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PRELIMINARY INTERMODEL COMPARISON OF GROUND HEAT EXCHANGER SIMULATION MODELS

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ABSTRACT

In the past ten years, a number of ground heat exchanger (GHE) models have been developed for use with building simulation programs. In practice, they are combined, directly or indirectly, with models of the building, heat pumps, and other components to give an hourly or shorter time-step prediction of heat pump entering fluid temperatures, ground heat transfer rates, heat pump energy consumption, etc. This paper presents a comparison of ground heat exchanger models developed for use with programs such as EnergyPlus, eQuest, HVACSIM+, TRNSYS, and EES.

1. INTRODUCTION

The comparisons between models are carried out for two ground heat exchangers. The first is a three-borehole ground heat exchanger at Oklahoma State University, for which experimental measurements are available for a 15-month period. For this ground heat exchanger, comparisons are made between the models and the experimental results. Over the 15-month period, this ground heat exchanger has relatively low borehole-to-borehole interference and very little heat build-up in the ground; this limits its utility as a comprehensive comparison. Therefore, a second comparison is performed for a 196-borehole system serving an office building for a twenty-year period. For this case, only model results are compared, as no suitable quality data set is available.

2. BACKGROUND

In general, simulation models for ground heat exchangers predict fluid temperature exiting the ground heat exchanger given the time-varying entering fluid temperature and flow rate. When coupled with models of heat pumps, circulating pumps, and a building, a complete system simulation is formed that can predict time-varying heat pump energy consumption and other variables of interest.

In order to keep the analysis of the ground heat exchanger tractable, it is common, but not necessary, to divide the solution domain into as many as three parts:

- Heat transfer between the fluid and the borehole wall. At a minimum, a steady-state borehole thermal resistance is used, though transient models of the heat transfer within the borehole are also used.
- Heat transfer between the borehole wall and the surrounding ground for a single borehole.
- Heat transfer between boreholes, often referred to as “thermal interference.”

All of the models must deal with a wide range of time constants and a long history of past heat transfer to/from the ground. In some cases, this results in the problem being further divided by time into shorter-term and longer-term responses.

The model labeled “GeoStar” is part of the GeoStar software package. (Cui, et al. 2007) Though primarily intended for use in design and simulation of ground heat exchangers, it is also capable of modeling GHE on an hourly time step. The GHE and surrounding ground are modeled as two domains: soil/rock outside the borehole and the borehole, including grout, U-tube and fluid. The outside-the-borehole domain is modeled with an explicit analytical solution (Zeng, et al. 2002) of the finite line source in a semi-infinite medium. With the assumption of the same heat transfer rate per unit length of each borehole, the borehole wall temperature of each individual borehole in a GHE can be obtained by means of the analytical solution. Inside the borehole, a quasi-three-dimensional model (Zeng, et al. 2003) which takes into account the fluid temperature variation along the borehole depth is used to calculate the fluid temperatures of the up-flow and down-flow channels. The solutions of the two domains are linked at the borehole wall. In addition, the modeling procedure uses spatial superposition for multiple boreholes and sequential temporal superposition to account for time-varying system loads.

Results presented under the acronym “GEOEASE II” were obtained using proprietary ground heat exchanger simulation software developed for Électricité de France (EDF). Within the borehole, the equivalent steady-state borehole thermal resistance is calculated using the relations proposed by Zeng et al. (2003). The temperature difference between the borehole wall and the ground for a single borehole is evaluated using the cylinder source model as outlined by Bernier et al. (2004). This method uses thermal response factors to obtain the average temperature increase (decrease) at the borehole wall caused by the thermal interaction from the other boreholes. The thermal response factors are generated using the finite line source method (Sheriff and Bernier, 2008). A load aggregation algorithm (Bernier et al., 2004) is utilized to improve computational efficiency.

The ground heat exchanger model used in TRNSYS (SEL 2005) is the "Duct Ground Heat Storage" (DST) model developed at the university of Lund (Hellström, 1989), as implemented in the component known as "Type 557" and distributed commercially. (TESS 2005). The DST model was originally intended for underground thermal storage systems, where the ground heat exchanger would be intentionally compact. The DST model calculates the ground temperature by spatially superposing the solutions to three sub-problems: the global heat transfer between the storage volume as a whole and the far-field, the local heat transfer occurring around the boreholes at a short time scale, and a local steady-flux heat transfer around the nearest pipe. The model uses numerical solutions for the global and local problems and an analytical solution for the steady-flux problem.

The three remaining models, implemented in HVACSIM+, EnergyPlus, and eQuest, have a common heritage and so will be described together. All three models are based on extensions to Eskilson's (1987) ground heat exchanger model, which is based on pre-computed response functions for specific ground heat exchanger geometries. The response functions, known as g-functions, are computed based on spatial superposition of a two-dimensional (radial-axial) simulation of a single borehole. This numerical simulation has limited accuracy at short time-steps and g-functions are typically pre-computed for times between a number of days and hundreds of years. All three models take the approach of extending Eskilson's g-functions to short time steps (an hour or less) by computing the response for a single borehole to a pulse. The HVACSIM+ model was originally developed using a two-dimensional (radial-angular) finite volume model (Yavuzturk and Spitler 1999), but Xu and Spitler (2006) simplified the computation to use a one-dimensional (radial) finite volume model, which gave acceptable accuracy as long as the material properties inside the borehole were carefully matched to the actual borehole resistance. The EnergyPlus model (Fisher, et al. 2006) uses essentially the same approach. The eQUEST model (Liu and Hellström 2006, Liu 2008) also uses Eskilson's g-functions for the long-time response, but extends the g-functions to short times with a line-source analytical solution.

3. COMPARISON 1: 3-BOREHOLE GHE

The first comparisons are based on an experimental system at Oklahoma State University. The experimental facility (Gentry, et al. 2006) was developed to study hybrid ground-source heat pump systems, but these comparisons only use measured data from the three borehole ground heat exchanger. The GHE has 3 vertical boreholes, each approximately 75 meters deep, 114 mm in diameter and consist of a single HDPE U-tube of nominal diameter 19.05 mm, backfilled with bentonite grout. Ground thermal conductivity was taken as the mean value (2.55 W/mK) from in situ tests on each of the three boreholes. Volumetric specific heat (2012 kJ/m^3K) was estimated from knowledge of the geology. Values for grout and pipe properties were taken from manufacturer's data. The undisturbed ground temperature was measured at 17.3°C.

Experimental data include inlet and outlet temperatures measured at a centrally-placed manhole and flow rate. All measurements were collected on 1 minute intervals, but since, for building simulation purposes, the most common time step is one hour, hourly averages of the data were used. Eighteen months of data are available, though some model results are only available for the first 12 months, as models implemented within some building simulation tools cannot readily be adapted to use more than 12 months of non-repeating data. Furthermore, models may be configured for input and output variables in at least two possible ways, and so two tests were developed and most of the models were only compared for one test. The two tests are:

- Test 1a: Fluid flow rate and borehole EFT (outputs:heat transfer rate and BH ExFT)
- Test 1b: Fluid flow rate and borehole heat transfer rate (outputs: BH EFT and ExFT.)

For Test 1a, average monthly heat extraction and rejection rates have been plotted in Figure 1. Month 3 is March of the first year; month 12, December of the first year, etc. Heat extraction is shown as positive; heat rejection as negative. In general, the three models follow the general trend of the experiment reasonably closely. For the summer cooling months of June-September of the first year, the EnergyPlus and TRNSYS model results lie within 7% of the experimental measurements. The HVACSIM+ results have higher differences, underpredicting the experimental measurements by up to 15%. In the peak heating months of December through February, the differences increase with maximum underpredictions of 6%, 11%, and 24% for EnergyPlus, TRNSYS, and HVACSIM+, respectively. Performance during the shoulder seasons is mixed, sometimes better, sometimes worse.

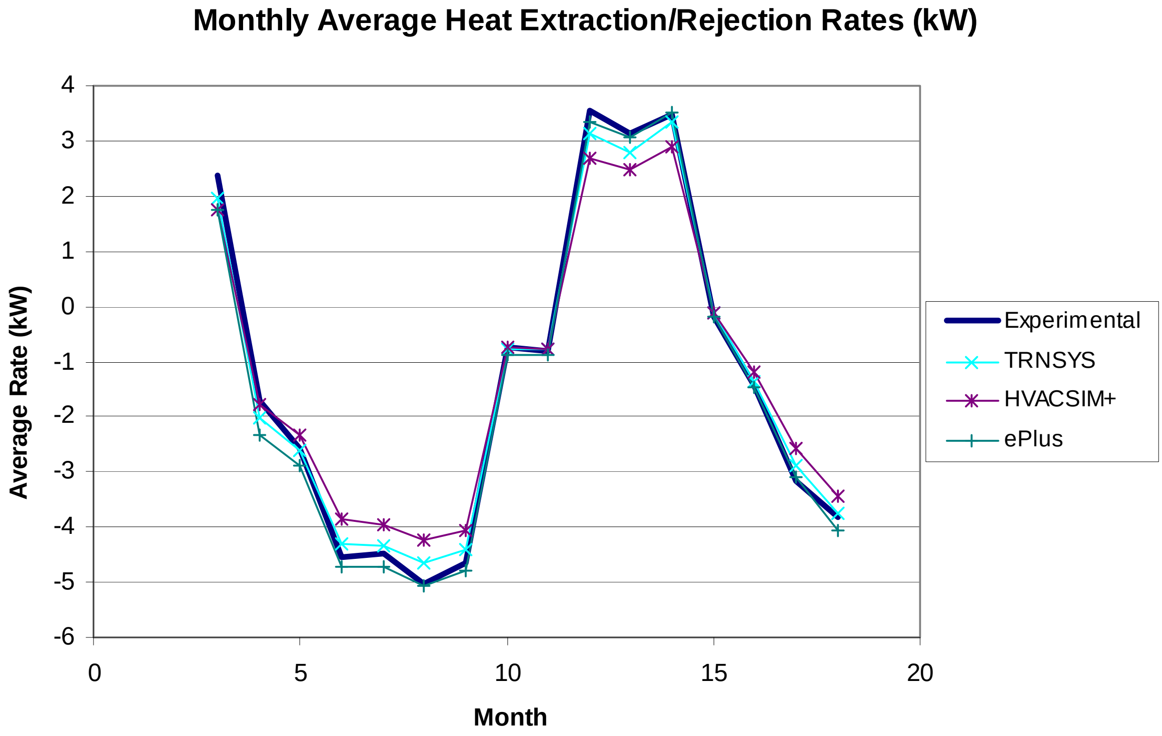

Figure 1: Test 1a—monthly average heat extraction/rejection rates

Figure 2 shows the monthly average borehole ExFT for Test 1b, when the hourly heat transfer rate is specified. For the summer cooling months during the first year, all of the models predict the ExFT within 1°C, except HVACSIM+ which overpredicts a maximum of 2°C. For the shoulder seasons and heating months, the error increases slightly.

Figure 3 shows hourly results for a single day. This ground heat exchanger served a single heat pump which was operated in on/off mode like almost all currently available unitary equipment. The oscillation in temperatures throughout the day reflects the on/off cycles of the heat pump. All models show higher amplitude of oscillation than the experiment. The comparison is likely complicated by the use of hourly time steps that do not correspond to the heat pump on/off cycles. It may be necessary to make comparisons at shorter time steps to determine how much of the differences are caused by this simplification.

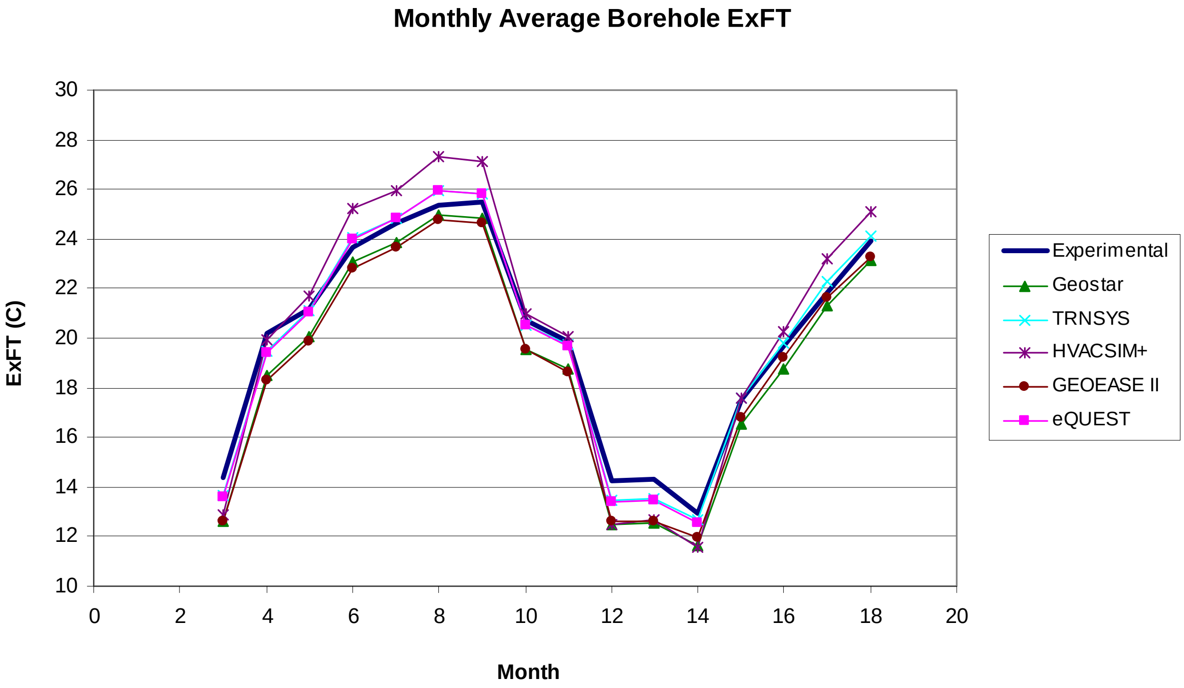

Figure 2: Test 1b—monthly average borehole ExFTs

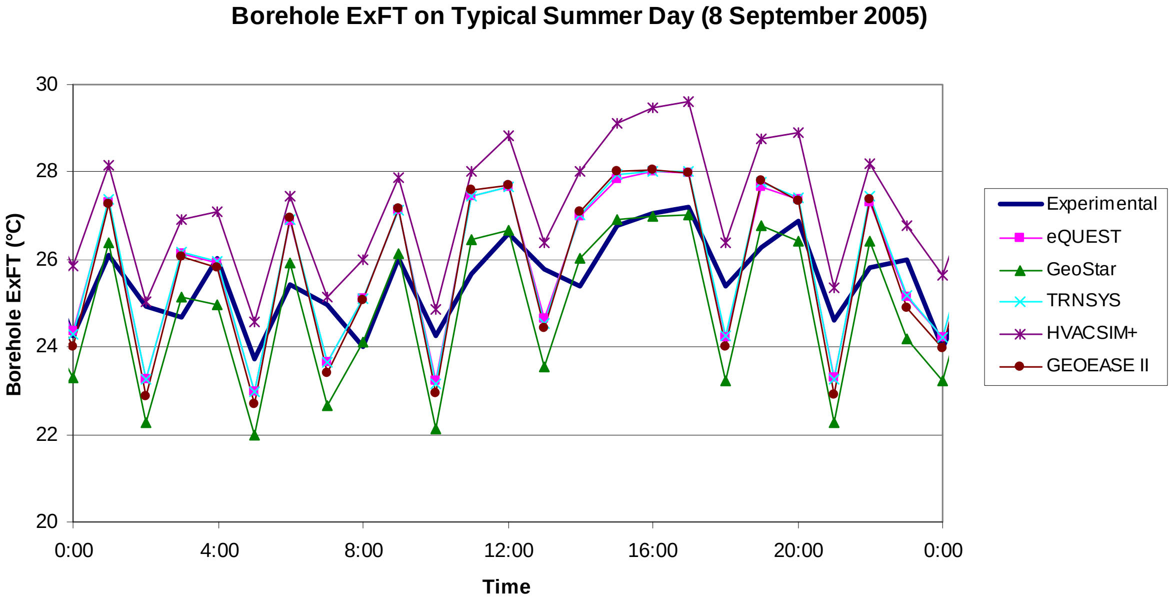

Figure 3: Test 1b—borehole ExFTs for a typical summer day

4. COMPARISON 2: 196 BOREHOLE GHE

For the second set of comparisons, hourly heating and cooling loads for a three-story office building with floor area of 7100 m^2, in Tulsa, Oklahoma were determined using EnergyPlus. The ground heat exchanger has 196 vertical boreholes, 73 m deep, arranged in a 14-by-14 grid, spaced 7.62m (25ft) apart. The boreholes are 128 mm in diameter, and use 1” Schedule 40 pipe (26.64mm inside diameter, 33.40mm outside diameter), with equal spacing between U-tube and pipe wall (shank spacing 20.4 mm) Typical ground and grout thermal properties are assumed (k_{ground} = 3.50 W/m-K, $(\rho c_p)_{ground}$ = 2160 kJ/m^3-K; k_{grout} = 0.744 W/m-K,

$(\rho c_p)_{grout}$ = 3900 kJ/m3-K) Undisturbed ground temperature is taken as 16.67 °C. The working fluid is a 20% solution of propylene glycol, with a total flow rate of 57.6 L/s. In order to keep the comparisons as simple as possible, the heat pumps were assumed to have fixed COPs: 3.5 in cooling; 4.5 in heating.

This ground heat exchanger was intentionally chosen to be slightly under-sized, so that differences in the model predictions would be emphasized. Whereas the Tests 1a and 1b had relatively little borehole-to-borehole thermal interference, it is expected that a cooling-dominated system with 196 vertical boreholes will show substantial heat build-up. Indeed, as shown in Figure 4, the average ExFT from the GHE (average heat pump EFT) for each year of the simulation increases significantly over the life of the system. However, as can be seen in Figure 4, the models show considerable disparity in prediction of the long-term temperature rise. For the last year of operation, Figures 5 and 6 show the monthly average HP EFT and monthly maximum HP EFT. Consistent with Figure 4, there is considerable disparity in prediction of the monthly temperatures. As the ground heat exchanger was intentionally marginally undersized, the maximum temperatures predicted by most, but not all, of the models would likely result in heat pump failures during the latter years of operation.

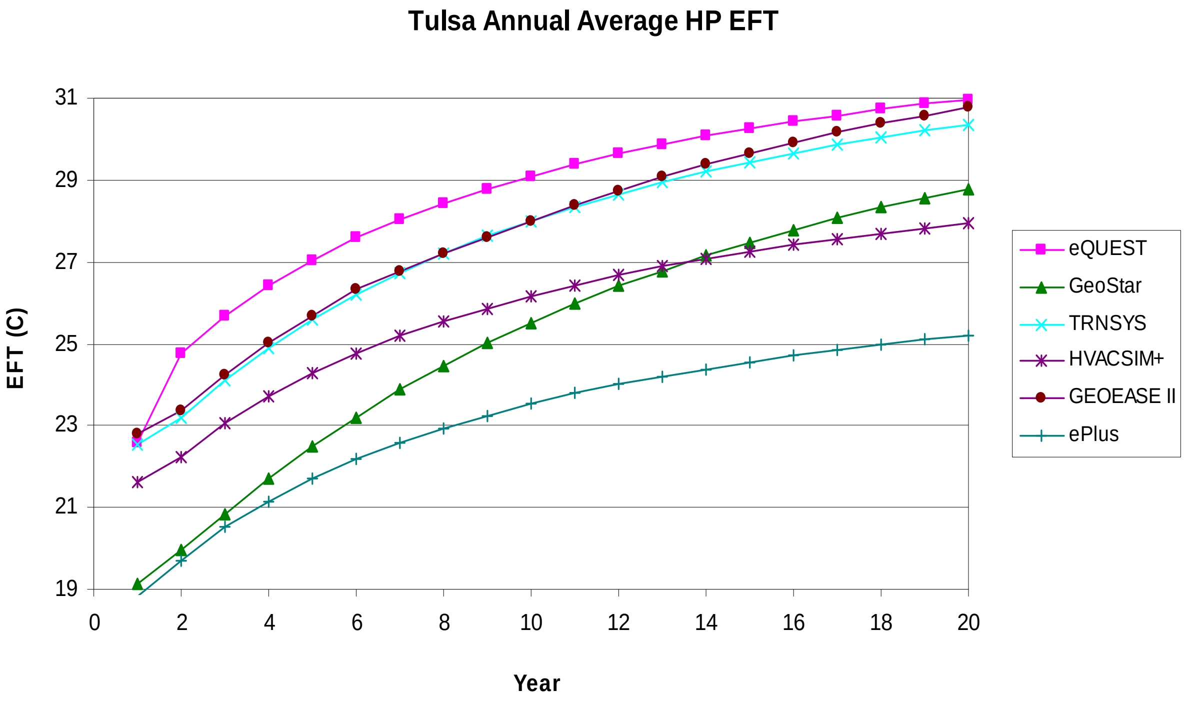

Figure 4: 20 year annual average heat pump EFTs

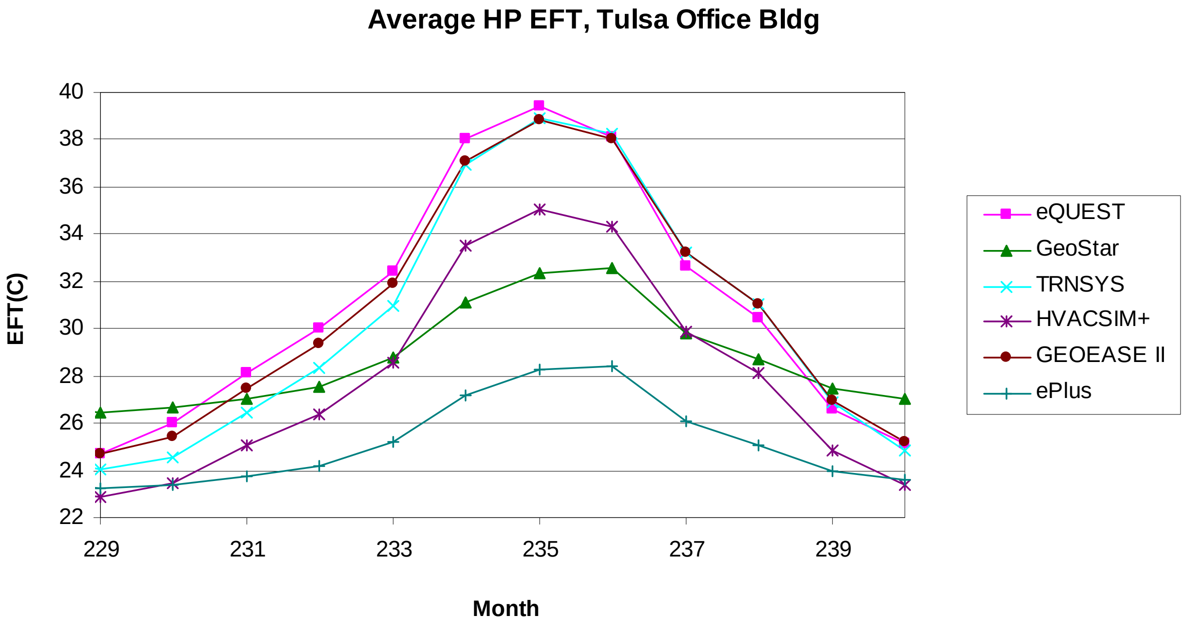

Figure 5: Tulsa office building, average heat pump EFT

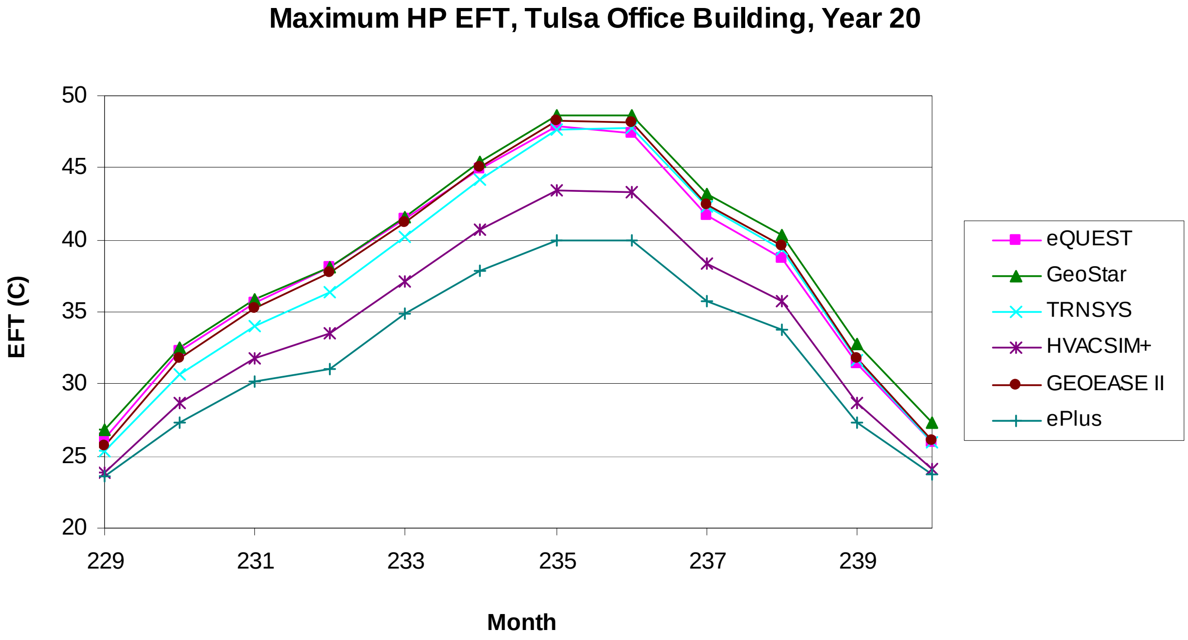

Figure 6: Tulsa office building, maximum heat pump EFT

5. DISCUSSION AND NEEDED FUTURE WORK

The study showed differences in the prediction of ground heat exchanger ExFT, which is in turn the EFT to the heat pump(s). The differences, for the second test, are large enough to lead to significant differences in heat pump energy consumption. Taking the worst case, July of year 20, the difference in average HP EFT suggests that with a current production high efficiency heat pump the Geostar and EnergyPlus models would predict about 20% lower energy consumption than the eQuest and GEOEASE II models. Accordingly, further work is needed to correctly identify the reasons for the differences. Speculation as to possible causes for the differences includes the following:

- With regards to the first test, there are a number of differences between real-life conditions and model assumptions. Some of the model assumptions that do not, with complete accuracy, reflect real-life conditions include: uniform undisturbed ground temperature; no groundwater flow, no moisture transport in the upper, unsaturated regions of the ground; and uniform heat transfer along the length of the borehole. Also, averaging of experimental data over one-hour periods while the heat pump cycles on and off at a similar period inevitably causes some error.
- With regards to the second test, the underlying assumptions for superposition of individual boreholes, boundary conditions and heat transfer along the borehole vary. This seems like the most likely cause of the differences.
- For both tests, contributions of other errors to the differences can not yet be ruled out. In a round robin test such as this, user input, model implementation, and post-processing of model results all may contribute to the differences between the results.

REFERENCES

Bernier, M.A., A. Chahla, P. Pinel. 2008. Long-term Ground Temperature Changes in Geo-Exchange System, ASHRAE Transactions, 114(2).

Bernier, M.A., P. Pinel, R. Labib, R. Paillot. 2004. A Multiple Load Aggregation Algorithm for Annual Hourly Simulations of GCHP Systems, HVAC&R Research, 10(4), 471-488.

Cui, P., H. Yang, Z. Fang. 2007. The Simulation Model and Design Optimization of Ground Source Heat Pump Systems. HKIE Transactions, 14(1):1-5.

Eskilson, P. 1987. Thermal analysis of heat extraction boreholes. Doctoral Thesis, Lund University, Sweden.

Fisher, D.E., A. Murugappan, S.K. Padhmanabhan, S.J. Rees. 2006. Implementation and Validation of Ground-Source Heat Pump System Models in an Integrated Building and System Simulation Environment. HVAC&R Research. 12(3a):693-710.

Hellström, G., 1989, Duct Ground Heat Storage Model, Manual for Computer Code, Department of Mathematical Physics, University of Lund, Sweden.

Liu, X. (2008). Enhanced design and energy analysis tool for geothermal water loop heat pump systems, Proceedings of 9th International Energy Agency Heat Pump Conference, 20 – 22 May 2008, Zürich, Switzerland.

SEL, 2005. TRNSYS 16 – A Transient System Simulation Program – Documentation set (9 Volumes). Version 16.00.0038. Solar Energy Laboratory, University of Wisconsin-Madison. Madison, WI.

Sheriff, F., Bernier, M. 2008. Simulations de champs de puits géothermiques verticaux de charges thermiques différentes, IBPSA-Canada - eSim 2008, Ville de Québec, Canada, pp.17-24.

TESS, 2005 TESS Libraries Version 2.02, Reference Manuals (13 Volumes). Thermal Energy Systems Specialists, Madison, WI. http://tess-inc.com.

Xu, X., J. D. Spitler. 2006. Modeling of Vertical Ground Loop Heat Exchangers with Variable Convective Resistance and Thermal Mass of the Fluid. Proceedings of Ecostock 2006, Pomona, NJ.

Yavuzturk, C., J.D. Spitler. 1999. A Short Time Step Response Factor Model for Vertical Ground Loop Heat Exchangers. ASHRAE Transactions. 105(2):475-485.

Zeng H.Y., N.R. Diao, Z.H. Fang. 2002. A finite line-source model for boreholes in geothermal heat exchangers, Heat Transfer Asian Research, 31(7): 558-567.

Zeng H.Y., N.R. Diao and Z.H. Fang. 2003. Efficiency of vertical geothermal heat exchangers in ground source heat pump systems, Journal of Thermal Science, 12(1): 77-81.