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GROUND-SOURCE HEAT PUMP SIMULATION WITHIN A WHOLE-BUILDING ANALYSIS

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ABSTRACT

This paper explores the integration of an algorithm for the simulation of ground-source heat pump systems into a whole-building energy analysis program.

GS2000™ is a software program released in 1995 for the sizing of ground source heat pump ground heat exchangers (also known as earth energy systems, geothermal heat pumps, and Geo-exchange systems) (Morrison, 1997). GS2000™ performs the ground loop heat transfer calculation, but requires the monthly building loads – as calculated by an energy simulation program. As the building load is dependent on the size of the ground loop and vice versa, the aim of this project is to incorporate the ground loop algorithms into the ESP-r/HOT3000 engine.

Development of the ESP-r/HOT3000 simulation engine is based upon the comprehensive and extensively validated simulation program, ESP-r (ESRU 2000). ESP-r has an extensible structure whereby models and algorithms can be easily incorporated.

Modifying the GS2000™ ground heat transfer algorithm, developing the water-source heat pump model accounting for part-load capacity, defining the heat pump COP/EER as a function of entering water temperature including cycling effects, as well as testing and validation will be examined.

This paper presents an account from a recent on-going software development project and examines the specific case of incorporating a ground-source heat pump model into ESP-r/HOT3000.

INTRODUCTION

A developmental version of CETC-Ottawa's HOT3000 program was used in this analysis. The interested reader is referred to Haltrecht et al. (1999) for the rationale for selecting ESP-r as the starting point for the HOT3000 development.

Numerous modelling capabilities have been added to ESP-r's extensible structure to support the HOT3000 development. These include the BASESIMP ground heat transfer algorithm (Beausoleil-Morrison and Mitalas 1997), the AIM-2 air infiltration model (Walker and Wilson 1990), and models to predict the performance of residential HVAC equipment (Purdy and Haddad 2002) as well as residential fuel cells (Beausoleil-Morrison et al., 2002). The simulation environment, including these additional models, is referred to as ESP-r/HOT3000 throughout the paper.

GS2000™ – a ground source heat pump (GSHP) ground heat exchanger sizing program – was previously developed by Caneta Inc. for CETC-Ottawa in 1995. GS2000™ has been compared to other software tools (Shonder et al., 1999) and the predictions have been shown to agree very well. Given this experience and confidence in the quality of the software, GS2000™ was chosen as the basis for the GSHP model implemented in ESP-r/HOT3000.

The incorporation of ground heat exchanger models into building energy analysis tools has been previously accomplished by Pahud and Hellstrom (1996) and Yavuzturk and Spitler (1999). In addition, Yavuzturk and Spitler (1999) give a thorough background and review of currently available system design and simulation tools.

Pahud and Hellstrom (1996) have incorporated their ground heat storage model (DST) into TRNSYS (Klein et al., 1990). The DST model is a duct ground heat storage system, whereby a ground heat exchanger – formed by a duct system – is used to exchange heat or cold between a fluid and the storage region.

Yavuzturk and Spitler (1999) have also chosen to incorporate the time step response factor model into TRNSYS[1]. This model predicts the short-term fluctuations in the ground loop heat exchanger return temperature.

Incorporating detailed models into building energy

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[1] Their short time step model is based on the temperature response factors of Eskilson (1987).

analysis tools allows the user to exploit the strengths of different simulation tools. For example, while GS2000™ performs a detailed calculation of the heat transfer through the ground heat exchanger, it requires the input of the monthly building loads. Coupling the GS2000™ algorithm with the detailed building load calculation offered by ESP-r/HOT3000 enhances the available modelling capabilities. In a similar way, Yavuzturk and Spitler's time step response factor takes advantage of the daily load profile calculated in TRNSYS.

Component Models in ESP-r/HOT3000

There are two methods by which component models can be incorporated into the ESP-r/HOT3000 structure. These include the explicit plant method or the implicit method. The latter was selected for this implementation.

ESP-r/HOT3000's explicit plant modelling domain is based upon a component-level approach whereby users assemble components into a coherent HVAC system using the ESP-r/HOT3000 plant facility. Nodes are used to represent each of the components, and users must define each component, the arrangement of the components, and how the components are controlled.

ESP-r/HOT3000 performs an energy and mass balance on each node. The equations for the energy and mass balances for all nodes are then solved to determine the mass flow rate and temperature field. One advantage of this method is the flexibility in defining how the components are connected to form a total system. It is, however, a more time consuming method of model development.

For the implicit method, independent component models are developed and then incorporated into the ESP-r/HOT3000 data structure. The ESP-r/HOT3000 plant facility is not employed. One disadvantage is that simulation algorithms added in this manner cannot be connected to form a complete system, as is the case for explicit systems.

A stand-alone model for the calculation of the temperature of heat transfer fluid coming out of a ground heat exchanger, i.e., the heat pump's entering water temperature (EWT), was created based on the GS2000™ algorithms. This model was modified to allow its incorporation into the ESP-r/HOT3000 source code. Information is transferred between the standard ESP-r/HOT3000 subroutines and the ground heat transfer subroutines.

GS2000™ Model

GS2000™ is based on the one-dimensional line source heat transfer equation, which neglects end effects of the heat exchanger pipes. The algorithm assumes a cylinder of soil acting between the pipe – grout in the case of vertical heat exchangers – and the far field radius of the affected ground. This far field radius is the distance at which the ground temperature can be approximated as being undisturbed by the heat exchanger pipes. The thermal resistance of the heat exchanger pipe and grout are accounted for in the algorithm, but thermal capacitance is ignored.

The amount of heat extracted or rejected by the heat exchanger is constant for each time step and is modelled as a constant pulse continuing for the duration of the simulation. An equal but opposite pulse is subtracted at the end of each time step to cancel the pulse for the remainder of the simulation.

The line source analysis is performed on a single pipe and the results are superimposed for a multi-pipe heat exchanger configuration.

The impact of soil freezing – horizontal models only – by heat extraction from the heat exchanger pipes is determined by checking the outside pipe temperature to determine if it is below the freezing point. If so, an estimation of the diameter of the frozen ground ring around the pipe is determined by assuming the outer edge of the ice ring is at 0°C.

Although GS2000™ does not explicitly calculate the latent energy associated with the freezing soil, its impact on the fluid temperature is accounted for. GS2000™ assumes that the outside temperature of the ice ring is a constant 0°C, as it expands and contracts throughout the heating season. This results in fluid temperatures remaining slightly below freezing – approximating what is observed in actual installations.

The GS2000™ algorithm was modified to allow for the water-source heat pump and ground-source heat exchanger modelling capability in ESP-r/HOT3000. This involved converting the subroutines from calculating the size of the heat exchanger to calculating the entering water temperature (EWT) (the new subroutines will assume that the heat exchanger is sized correctly by the user); converting the monthly load calculation to an appropriate time step; and testing and validating the modified algorithms.

The following sections detail the development of ground-source heat pump modelling capability for ESP-r/HOT3000. Included is a description of the GS2000™ model algorithm, its implementation into the ESP-r/HOT3000 core as well as the validation of the algorithm and its implementation.

GSHP MODEL ALGORITHM DEVELOPMENT

As mentioned in the previously, the GSHP model implemented into the ESP-r/HOT3000 engine is based on the GS2000™ algorithms.

The model consists of two loops: the ground loop and the heat pump loop. The ground loop model is used to calculate the entering water temperature (EWT) – the temperature of the water entering the heat pump. The performance of the heat pump loop is a function of the heat pump capacity and the entering water temperature.

Ground Loop

Four ground loop configurations were implemented into ESP-r/HOT3000: vertical single bore hole; horizontal 4-pipe, 2x2 arrangement; horizontal 2-pipe, side-by-side arrangement; and horizontal slinky arrangement.

For input simplicity, the original GS2000™ algorithms performed the ground heat transfer calculations on a monthly basis. For the ESP-r/HOT3000 model, this was reduced to a daily calculation – independent of the simulation timestep – as this is the minimum timestep for which the algorithms are applicable (Hart and Couvillion, 1986).

The required inputs for the ground heat transfer calculation are: the ground loop configuration, the daily load on the ground loop, the ground properties, the piping properties and configuration, and the ground temperatures. The daily load on the ground loop[2] is calculated within the ESP-r/HOT3000 building simulation whereas the other inputs are specified in the GSHP input file.

Within this ground-loop calculation, there are two time loops – the so-called i-loop and the j-loop. The i-loop is the simulation timestep, counting the day of the simulation. The j-loop is contained within the i-loop and is designed to take into account the effects of previous heat pump cycles (the thermal history) on the ground. Since it is the time since a thermal event occurred that determines its influence, the routines in the j-loop are performed recursively for each day starting at the beginning of the simulation to the current day each timestep, i.e., for the simulation of day 4, the j-loop will cycle through days 1, 2, 3, and 4.

Heat Pump

The capacity and coefficient of performance (COP) of an air-source heat pump is dependent on the external conditions and the condenser airflow rate. Conversely, the performance of the water-source heat pump is based on the entering water temperature (EWT). Therefore, modifications to the air-source heat pump model currently available in ESP-r/HOT3000 were required to simulate a GSHP. New functions were created to calculate the operating capacity and COP based on the correlations for EWT derived from Caneta (1994).

A GSHP system requires a pump to circulate the heat transfer fluid through the ground and into the heat pump unit. The pump power (*P*) is calculated based on the heat pump capacity (H_C) and the ground loop configuration.

The following correlation is based on the GSHP rating equation for estimating pump power in CSA C446-94 (1994). The original equation was expanded to replace flow rate with heat pump capacity (H_C) and a more accurate representation of the pipe pressure drop.

$$P = 0.16 \cdot H_C \cdot 4.22 \cdot (\Delta P + R_P + \frac{L_T}{H_C} \cdot C_P + F_R + F_C)$$

- L_T is the total circuit pipe length (m).
- The circuit pressure drop (C_P) is based on the heat exchanger configuration:
  - for 2-pipe horizontal, 4-pipe horizontal, and vertical single bore hole systems, $C_P = 0.1855$ kPa/m, and
  - for horizontal slinky systems, $C_P = 0.2041$ kPa/m.
- The heat pump pressure drop (ΔP), run out pressure drop (R_P), run out fitting pressure drop (F_R), and circuit fitting pressure drop (F_C) are dependent on heat pump capacity (H_C) as defined in Table 1.

H_C (tons)	ΔP (kPa)	R_P (kPa)	F_C (kPa)	F_R (kPa)
2	26.7	3.4	0.33	0.48
2.5	17.2	4.8	0.33	0.71
3	28.4	6.6	0.33	1.02
4	34.0	11	0.33	1.83

Table 1: Summary of Piping and Fitting Losses.

In heating mode, the heat pump coefficient of performance, COP, is a function of the steady state COP (*COP_{SS}*) and the EWT, as defined for closed-loop systems by the following the correlation is:

$$COP = COP_{SS} \cdot \left(a_{COP} + b_{COP} \cdot EWT + c_{COP} \cdot EWT^2\right)$$

where,

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[2] Since a heating load in the house will result in an energy draw from the ground, it will be represented as a negative load on the ground and a cooling load in the house will be represented as a positive load on the ground.

$a_{COP} = 1.00098$
$b_{COP} = 0.01756$
$c_{COP} = -0.00011$

The cooling efficiency measurement for heat pumps is the Energy Efficiency Rating, EER. For cooling mode, a similar correlation is defined as:

$$EER = EER_{SS} \cdot \left(a_{EER} + b_{EER} \cdot EWT + c_{EER} \cdot EWT^2 \right)$$

where,
$a_{EER} = 1.06396$
$b_{EER} = -0.00607$
$c_{EER} = -4.4498 \times 10^{-5}$

The values given for the COP and EER are defined for closed-loop systems and are hard-coded.

GSHP SIMULATION IN ESP-r/HOT3000

Input Parameters

For the simulation of a GSHP system in ESP-r/HOT3000, the following modifications are required to the user input files:

i. Create GSHP Input File
This file contains all the input parameters required to simulate the ground loop, as defined in Table 2. The user specifies which ground loop configuration is being modelled.

ii. Modify Main Configuration File
This file will include a flag for the GSHP input file.

iii. Modify HVAC Definition File
The GSHP model incorporated into ESP-r/HOT3000 (Caneta 2001a) is very similar to the existing ASHP model. The differences between the modelling of a ground-source or water-source heat pump and an air-source heat pump can be summarized as follows:

- calculation of the capacity and coefficient of performance;
- accounting for the cyclic performance; and
- calculation of the pump performance.

Start-up Period

For the simulation of GSHP systems in ESP-r/HOT3000, it was determined that the ideal start-up period is 10 days. This start-up period is required to precondition the ground conditions. The user may specify any length of start-up period, with a minimum of 10 days, for an annual simulation.

The user-specified building start-up period is taken as the GSHP pre-simulation period; therefore, the building energy analysis tool is run throughout the ground preconditioning.

Global Parameters	
ID, OD	Pipe inside and outside diameter, cm
K_{pipe}	Pipe thermal conductivity, W/m K
L	Length of pipe, m
Density	Density of fluid, kg/m3
Cp	Heat capacity of fluid, J/kg K
Flow	Heat exchanger flow rate, L/s
T_{mean}	Earth mean temperature, °C
A_{temp}	Surface temperature amplitude, °C
DAY_o	Time of minimum surface temperature
System Specific Variables	
K_s	Soil conductivity in summer, W/mK
K_w	Soil conductivity in winter, W/mK
D_s	Soil diffusivity in summer, W/mK
D_w	Soil diffusivity in winter, W/mK
Horizontal 4-pipe 2x2	
PD(1)	Depth of heat exchanger pipe 1, m
PD(2)	Depth of heat exchanger pipe 2, m
SD	Spacing between pipes, m
Horizontal 2-pipe side-by-side	
SD	Spacing between pipes, m
BD	Depth below surface, m
Horizontal Slinky	
BD	Depth of heat exchanger pipe, m
Spiral	Diameter of slinky spirals, m
NumP	Number of pipes per trench
Vertical Single Bore Hole	
U_{tube}	Number of U-bends per bore hole
N_{soil}	Number of layers of different soil
Depth	Depth of bore hole
SP	Space between pipes, cm
D_{top}	Distance below surface of top U-tube, m
D_{bore}	Diameter of bore holes, cm
K_{grout}	Grout conductivity

Table 2: GSHP model input parameters required for simulation in ESP-r/HOT3000.

Output of Results

The standard output reporting facilities were updated to incorporate the GSHP components.

INCORPORATION OF THE GSHP MODEL INTO ESP-r/ HOT3000

The previous sections detail the new algorithm developed to model ground source heat pump systems. To incorporate this algorithm into the ESP-r/HOT3000 structure required the modification of the previously developed GSHP subroutines as well as the modification of some existing ESP-r/HOT3000 subroutines and the creation of new subroutines.

The required modifications to the GSHP subroutines included:

- using standard ESP-r/HOT3000 *read* statements for all variables located in input files;
- creating modules to contain the *global* variables used in several subroutines - to avoid lengthy subroutine call statements; and
- reading in the zone heating and cooling loads from the ESP-r/HOT3000 building simulation.

The following section details the modifications made to existing ESP-r/HOT3000 subroutines while the subsequent section describes the new subroutines created for the GSHP modelling.

Modifications to Existing Subroutines

Many existing subroutines required modifications to incorporate the independent component models into the ESP-r/HOT3000 data structure.

MZINPT: If a GSHP system is being modelled, then call to the GSHPINPUT subroutine (Figure 1).

MZNUMA: If a GSHP system is being modelled, call to the GSHPSIM subroutine once every day, after zone and hourly calculations (Figure 2).

HVACINPUT: If the HVAC system being modelled is a GSHP system then call to ASHP_INPUT. The heat pump input file for GSHP systems is identical to that for ASHP systems, except for the system-specific variable for HVAC type.

START_HVAC_SIM: If a GSHP system is being modelled, then call to HVACSIM. This step was required because the GSHP model requires that the HVAC loads be calculated during the start-up period, and this is not done for standard HVAC simulations.

HVACSIM: If a GSHP system is being modelled, call to GSHP_load to sum the daily heating and cooling loads.

HVACSIM calls GSHP_HEAT_COEFF – to calculate the part load coefficients in heating mode - and GSHP_COOL_COEFF for cooling mode.

Note: the remainder of the HVACSIM calculations remains unchanged. For a full description of the HVACSIM subroutine, please see Purdy and Haddad (2002).

In addition to the above listed subroutines, several subroutines required modification to recognize the GSHP flag. This flag is defined in the main simulation configuration file to indicate that a GSHP simulation is being run.

Creation of New Subroutines

Data Collection

GSHPINPUT: This subroutine controls the reading of the required input data for the GSHP system from the data file.

GLOBAL_READ: Reads the general input applicable to all systems. Depending on which system is being modelled; the model-specific input-reading subroutine is then called, i.e., one of: V1_READ, HS_READ, H4_READ, or SL_READ.

The data read in from the GSHP data file is saved into modules for use throughout the simulation.

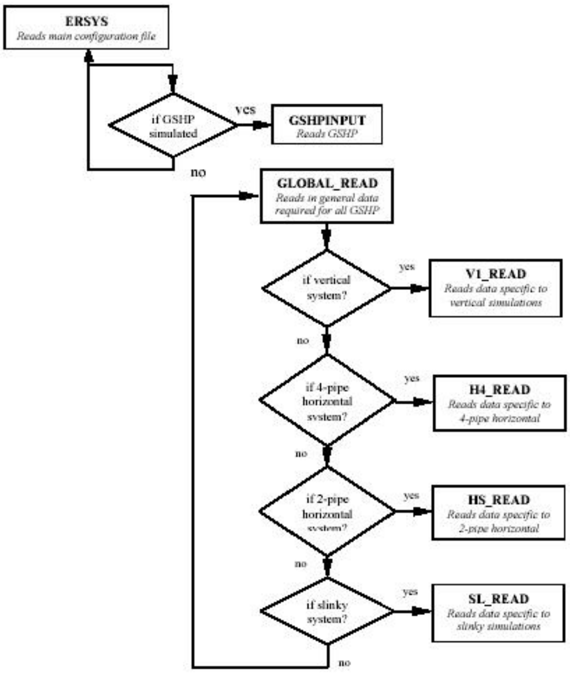

Figure 1: Flowchart of the main data file reader for GSHP input variables.

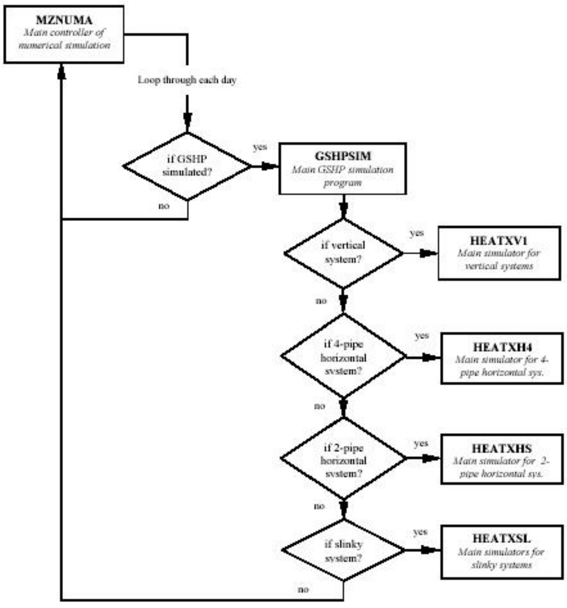

Figure 2: Flowchart of the main simulation procedure for GSHP EWT calculation.

EWT Calculation

GSHPSIM: The main ground loop simulation subroutine is called once per simulation day from MZNUMA (the main numerical simulator). Depending on the GSHP system being modelled, GSHPSIM calls one of: HEATXVI, HEATXH4, HEATXHS, or HEATXSL, as shown in Figure 2.

These GSHP system-specific subroutines calculate the entering water temperature (EWT) in the heat pump for the simulation day.

Heat Pump Performance Calculation

In addition to the ground loop, the performance of the equipment associated with the heat pump must be calculated, including the coefficient of performance (COP) and the capacity – which are calculated based on heating or cooling operation.

The flowcharts for the heat pump code incorporation into the main ESP-r/HOT3000 core are very similar to those presented in Purdy and Haddad (2002).

VALIDATION

Software users expect that the simulation tool will return appropriate results and that model algorithms have undergone validation testing. It is therefore critical that any new developments be adequately verified.

The following sections examine two separate validation processes. The first was designed to validate the GSHP model and the second was designed to validate its incorporation into the ESP-r/HOT3000 core.

Algorithm Validation

The validation performed on the algorithms include comparisons with the existing GS2000™ program from which the algorithms were derived and comparisons with monitored data for the vertical and slinky models to ensure input variations change the predicted EWT as expected. This validation process is outlined in Caneta (2001c).

The GSHP algorithm was validated as a stand-alone program – before its incorporation into ESP-r/ HOT3000. This stand-alone program was designed to allow for daily or monthly time-steps. The monthly stand-alone algorithm was compared against GS2000™ whereas the daily algorithm implemented into ESP-r/HOT3000 was compared against the monitored data.

In GS2000™, the calculation period begins in October, due to a relatively neutral ground temperature at this time of year. This eliminates the need for a pre-conditioning start-up period.

In contrast, the GSHP model incorporated into ESP-r/HOT3000 was designed to begin its calculation period in January, thus necessitating a pre-conditioning period. For the monthly algorithm, this pre-conditioning period was set to three months, October to December.

Comparison with GS2000™ Results

To ensure consistency with the current GS2000™ predictions, the monthly algorithms are compared with the existing GS2000™ program. Three tests were performed for each heat exchanger configuration.

Once the inputs are determined for each test case, they are entered into GS2000™. The only additional variables required for GS2000™ were the lower and upper EWT limits. For the vertical single bore hole calculation, the lower and upper EWT limits were set to 1°C and 23°C respectively; whereas for the horizontal 4-pipe configuration, they were set to –5°C and 23°C respectively.

GS2000™ calculates the heating and cooling pipe lengths and monthly temperature profile. For each test, the longest pipe length and associated temperature profile were recorded. This pipe length was then input into the modified algorithm. The result of one of these analyses – for a horizontal 4-pipe system – is shown in Figure 3.

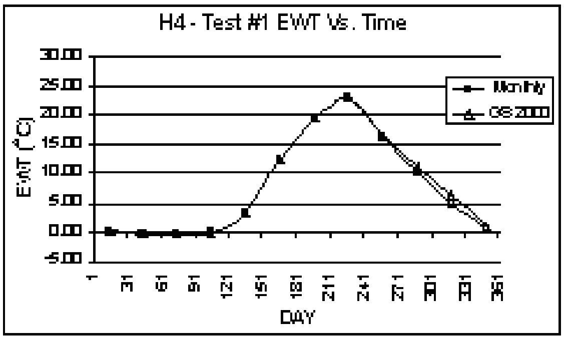

Figure 3: EWT for Monthly Stand-alone Algorithm and GS2000™, Horizontal 4-pipe System.

The monthly EWT profile matches the GS2000™ profile for similar inputs except during the final 3 months of the year (October to December) where the GS2000™ results are slightly higher. In addition, the monthly algorithm reports a smoother transition between December and January. This discrepancy is a result of the lack of preconditioning of the ground temperatures before October in GS2000™.

For details on the test inputs and results for the

GS2000™ comparison, see Caneta (2001c).

Comparison with Monitored Data

The four GS2000™ algorithms were modified to include a daily time step analysis. In order to validate the daily analysis, two of the four algorithms, the vertical single bore hole and the slinky, have been compared to monitored data obtained in the *Enhanced Residential Heat Pumps Wisconsin Case Study* (CDH Energy Corporation 1997). Since site data for the 2-pipe and 4-pipe horizontal systems are not available, their validation will rely solely on a series of parametric tests as will be discussed in the following section.

i. Horizontal Slinky GSHP Analysis

As seen in Figure 4, the slinky model provides a good prediction of the heat pump EWT when compared to the monitored data. The minor differences will have a very small impact on the predicted energy consumption of the GSHP.

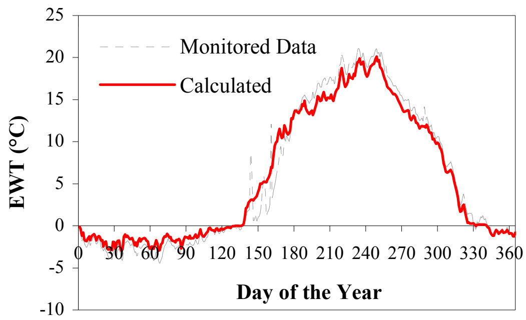

Figure 4: EWT for Daily Stand-alone Algorithm and Monitored Data, Slinky System.

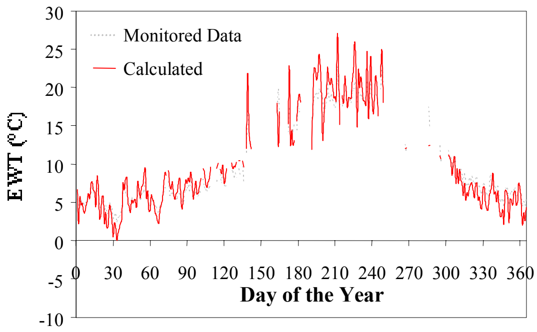

Figure 5: EWT for Daily Stand-alone Algorithm and Monitored Data, Vertical System.

ii. Vertical Single Borehole GSHP Analysis

Gaps in the monitored data, Figure 5, occur when the heat pump is not operating and fluid is not being circulated through the ground heat exchanger. During these periods, ground loads are set to zero in the input file for the daily algorithm since the heat pump is not rejecting or extracting heat to/from the ground. The predicted entering water temperatures are not plotted for these periods. These un-plotted EWT regions are a result of 0-ground loads when the GSHP is inactive. Because these periods occur when the GSHP is not operating or operating for short periods, they will have little impact on energy predictions.

Implementation Validation

Three rounds of testing were performed on the incorporation of the GSHP model into ESP-r/HOT3000.

The first rounds included reading in the heating and cooling loads used by Caneta to validate the EWT calculation and implementation. Figures 6 and 7 show the correlation between the values calculated from the ESP-r/HOT3000 implementation and the values from the daily algorithm (as presented in the previous section) for two systems – a vertical ground loop and a slinky.

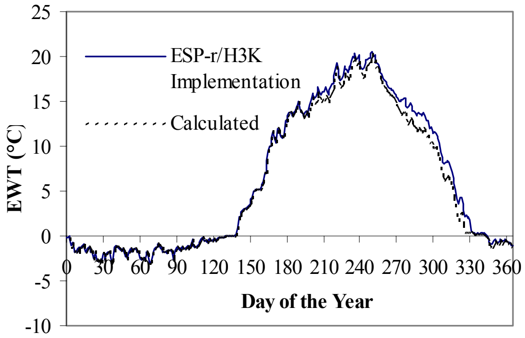

Figure 6: EWT for Daily Stand-alone Algorithm and ESP-r/HOT3000, Slinky System.

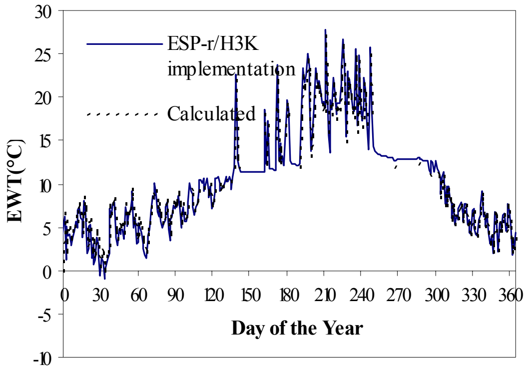

Figure 7: EWT for Daily Stand-alone Algorithm and ESP-r/HOT3000, Vertical System.

It can be seen that for the slinky loop, Figure 6, the results are in good agreement until mid-summer when they start to diverge slightly, whereas, for the vertical loop, Figure 7, the correlation is very good.

The second round of testing included running a set of simulations with the loads applied to an adiabatic zone via infiltration. System-specific weather files were created to simulate the required heating and cooling loads for a one-zone building with a specified amount of infiltration air. The results from these tests mirrored the results obtained from the above cases.

The third round of testing was performed to ensure that the incorporation of the GSHP model would not impact the results for ESP-r/HOT3000 simulations that do not use the model. Two test cases were run with both the standard version of the simulator and with the version compiled including the GSHP coding. The results with the two simulators were identical.

CONCLUSIONS

The capability to model ground source heat pumps was recently added to the ESP-r/HOT3000 engine. This model was based on the well-respected ground heat exchanger sizing program, GS2000™.

As GS2000™ requires the monthly building loads to be input, it was decided that it would be a good fit to incorporate the GS2000™ ground heat transfer calculation into ESP-r/HOT3000.

The GSHP model was shown to compare well with GS2000™ results as well as monitored data. In addition, its implementation into the simulation engine was shown to perform as expected.

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