SIMULATION MODELING OF GROUND SOURCE HEAT PUMP SYSTEMS FOR THE PERFORMANCE ANALYSIS OF RESIDENTIAL BUILDINGS

Soolyeon Cho and Sedighehsadat Mirianhosseinabadi
School of Architecture, College of Design, North Carolina State University
Raleigh, North Carolina, USA

ABSTRACT

This paper presents the simulation modeling process of Ground Source Heat Pump (GSHP) systems as part of a whole building simulation. A large number of GSHP systems have been used in both commercial and residential buildings as they provide high efficiency in the heating and cooling processes. However, there are some critical challenges in analyzing the performance of the GSHP systems in current technologies. This paper identifies the challenges/problems through a rigorous literature review in the context of whole building simulation. Several widely used computer simulation programs were reviewed and compared regarding their GSHP simulation capabilities. Finally, addressed are advantages and disadvantages, problems and barriers of GSHP's application technologies, and the challenges and issues that need to be solved in short and long term period to facilitate the performance analysis of GSHP systems in buildings.

INTRODUCTION

The increase of energy consumption, necessarily required to drive our modern life, has led us to a concern about environmental issues. Also, one of the largest energy consumption areas is Heating, Ventilating, and Air-Conditioning (HVAC) systems in buildings. As an alternative, utilizing geothermal heat, the Ground Source Heat Pump (GSHP) system has extensively gained in popularity through the last couple of decades. The so-called systems use the ground as a heat source/sink to provide thermal energy for space heating, cooling, and domestic hot water. The GSHP technology can offer higher energy efficiency compared to conventional Air Source Heat Pump (ASHP) systems due to less temperature fluctuations in soil temperature than ambient air temperature change. Consisting mainly of three mechanisms; i.e., the ground loops to get heat out of or into the ground, the heat pump to convert that heat to a suitable temperature level, and the building side transferring the heat into the rooms. A worthy design must take care of the whole system, matching the modules in such a way that the most effective action and the highest comfort can be achieved. The prevailing term of GSHP consists of the Ground Coupled Heat Pump (GCHP), Ground Water Heat Pump (GWHP), and Surface Water Heat Pump (SWHP). By and large, growing interest is more on the GCHP system that uses closed loop for the Ground Heat Exchanger (GHX) systems than the systems that consist of an open loop. The GCHP system, which has the vertical closed loop GHX, is used more commonly in residential use than the horizontal loop GHX due to the compact area required. Despite their approval, high initial cost of GCHPs has somewhat limited the GCHP design and installation infrastructure. In addition, the design of GCHP systems has been slower than expected because of the deficiency of reliable, user friendly simulation tools for GCHP systems (Liu and Hellström, 2006).

This study contains a comprehensive literature review on the development of the GSHP technology applications in buildings, its evolution and typical modeling procedures of the Vertical Ground Heat Exchangers (VGHXs) during the time. A number of commonly used computer simulation programs for building energy analysis are compared based on their GSHP simulation capability. This paper identifies the challenges/problems and efforts to provide methodologies to better evaluate the performance of the systems in the context of whole building simulation. The three residences, used as case studies for the GSHP performance analysis, have GSHPs installed in different times for different projects; however just one of them is presented in detail in this paper. The other two residences and detailed comparative analysis will be presented in the near future in another paper.

To examine the performance of GSHPs of the houses, whole building energy simulation programs are reviewed such as EnergyPlus (USDOE, 2011), DOE-2.1e (Winkelmann et al., 1993), eQUEST (Hirsch, 2006), TRNSYS (Klein et al., 1990), and EnergyGauge USA (Center, F. S. E., 1999). These programs include the functions to handle and analyze GSHP systems. Apex House, which is one of the three case study houses, has been modeled in SketchUp with OpenStudio (Ellis, 2009) plugged-in and imported to EnergyPlus to evaluate the performance of Apex House's GSHP system. One of the important parts of the GSHP system is the GHX model, which is used to calculate the supply and return water temperatures of the ground loop. The design of GHXs has relatively become easier these days using simulation tools such as EED (Hellström & Sanner, 1994), GchpCalc (Kavanaugh and Rafferty, 1997), and GLHEPRO (Spitler, 2000). These tools were developed for system sizing and analyzing the performance of GHXs. Moreover, their outputs can be used in whole building energy simulation processes as input data.

Overview on the development of GSHP

The first documented idea of using the ground as a heat source appears to have been in 1912 in Switzerland (Wirth, 1955). In the 1940s, investigation into GSHP started up again both in the UK and the US, and some initial efforts about the installation of GSHPs have been done (Rawlings et al., 1999). The first outburst of interest in the GSHP technology began in both North America and Europe after World War II and lasted until the early 1950s when gas and oil became broadly used as heating fuels. At that time, the basic analytical theory for the heat conduction of the GSHP system was proposed by Ingersoll and Plass (1948), which had been used as a foundation for the development of some of the later design programs. After the first oil shock in 1973, commercial use of the ground as a heat source/sink began, but it was well established by the end of the 1970s (Granryd, 1979). After the 1970s, the research was generally focused on the generation of the vertical borehole system due to the advantage of less land area requirement for borehole settings.

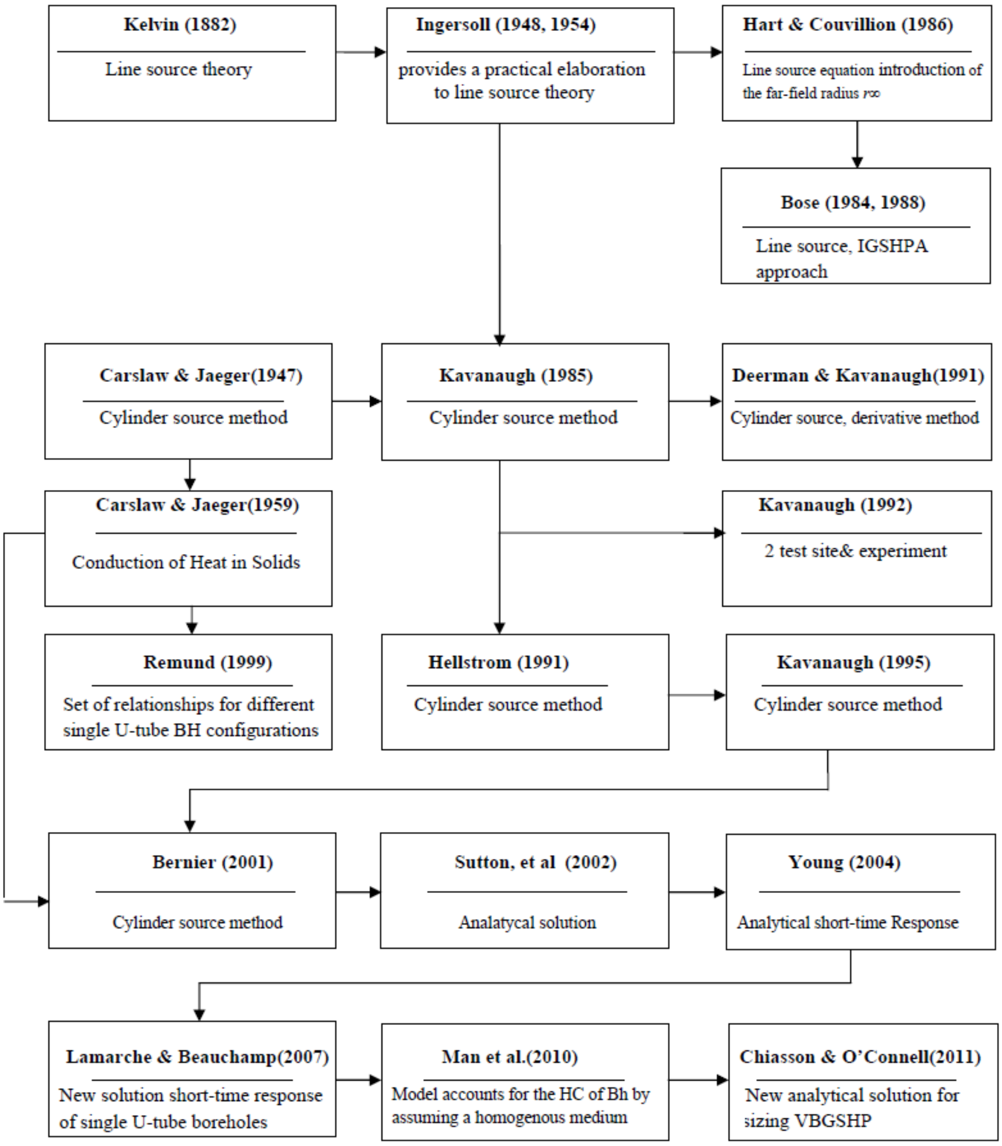

Figure 1 History diagram of analytical models of GHX systems, chronologically.

In the literature, several calculation models were found for ground heat exchangers. During the first stage of the geothermal systems study, one-dimensional models were devised, which were replaced by two-dimensional models later during the 1990s, and three-dimensional systems during the recent years (Florides and Kalogirou, 2007). The analytical models are usually created based on a quantity of assumptions and simplifications in order to answer the complex mathematical algorithms; consequently, the so-called assumptions slightly reduced the accuracy of analytical results. Though, the essential calculation time of the analytical model is much less compared to the numerical models. Another benefit is that the straightforward algorithm inferred from the analytical models can be readily integrated into a design/simulation program (Yang et al., 2010).

Figure 1 shows a schematic diagram of developing the analytical models of GHXs systems, chronologically. Analytical solutions such as line source model (Ingersoll and Plass 1948; Bose et al., 1985; Hart and Couvillion., 1986), cylindrical heat source (Carslaw and Jaeger, 1947; Kavanaugh, 1985; Deerman and Kavanaugh 1991; Hellstrom, 1991; Kavanaugh, 1995; Bernier, 2001), and other analytical solutions (Hellstrom, 1991; Sutton et al., 2002), have been used for dimensioning vertical ground heat exchangers.

Although the numerical models in describing the GHXs model can suggest a high degree of flexibility and accuracy (especially on short-term scales) compared to the analytical models, most of them using polar or cylindrical grids may be computationally inefficient because of the large number of complex grids. Besides, the numerical models are inconvenient to be incorporated directly into a design and energy analysis program, unless the simulated data are pre-computed and stored in a huge database (Yang et al., 2010). Direct numerical solutions, such as finite difference, finite volume, finite element (Mei and Emerson, 1985 (Model for horizontal coils); Muraya, 1994; Muraya et al., 1996; Rottmayer et al., 1997; Thornton et al., 1997; Zeng, et al., 2003; Al-Khoury et al., 2005) have been used to model GHXs and developed to examine the nature of heat transfer around borehole heat exchangers for research purposes (Xu et al., 2007).

Figure 2 shows the schematic diagram of developing the numerical models of GHXs chronologically. In a number of numerical GHX models that have been developed, two numerical approaches are the most common: the g-function model developed by Eskilson (Eskilson, 1987) and the duct storage (DST) model developed by Hellström (Hellström, 1989).

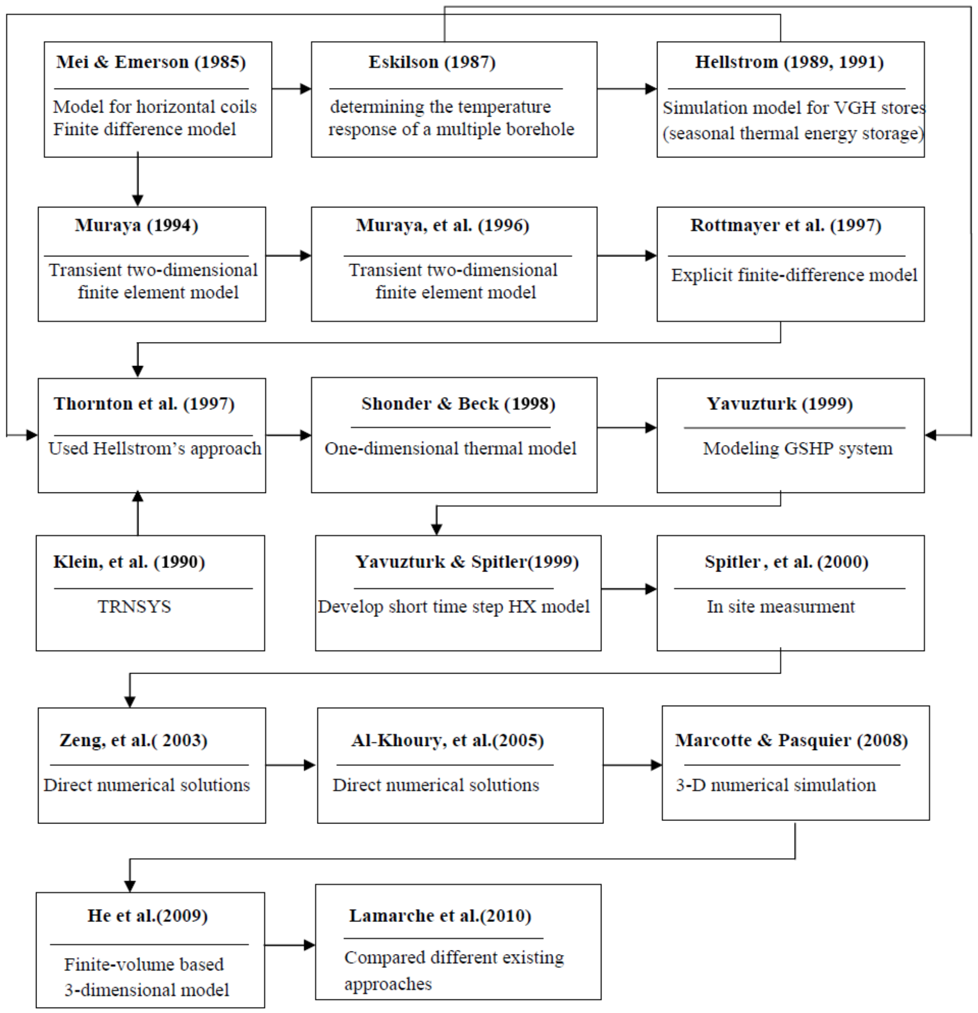

Figure 2 Schematic diagram of numerical models of GHXs systems, chronologically.

In most of the literatures, g-function is categorized as a third approach after analytical and numerical methods due to its important role in design/simulation programs. The G-function allows for computationally efficient simulation and leads to the development of response functions, which allow the GHX to be modeled with a time series. Eskilson (1987) developed g-functions for long time step, and later a short time step response factor method was developed by Yavuzturk and Spitler (1999). Although this model is capable of simulating the heat transfer of ground loop heat exchanger in any time scale, it could not model different thermal resistance and fluid thermal mass (Xu, 2007). Li and Lai (2012) also developed a new approach for modeling of heat transfer by ground heat exchangers, involving unsteady heat conduction in composite media together with complex geometry (Li and Lai, 2012).

GSHP MODELING AND SIMULATION TOOLS

To attain a trustworthy and economically reasonable GSHP system, the GHX must have the capacity of sufficient heat transfer, but not be oversized. Because of the complexity of this design process, computer programs are usually used to facilitate the design. Regardless of the low energy and lower maintenance merits of GSHP systems, work has not been sufficiently done on the analysis and simulation of so-called systems (Liu and Hellstrom, 2006). There are three commercially available tools for the design of GHX system with VGHXs such as EED (Hellström & Sanner, 1994), GchpCalc (Kavanaugh and Rafferty, 1997) and GLHEPRO (Spitler 2000). These tools only deal with the peak load calculations and are used to determine the length of GHXs. In the building energy research, moreover, in most of the cases, the results from the so-called tools are used as a GHX parameters input for hourly whole-building computer simulation programs such as DOE-2.1e (Winkelmann et al., 1993), eQUEST (Hirsch, 2006), EnergyPlus (USDOE, 2011), TRNSYS (Klein et al 1990), and EnergyGauge USA (FSEC, 2010), which are broadly and extensively used for appraising complex building performance to advance energy efficiency.

The theoretical basis for the single U-tube, multiple borehole ground-loop heat exchanger models comes from the work of Eskilson (1987). His approach to the problem of determining the temperature distribution around a borehole is a hybrid model combining analytical and numerical solution techniques. The temperature response of the borehole field is converted to a set of non-dimensional temperature response factors, called g-functions. The g-function allows the calculation of the temperature change at the borehole wall in response to a step heat input. Eskilson has calculated g-functions (data sets) for a wide variety of borehole configurations (Yavuzturk and Spitler, 2001). Eskilson's method in determining the long time g-function and Yavuzturk and Spitler' s approach in developing the short time g-function have been used in most of the GHX design tools, which are explained below.

Tools for the design of vertical GSHX systems

EED (Earth Energy Designer): The EED tool, relatively a user-friendly program, has been developed based on the Eskilson's approach by a group of researchers from University of Lund, Sweden for the sizing of vertical GHEs (Yang et al., 2010). The early PC-programs calculation of brine temperatures is done for monthly heat/cool loads, and the outputs are the length of ground heat exchangers, system COP, and energy (electrical) consumption (Hellström and Sanner, 2001).

GchpCalc: The GchpCalc tool has been applied broadly within the United States for the design of vertical GHX's. Based on the research by Kavanaugh (1985), a method has been developed that uses the cylindrical source solution and approximates the time varying nature of the heat extraction/addition to the ground using a steady state solution and effective thermal resistance (Hellström and Sanner, 2001). The rudimentary technique follows the approach of Ingersoll et al. (1954) where cyclic pulses of heat from a line source are approximated (Kavanaugh and Rafferty, 1997). The outputs are length of ground heat exchangers, heat pump COP, system COP and energy (electrical) consumption. Kavanaugh's method also considers the thermal interaction of adjacent boreholes and the possibility for long term heat buildup/depletion within the ground (Hellström and Sanner, 2001).

GLHEPRO: The GLHEPRO program, using Eskilson's approach by Spitler (2000) is developed to design vertical GHXs used in commercial or institutional buildings. It lets users to attain a simulation of their ground loop heat exchanger to determine monthly peak and average entering fluid temperatures to the heat pump from the borehole(s), the power used up by the heat pump, the heat extraction rate per unit length of borehole and the required depth of the borehole(s) (Spitler, 2007).

Whole-building energy simulation programs including GSHP systems

In the scope of building energy research, the main tools are the whole-building energy simulation programs, which provide users with crucial building performance indicators such as energy use and demand, temperature, humidity, and costs (Crawley et al., 2008). The U.S. Department of Energy (DOE) offers information on about 400 building software tools for estimating energy efficiency and sustainability in buildings. Among these tools, the most broadly well-known tools related to whole-building energy simulation are the DOE-2.1e program, eQUEST, EnergyPlus, TRNSYS, and EnergyGauge USA.

DOE-2.1e: This program simulates the performance of a GCHP system using a water source heat pump system with vertical or horizontal GHXs and uses g-function approach to model the GHXs, but it does not account for the effects of grouting materials and anti-freeze on the heat transfer performance of GHX.

eQUEST: The DOE-2.2 is the simulation engine of eQUEST, which simulates the performance of a GCHP system at a certain hour using an improved water source heat pump system simulation module. The eQUEST program uses an improved g-function algorithm developed by Yavuzturk & Spitler (1999) to calculate the temperature of the borehole walls.

TRNSYS: This is a transient system simulation program with a modular structure. TRNSYS uses the Duct STorage (DST) model by Hellstrom (1991) to simulate GHX and calculate the performance of water source heat pump with a GHX for its GCHP system.

EnergyPlus: This is a flexible and modular-structured whole-building simulation program based on the most general features and capabilities of BLAST and DOE-2.1e. It is a simulation engine with input and output of text files. A water source heat pump model with GHXs is used in the whole-building GCHP annual energy simulation in EnergyPlus. This program was used to test the GSHPs in this study.

EnergyGauge USA: This tool simulates the performance of a GCHP system using a geothermal heat pump for residential buildings during an acceptable run time.

CASE STUDY

In this study, three houses were introduced; i.e., the Solar House, Chancellor's New Residence and Apex House. These houses have GSHPs installed in different times for different projects. The Solar House has GSHPs installed in 25 years ago and now operational in a 30 year-old house. Apex House has GSHPs installed one year ago as a replacement of Air Source Heat Pumps (ASHPs) to a 25 year-old house. The Chancellor's New Residence has GSHPs installed less than a year ago with a new construction.

In this study, however, only the Apex house was modeled using the EnergyPlus simulation program. The other two residences and detailed comparative analysis will be presented in the near future in another paper.

Description of Apex House:

Apex House is a residential house located in unincorporated Wake County (near Apex/Cary) of North Carolina. It was originally built in 1987 with unfinished second floor. The second floor was finished about ten years later in 1997 with 500 sqft added to the existing conditioned space of 1,600 sqft in the first floor. The existing equipment for the first floor was a 2.5-ton Air Source Heat Pump (ASHP), which was installed in 1987 with air handler and duct work in crawl space; and for the second floor was 1.5-ton ASHP, which was installed in 1997. Both systems included auxiliary electric resistance heating.

In later 2011, these two existing ASHPs were replaced with GSHPs. The replacement costs were $37,730. However, after all of the rebates, which includes 30% Residential Renewable Energy Tax Credit ($11,320), 35% North Carolina Renewable Energy Tax Credit (max $8400 for geothermal) and Progress Energy Carolina's Residential Energy Efficiency Rebate Program ($300 per system: $600), the final project costs were reduced to about $17,400. The package heat pump for the 1st floor (2 ton capacity) has a two-stage compressor with variable speed blower and 8 kW back up heat strips.

The split heat pump for the 2nd floor (2 ton capacity) also has a two-stage compressor and variable speed blower. Based on the owner's information for GSHP, the cooling Energy Efficiency Ratio (EER) is 18.5/26.0. EER is a term generally used to define cooling efficiencies of unitary air-conditioning and heat pump systems. As a general rule, a compressor that has a higher EER at a given rating condition could be expected to perform better in a system than one that has a lower EER. Also the heating Coefficient of Performance (COP) for Apex House is 4.0/4.6. When calculating the COP for a heat pump, the heat output from the condenser is compared to the power supplied to the compressor. In general a higher COP heat pump will consume less purchased electricity than one with a lower COP.

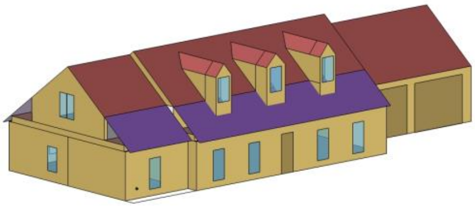

Figure 3 Geometry model of Apex House

The geometry model of the Apex house was developed using the SketchUp program, as shown in Figure 3, and then exported to EnergyPlus for further HVAC systems modeling of GSHPs.

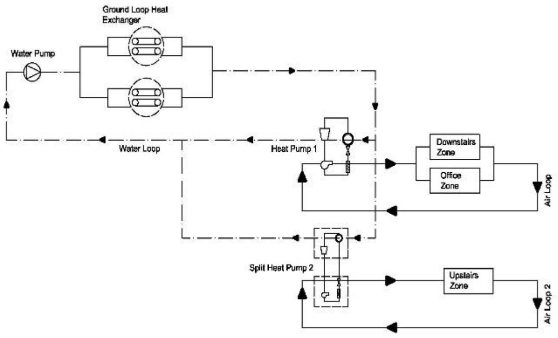

Figure 4 HVAC Diagram of Apex House

Figure 4 shows the HVAC diagram of the house, which has been used for the modeling of the two GSHPs. The Heat Pump-1 provides heating and cooling for downstairs and office zone. The split Heat Pump-2 provides heating and cooling for upstairs. Historical data and Electric utility bills for the Apex House were obtained for the period of January 2009 through December 2012.

Mid-Atlantic Climate

The Mid-Atlantic region, as shown in Figure 5, has weather influences dictated by the Atlantic Ocean, Great Lakes and Midwest. This climate region has a humid subtropical climate, with regularly moderate temperatures during spring and autumn. Summers are typically warmer. Winters are mild and wet with highs generally in the range of 47–53 °F (8–12 °C) with lows around or just below freezing. Spring and autumn features warm days and cool nights. Summer daytime highs average in the upper 80s to low 90s °F (31-34 °C) with warm and humid nights in the upper 60s °F (19-21 °C).

EnergyPlus GSHP simulation Process

The EnergyPlus simulation model was developed after the geometry of the Apex House has been imported into EnergyPlus. The GSHPs of the house are both water-to-air heat pumps.

Figure 5 US Mid-Atlantic States.

The process of modeling of HVAC systems of Apex house in EnergyPlus requires the combination of objects such as Airloop, Unitary Heat Pump:Water to Air, Cooling/Heating Coil, Condenser Loop and Ground heat exchanger. Air loops along with zone equipment arrange the entire forced air heating and cooling system (air side). The next object, unitary water-to-air heat pump is a complex module consisting of a fan, water-to-air cooling and heating coils, and a supplemental heating coil. The heat pump switches between cooling and heating depending on the zone's heating and cooling demand.

The load side (air) of the zone water-to-air heat pump consists of an On/Off fan component, a WaterToAirHeatPump cooling coil component, a WaterToAirHeatPump heating coil component, and a Gas or Electric supplemental heating coil component. The source side (water) of the heat pump is connected to a condenser loop with a heat exchanger (ground heat exchanger) or a plant loop with a heating source such as a boiler and a cooling source such as a chiller or cooling tower. In this study ground heat exchanger is coupled to the water-to-air heat pumps. Figure 6 shows the arrangement and assembly of the heat pump for the source side and demand side for a ground heat exchanger configuration.

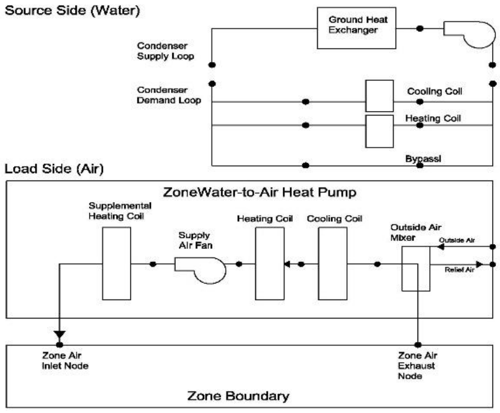

Figure 6 GSHP diagram for supply and demand

In this study, the Coil: Cooling: Water to Air Heat Pump: Equation Fit coil and Coil: Heating/Cooling was examined in EnergyPlus model. The so-called coil is a deterministic model that needs factors to define the functioning conditions of the heat pump's components. The factors are generated from the manufacturer catalog data using multivariable optimization method (DOE, 2010).

The EnergyPlus GHX is a condenser module which serves the condenser supply side in addition to the cooling towers and other condensing components. The heat exchanger response is defined by a g-function, a non-dimensional function. The g-function is different for each borehole field configuration and the borehole thermal resistance. It is also dependent on the ratio of borehole spacing to depth. For accurate simulation, g-function values have to be calculated for each specific heat exchanger design. Also when we want to assign a VGHX for a heat pump in EnergyPlus, parameters such as maximum flow rate, number of bore holes, borehole length, ground thermal conductivity, ground thermal heat capacity, ground temperature, design flow rate, grout thermal conductivity, pipe thermal conductivity, pipe out diameter, U-tube distance, pipe thickness and g-function reference ratio should be defined.

RESULTS AND ANALYSIS

A whole building simulation model was developed using EnergyPlus for a case study house. The GSHP model was based on the equation fit model of a water-to-air heat pump. The simulated amount of electricity usage in the building was compared to the measured data from the house's utility bills. Figure 7 shows the comparison between the monthly utility bill data for the year 2012 and the EnergyPlus simulation results.

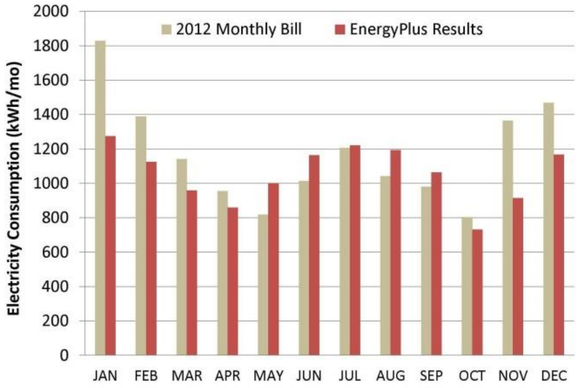

Figure 7Monthly electricity consumption comparison between billed data and simulation results

The difference between EnergyPlus results and measured data could be due to various parameters such as different weather conditions, diverse occupancy, lighting and equipment schedule, and dissimilar building's material. The significant discrepancy between electricity consumption of the real building and EnergyPlus model during cold months might be due to the behavior of the occupant during the winter months. Turning off the heat pump during the daytime while the occupants are out increases the use of supplemental heating which causes to excessive electricity consumption. Whereas in the EnergyPlus simulation process, the GSHPs consistently maintained the room temperature within comfort conditions, and so the supplemental heating was either unnecessary or much less needed than real case. EnergyPlus also uses the Typical Meteorological Year (TMY) data which is a collation of selected weather data for a specific location, generated from a data bank. However, the measured data were based on the 2012 actual weather condition. Figure 8 shows the differences between the TMY 3 weather data in EnergyPlus and the specific 2012 weather data.

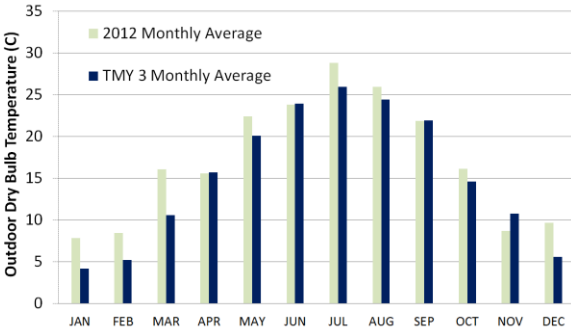

Figure 8 Temperature differences between the TMY 3 data in EnergyPlus and 2012 actual weather data

There were some advantages indicated from using the GSHP function in EnergyPlus such as: 1) available reference data sets, containing examples of input data for 1x2, 4x4 and 8x8 configurations of GHXs which can be used in some residential cases without complicated calculation, 2) reference models for VGHX, pond heat exchanger and surface heat exchanger, 3) reasonable simulation time for a medium size residential house, and 4) the ability of adding relatively reasonable ground temperatures and modeling the GSHP system in most of the buildings. However, there were also challenges and issues that need to be resolved and facilitated in the modeling process of GSHP systems such as: 1) the g-function values to be calculated for each specific heat exchanger design in other GHX simulation tools for better accuracy. 2) lack of horizontal heat exchanger model in EnergyPlus, 3) to obtain the accurate ground temperature, modelers need additional tools, and 4) more validation works needed with real buildings.

CONCLUSION

A comprehensive literature review on GSHP technology applications in buildings was presented. Several widely used computer simulation programs for building energy analysis are compared regarding their GSHP simulation capabilities. A residential house (Apex House) was used for a case study to test the EnergyPlus' functionality of modeling the GSHP systems. The simulation results were compared to the monthly bill data to quickly investigate its capability and applicability for engineering practices. The potential problems and barriers of modeling the GSHP systems in whole-building simulation analyses were addressed. The detailed simulation processes and simulation results will also be presented in the near future.

REFERENCES

Al-Khoury, R., Bonnier, P. G., & Brinkgreve, R. B. J. (2005). Efficient finite element formulation for geothermal heating systems. Part I: Steady state. International journal for numerical methods in engineering, 63(7), 988-1013

Bernier, M. A. (2001). SYMPOSIUM PAPERS-AT-01-8 Pumping Design and Performance Modeling of Geothermal Heat Pump Systems-Ground-Coupled Heat Pump System Simulation. ASHRAE Transactions-American Society of Heating Refrigerating Airconditioning Engin, 107(1), 605-616.

Bose, J. E. (1984). Closed-loop ground-coupled heat pump design manual. The University.

Bose, J. E. 1988. Closed-Loop/Ground-Source Heat pump Systems: Installation Guide, International Ground Source Heat Pump Association, Stillwater, OK.

Carslaw, H., & Jaeger, J. (1947). Heat Conduction in Solids. Oxford: Claremore Press.

Carslaw, H. S., & Jaeger, J. C. (1959). Conduction of heat in solids. Oxford: Clarendon Press, 1959, 2nd ed., 1.Chiasson, A., & O'Connell, A. (2011). New analytical solution for sizing vertical borehole ground heat exchangers in environments with significant groundwater flow: Parameter estimation from thermal response test data. HVAC&R Research, 17(6), 1000-1011.

Crawley, D. B., Hand, J. W., Kummert, M., & Griffith, B. T. (2008). Contrasting the capabilities of building energy performance simulation programs. Building and Environment, 43(4), 661-673

Center, F. S. E. (1999). EnergyGauge USA: A Residential Building Energy Simulation Design Tool

DOE, U. (2010). EnergyPlus Input Output Reference. US Department of Energy, April.

Do.S.L. , Haberl. J. S. (2010). A Review of ground coupled heat pump models used in whole-building computer simulation programs. Department of Architecture, Texas A&M University.

Deerman, J. D., Kavanaugh, S. P. (1991). Simulation of Vertical U-Tube Ground Coupled Heat Pump Systems Using the Cylindrical Heat Source Solution. ASHRAE Transactions 97(1): 287-295.

Ellis, P. (2009). OpenStudio plugin for Google SketchUp3D, Version 1.0, January 2009.

EnergyPlus, U. D. (2011). EnergyPlus Energy Simulation Software. Energy Efficiency & Renewable Energy, US Department of Energy.

Eskilson P.(1987),Thermal analysis of heat extraction boreholes. Ph.D. thesis. Sweden:University of Lund.

Fairey, P., Vieira, R. K., Parker, D. S., Hanson, B., Broman, P. A., Grant, J. B., ... & Gu, L. (2002). EnergyGauge USA: A residential building energy simulation design tool.

Florides, G., & Kalogirou, S. (2007). Ground heat exchangers—A review of systems, models and applications. Renewable Energy, 32(15), 2461-2478.

Granryd E. G.(1979).Ground source heat pump systems in a northern climate. 15th IIR Congress, Venice Paper no. E1-82

Hart, D. P., & Couvillion, R. (1986). Earth coupled heat transfer. Publication of the National Water Well Association.

He, M., Rees, S., & Shao, L. (2009, July). Simulation of a domestic ground source heat pump system using a transient numerical borehole heat exchanger model. In Eleventh International IBPSA Conference

Hellström, G. (1989). Duct ground heat storage model, Manual for Computer Code. Department of Mathematical Physics, University of Lund, Sweden.

Hellström, G. (1991). Thermal analysis of duct storage system. Dep. of Mathematical Physics University of Lund, Lund, Sweden, 262

Hellström, G., & Sanner, B. (1994). Earth energy designer: software for dimensioning of deep boreholes for heat extraction. Department of Mathematical Physics, Lund University, Sweden.

Hellström, G., & Sanner, B. (2001). PC-programs and modelling for borehole heat exchanger design. Proceedings of International Geothermal Days. www. info. hotims. com/30917, 15.

Hirsch, J. J. (2006). eQuest, the QUick Energy Simulation Tool. DOE2. com.

Ingersoll LR, Plass HJ.(1948), Theory of the ground pipe source for the heat pump. ASHRE Trans ;54:339–48.

Ingersoll LR, Zobel OJ., Ingersoll AC. (1954). Heat conduction with engineering, geological, and other applications. New York: McGraw-Hill.

Jin, H., & Spitler, J. D. (2002). A parameter estimation based model of water-to-water heat pumps for use in energy calculation programs. ASHRAE Transactions, 108(1), 3-17.

Kavanaugh, S. P. (1985). Simulation and experimental verification of vertical ground-coupled heat pump systems. Oklahoma State Univ., Stillwater (USA).

Kavanaugh, S. P., (1992). Field Test of a Vertical Ground Coupled Heat Pump in Alabama. ASHRAE Transactions

Kavanaugh, S. (1995). A design method for commercial ground-coupled heat pumps. TRANSACTIONS-AMERICAN SOCIETY OF HEATING REFRIGERATING AND AIR CONDITIONING ENGINEERS, 101, 1088-1094

Kavanaugh, S. P., & Rafferty, K. 1997, Ground-Source Heat Pumps: Design of Geothermal Systems for Commercial and Institutional Buildings. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Kelvin, Sir W. Thomson. 1882. Mathematical and Physical Papers, II, pp. 41ff., cited by Ingersoll et al.(1954)

Klein, S. et al. (1990). TRNSYS: A transient simulation program – version 13.1. Solar Energy Laboratory, University of Wisconsin, Madison, USA.

Lamarche, L., & Beauchamp, B. (2007). A new contribution to the finite line-source model for geothermal boreholes. Energy and Buildings, 39(2), 188-198.

Lamarche, L., Kajl, S., & Beauchamp, B. (2010). A review of methods to evaluate borehole thermal resistances in GHP systems. Geothermics, 39(2), 187-200.

Li, M., & Lai, A. C. (2012). New temperature response functions (G-functions) for pile and borehole ground heat exchangers based on composite-medium line-source theory.

Liu, X., & Hellström, G. (2006). "Enhancements of an integrated simulation tool for ground-source heat pump system design and energy analysis". Proceedings of Ecostock 2006, The Richard Stockton College of New Jersey.

Marcotte, D., & Pasquier, P. (2008). Fast fluid and ground temperature computation for geothermal ground-loop heat exchanger systems. Geothermics, 37(6), 651-665.

Man, Y., Yang, H., & Wang, J. (2010). Study on hybrid ground-coupled heat pump system for air-conditioning in hot-weather areas like Hong Kong. Applied Energy, 87(9), 2826-2833.

Mei, V. C., & Emerson, C. J. (1985). New approach for analysis of ground-coil design for applied heat pump systems. ASHRAE Trans.;(United States), 91(CONF-850606-).

Muraya, N. K. (1994). Numerical modeling of the transient thermal interference of vertical U-tube heat exchanges (Doctoral dissertation, Texas A&M University).

Muraya, N. K., O'Neal, D. L., & Heffington, W. M. (1996). Thermal interference of adjacent legs in a vertical U-tube heat exchanger for a ground-coupled heat pump. ASHRAE Transactions, 102(2), 12-21.

Rawlings RHD, Sykulski JR.(1999), Ground source heat pumps: a technology review. Build Serv Eng Res Technol ;20(3):119–29

Remund, C. P. (1999). Borehole thermal resistance: laboratory and field studies. Transaction American Society of Heating Refrigerating and Air Conditioning Engineers, 105, 439-445

Rottmayer, S. P., Beckman, W. A., & Mitchell, J. W. (1997). Simulation of a single vertical U-tube ground heat exchanger in an infinite medium. ASHRAE Transactions, 103(2), 651-659.

Shonder, J. A., & Beck, J. V. (1998). Determining effective soil formation thermal properties from field data using a parameter estimation technique (No. ORNL/CP--99428; CONF-990102--). Oak Ridge National Lab., TN (United States).

Spitler, J. D., Yavuzturk, C., & Rees, S. J. (2000). In situ measurement of ground thermal properties. In Proceedings of Terrastock (Vol. 1, pp. 165-170).

Spitler, J. D. (2000, August). GLHEPRO-A design tool for commercial building ground loop heat exchangers. In Proceedings of the fourth international heat pumps in cold climates conference, Aylmer, Québec (pp. 17-18)

Spitler, J. D. (2007). GLHEPro 4.0 for Windows users guide. School of Mechanical and Aerospace Engineering, Oklahoma State University.

Spitler, J. D., Cullin, J., Bernier, M., Kummert, M., Cui, P., Liu, X., ... & Fisher, D. (2009, June). Preliminary intermodel comparison of ground heat exchanger simulation models. In Proceedings of 11th International Conference on Thermal Energy Storage (pp. 14-17). Stockholm.

Sutton, M. G., Couvillion, R. J., Nutter, D. W., & Davis, R. K. (2002). An algorithm for approximating the performance of vertical bore heat exchangers installed in a stratified geological regime. Ashrae Transactions, 108(2), 177-184.

Thornton, J. W., McDowell, T. P., Shonder, J. A., Hughes, P. J., Pahud, D., & Hellstrom, G. A. (1997). Residential vertical geothermal heat pump system models: calibration to data. ASHRAE Transactions, 103, 660-674.

Wetter, M., & Huber, A. (1997). TRNSYS Type: Vertical Borehole Heat Exchanger, EWS Model. Zentralschweizerisches Technikum ZTL, Luzern.

Wirth P. E .,(1955), History of the development of heat pumps , SchzLeiz Bauzeits,73(42) 47-51

Winkelmann, C., B. Birdsall, W. Buhl, K. Ellington, and A. Erdem. (1993). DOE-2 supplement, version 2.1E. LBL-34947. Berkeley, CA: Lawrence Berkeley Laboratory.

Xu, X. (2007). Simulation and optimal control of hybrid ground source heat pump systems. ProQuest.

Yang, H., Cui, P., & Fang, Z. (2010). Vertical borehole ground-coupled heat pumps: A review of models and systems. Applied energy, 87(1), 16-27

Yavuzturk, C. (1999). Modeling of vertical ground loop heat exchangers for ground source heat pump systems (Doctoral dissertation, Oklahoma State University).

Yavuzturk, C., & Spitler, J. D. (1999). A short time step response factor model for vertical ground loop heat exchangers. Ashrae Transactions, 105(2), 475-485.

Young, T. R. (2004). Development, verification, and design analysis of the borehole fluid thermal mass model for approximating short term borehole thermal (Doctoral dissertation, Oklahoma State University).

Zeng, H., Diao, N., & Fang, Z. (2003). Heat transfer analysis of boreholes in vertical ground heat exchangers. International Journal of Heat and Mass Transfer, 46(23), 4467-4.