulation uses single-stage heat pumps and the second uses two-stage heat pumps that have the same cooling and heating capacities as the single-stage heat pumps. Fans of heat pumps of the two systems run continuously when the office is occupied (Monday through Friday, 7 am through 6 pm). The two systems are coupled with same VGLHE and circulate same constant water flow through same water loop continuously when the office is occupied. The efficiencies of the heat pumps at ARI standard rating conditions are listed in Table 3. As shown in Table 3, although the single stage heat pump has higher cooling COP than that of the two-stage heat pump at its high stage (5.6 vs. 5.3), the two-stage heat pump has much higher COP at its low stage (5.6 vs. 7.9).

Table 3; Efficiency of single or two stage heat pumps at ARI conditions

ARI conditions	Efficiency	
	Single stage	Two stage
Cooling: 27 °C DB, 19 °C WB entering air; 25 °C entering fluid	COP (cooling): 5.6 COP (heating): 3.9	At high stage COP (cooling): 5.3 COP (heating): 4
Heating: 20 °C DB, 15 °C WB entering air; 0 °C entering fluid		At low stage COP (cooling): 7.9 COP (heating): 4.5

The simulation results presented in Table 4 shows that the GWLHP system using two-stage heat pumps reduces the HVAC system energy consumption by 27.8% compared with the GWLHP system using single-stage heat pumps. Compared with the single-stage heat pump, the two-stage heat pump saves 29% in compressor energy consumption in space cooling; 22.9% of compressor energy in space heating, 43.8% of fan energy, and 0% of pump energy. In this example, the energy savings in space cooling and fan are predominant, which account for 50.5% and 40.2% of the total energy savings, respectively.

Table 4; Energy consumption of GWLHP systems using single or two stage heat pumps

End Use Category	Single stage	Two stage	Saving [%]	Contribution to total saving [%]
Space cooling compressor [kWh]	90,320	64,110	29	50.5
Space heating compressor [kWh]	21,040	16,230	22.9	9.3
Fan (of heat pump) [kWh]	47,670	26,790	43.8	40.2
Pump [kWh]	27,600	27,600	0	0.0
Total [kWh]	186,630	134,730	27.8	

5 CONCLUSIONS

The simulation capability of eQUEST/DOE-2.2 for GWLHP system has been recently enhanced. The first enhancement is a new simulation capability for two-stage water-to-air heat pumps. An algorithm for modeling two-stage water-to-air heat pumps has been developed and the required performance curves for the simulation have been generated. The second enhancement includes modeling VGLHE with the most widely accepted g-function algorithm and integrating a dedicated interface into the wizard system of eQUEST for conveniently specifying VGLHE. Verification and validation results show that the VGLHE

leaving fluid temperature predicted by the newly implemented VGLHE model in eQUEST/DOE-2.2 matches well with that predicted by an experimentally validated VGLHE model. The enhanced eQUEST/DOE-2.2 is able to reasonably predict the performance of the two-stage water-to-air heat pump. As shown in the examples, the enhanced eQUEST/DOE-2.2 is a very useful tool for GWLHP system design and energy analysis.

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