Latest Developments and Trends in Ground-Source Heat Pump Technology

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Keywords: ground-source heat pumps, geothermal heat pumps, ground heat exchangers.

ABSTRACT

Ground-source heat pump (GSHP) systems are one of the most widespread "green" technologies for heating and cooling of buildings. According to Lund and Boyd (2016) the installed heating capacity of GSHP systems is over 50 GW and the annual heating production is over 90 TWh/year. Over the 5-year period, 2010-2015, the growth rate measured in terms of capacity was 52% and in terms of heating provided, it was 63%. This paper and the accompanying presentation attempt to give an overview of the current state-of-the-art, latest developments and trends in GSHP system technology.

1. INTRODUCTION

Kelvin (Thomson 1853) proposed the heat pump in 1852, suggesting air as a working fluid. Zoelly (1912) patented a ground-source heat pump but the first report of a groundwater heat pump was that of T.G.N. Haldane (1930) who installed a residential system at his home in Perthshire, Scotland. In the 1930s and 1940s, several large scale (100-235 kW heating capacity) systems using rivers or groundwater as the sources were developed. Then, after the Second World War, there was quite a bit of interest and development of mainly residential scale ground-source heat pump systems in the USA. By the mid-1950s though, most of this work had been abandoned due to problems with leakage of buried metal tubing and problems related to improper-sizing of the ground heat exchanger.

In the 1970s though, there was a resurgence of research interest in the USA and Sweden. Some of the early work in Oklahoma looked at a range of ground heat exchanger configurations and materials, but after problems with leakage and performance, the grouted single U-tube made of HDPE emerged as the best/most reliable design. Since that time, development of GSHP technology has proceeded, albeit in an incremental fashion.

In this paper and the accompanying talk, I will discuss the current state-of-the-art, current developments and future possibilities for five aspects of GSHP systems:

- System components including ground heat exchangers.
- Design, Simulation and Integration
- Site Characterization
- Control and Operation
- New Applications

For every aspect, the general market driving forces lead development in the direction of reducing first cost and/or improving performance.

2. SYSTEM COMPONENTS

A GSHP system requires, at a minimum, a ground heat exchanger, a water-to-air or water-to-water heat pump, a circulating pump to move heat on the ground-side, and a fan or pump to move heat on the building-side. Fans and pumps on both sides may be integrated with the heat pump unit. The heat pump(s) may be centrally located for the building with a sophisticated distribution system to control temperatures around the building, or, as is common in North America, the heat pumps may be distributed around the building. Of all the components, the main emphasis of published research continues to be the ground heat exchanger.

2.1 Borehole Heat Exchangers

The higher cost of ground-source heat pump systems is usually attributed to the cost of the ground heat exchanger, though the cost of the ground heat exchanger relative to the total system cost is highly variable. Based on cost data for about 140 residential and commercial installations in the USA, the ground heat exchanger costs make up between 20% and 60% of the total system cost. So, while the importance of the ground heat exchanger cost is highly variable, it can be quite significant and the perception that it is the dominant cost component has led to many, many attempts to develop a better borehole heat exchanger that will lead to lower costs.

In the early 1990s, the standard technology in the USA utilized a single HDPE U-tube surrounded by bentonite grout. Since that time, several types of performance improvements have been made: increased thermal conductivity grout, and HDPE pipe, "rifled" pipe to enhance the convective heat transfer inside the pipe, and spacers to push the two legs of the U-tube towards the edge of the borehole. With the exception of the spacers, the other improvements can be adopted with little penalty in installation time. According to the manufacturer of the "rifled" pipe (Muovitech) the chief advantage of the internal enhancements is to maintain turbulent flow at lower Reynolds numbers, which gives a lower borehole thermal resistance while pumping power is decreased.

Figure 1 shows (as a line) the change over time of thermal conductivity of commercially available grouts). The bars represent the required borehole depth for one case: a 3-story office building in Tulsa, Oklahoma, with a 36-borehole ground heat exchanger. The individual boreholes are 110 mm in diameter and the ground thermal conductivity is 2.4 W/m·K. Available grout thermal conductivity has increased, resulting in lower required ground heat exchanger length. The last two columns show further improvements – thermally-enhanced HDPE pipe and spacers. Using the highest available thermal conductivity grout and enhanced HDPE pipe, but not spacers, gives a 27% savings in required depth compared to the standard bentonite grout. Adding spacers significantly increases the installation time, but only gives a further reduction of 3% in required depth.

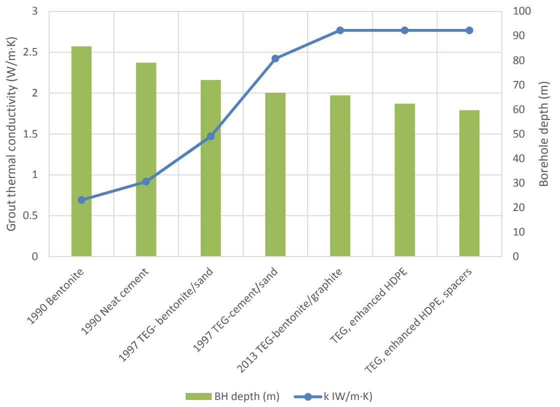

Figure 1: Effects of improvements in grout thermal conductivity, enhanced HDPE pipe and spacers on required borehole depth.

There have been and continue to be numerous attempts at developing improved borehole heat exchanger configurations, including double U-tubes (which have received a significant amount of market penetration), triple U-tubes arranged in a spiral configuration, co-axial heat exchangers, and "spider" designs with a single tube in one direction and multiple smaller tubes in the other direction. Many such designs can actually decrease the borehole thermal resistance. However, installation time and hence installation cost can be significantly higher than the single U-tube. (And we can include the single U-tube with field-installed spacers in this category.) Furthermore, pressure drop may be excessive in some designs. But, the jury is still out, and independent testing with publication in the peer-reviewed literature is really needed.

So, while there is ample room for innovation with improved designs, the near-term state of the art might be represented by a single U-tube combined with an easily deployable spacing system, thermally-enhanced bentonite (with graphite) grout, and thermally-enhanced HDPE with turbulence-promoting interior surface features. Such a ground heat exchanger would satisfy most of the performance demands: low borehole thermal resistance; low pressure drop; low short-circuiting, fast and low-cost installation, sufficient environmental protection, readily transportable to job site, and capable of withstanding collapse due to external pressures. (The risk of collapse due to external pressures is increased with non-round pipe.)

2.2 Other Ground Heat Exchangers – Piles, etc.

Beyond borehole heat exchangers, thermal piles and ground heat exchangers that are installed in relatively shallow augured holes are relatively recent developments. Most of the work to date (Bourne-Webb et al. 2016) on thermal piles has addressed fundamental problems of analysis of pile heat exchangers; the design problem for thermal piles is quite different from borehole heat exchangers where placement and depth are controlled by the thermal design. In the case of thermal piles, the placement and depth are controlled by the structural design, so the design question is more related to what contribution the piles can make to the thermal source/sink needs of the building. Design tools that can adequately address this question are yet to be developed. Also, as in the case of borehole heat exchangers, the time needed to install heat exchanger tubing in a standard pile may be problematic. Further research and field experience is needed to establish acceptable best practices.

2.3 Deep Boreholes

Deep boreholes are of interest for some applications. While the definition of deep is highly variable, in the USA, boreholes that exceed more than about 100 m in depth might be considered deep. On the other hand, in Sweden, the average depth of boreholes has steadily increased since the mid-1990s, and as of 2013 was 171 m. (Gehlin et al. 2016) In some geologies deeper boreholes can be less expensive per unit length than shallower boreholes. There are a number of issues that complicate design of ground heat exchangers for deep boreholes, including grouting procedures for avoiding pipe collapse, maintaining satisfactorily low pressure drop, limiting of short-circuiting effects and advantages/disadvantages of ground temperatures at deeper depths.

2.4 Heat Pumps

Rated efficiencies of ground-source heat pumps have increased since they were introduced to the market in the 1980s. However, as discussed by Corberan (2016), on-off ground-source heat pumps have cycling losses and standby losses due to electronic control boards and valves that remain energized when the compressor is off. These losses are small, but standby losses degrade the system performance when the run-time fraction is low. (It should be noted that these same losses may also affect variable-speed heat pumps.) Research aimed at reducing the standby losses may be particularly useful for increasing off-peak-season performance.

3. DESIGN, SIMULATION, INTEGRATION

A GSHP system is more than simply a ground-source heat pump and ground heat exchanger. No matter how high the rated performance of the installed heat pumps, the system performance depends on all of the components and how they are integrated into a system. Problems resulting when high-performance components are combined into a poor-performing system are sometimes called system integration effects. Presumably, these problems are usually due to flaws in the system design, though they may also be caused by installation errors and field substitutions. The most common problems are undersizing or oversizing of the ground heat exchanger, leading to poor performance or excessive first cost, and excessive electricity consumption due to poor hydraulic design. (That would include both excess pressure drop due to small pipes or control valves and pumping configurations that cannot adequately adjust to the system flow requirements.)

Therefore, design tools are an important part of achieving energy-efficient and cost-effective designs. Recent developments have increased the flexibility of design tools and confirmed their validity but additional work is needed.

3.1 Design Tools

Simulation-based design tools have relied primarily on libraries of g-functions originally developed by Claesson and Eskilson (Eskilson 1987). One of these tools has been shown (Cullin et al. 2015) for a limited number of field measurements to give reasonably accurate ground heat exchanger sizes when the loads on the ground heat exchanger are known. Figure 2 summarizes the results of the validation study.

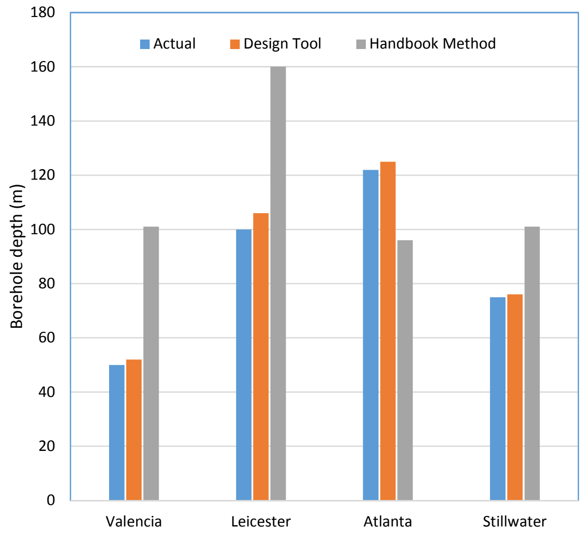

Figure 2: Actual and predicted borehole depths.

However, these four cases represent measurement periods at the longest of only six years and all of the ground heat exchangers have reasonably balanced annual heat extraction and rejection, so there is no case where long-term heat build-up or draw-down is a problem. Validation against additional field measurements is highly desirable. However, the general requirement that measurements of temperatures and heat extraction and rejection be made continuously for a number of years has limited the availability of acceptable data sets.

Reliance on libraries of g-functions limits the applicability of the design tools for some real-world cases where site constraints or drilling problems require deviation from library configurations. Simpler finite line source methods (Marcotte and Pasquier 2009, Claesson and Javed 2011) can be used for cases with smaller numbers of boreholes that are not too densely packed (Malayappan and Spitler 2013) and are fast enough to be used for custom configurations within a design tool. However, more broadly applicable methods capable of handling uniform borehole wall temperature boundary conditions while being fast enough to calculate g-functions within the design tool are needed. And, for that matter, further investigation of the best boundary conditions is also needed. Claesson and Eskilson used the uniform borehole wall temperature and this is usually regarded as being closer to the actual condition than uniform heat flux boundary conditions. But the actual situation is different and further investigation is warranted.

Design tools also rely on methods for estimation of borehole thermal resistance. For grouted boreholes with single or double U-tubes, the variable-order multipole method (Claesson and Hellström 2011) is highly accurate, though non-trivial to implement. Javed and Spitler (2016) have reviewed a number of the simplified approximations and the closed-form lower-order multipole expressions give the best performance. For groundwater-filled boreholes, it has been shown experimentally and computationally (Gustafsson and Gehlin 2008, Gustafsson et al. 2009, Gustafsson and Westerlund 2010) that the natural convection in the borehole leads to borehole thermal resistances that vary with borehole temperature and heat flux rate. Only recently, though, have convection correlations for single U-tubes in groundwater-filled boreholes (Spitler et al. 2016) been published. Correlations for other geometries are still needed.

3.2 Improving Pump Energy Consumption

A common problem for GSHP systems is excess electrical energy consumption by the circulating pumps due to poor hydraulic design. This includes specifying a non-optimal, overly high flow rate; using U-tubes of too small a diameter; using unnecessary control valves (or choosing a design that requires control valves when an alternative is available); or operating a central circulating pump on a 24-7 basis instead of shutting it off when it is not needed. The energy used for circulating fluid between the ground source heat pumps and the ground heat exchanger is often erroneously considered to be negligible. While it can represent a fairly small portion of the total energy consumed, too many GSHP systems have been found to have excessive pumping energy. While the problem may be exacerbated in distributed heat pump systems as used in North America, there is plenty of anecdotal evidence for excessive pumping energy problems in Europe.

Kavanaugh (EPRI 2012) surveyed 40 systems with distributed heat pumps serving: 27 schools, 5 office buildings, 3 houses, and 5 miscellaneous buildings (senior care facility, courthouse, restaurant, credit union, and laboratory). Although this is a limited sample relying on utility metering data, systems relying on a single central circulating pump with a variable-speed drive generally performed poorly. Systems with unitary loops, one-pipe central loops with both a central pump and distributed pumps, and common loops with distributed pumps generally performed better.

Another problem that sometimes occurs is excessive pressure drop in the ground heat exchanger or internal distribution network. This can lead to high pump energy consumption with any pumping configuration.

3.3 Optimization of Flow Rates

Closely related to pump energy consumption is choosing flow rates that give the maximum or near maximum system coefficient of performance or EER. As the flow rate to the heat pump increases, the heat pump COP or EER will increase, but the pumping power will also increase, decreasing the system COP or EER. As a result of the two countervailing trends, the system COP will have a maximum at some flow rate. In larger systems with multiple distributed heat pumps, it may not be possible to closely control the flow rate to each heat pump; it is common to control the pump speed to maintain a constant pressure differential (ΔP) across the heat pumps. In this case, increasing the ΔP setting will increase the flow of all the heat pumps. What should the optimal setting be?

The ASHRAE headquarters building (Southard et al. 2014a, b) was intended to serve as a showcase for energy-efficient heating and cooling technologies; it received both an Energy Star rating and a LEED Platinum rating. Its GSHP system relies on a central circulating pump with a variable speed drive but nevertheless gives good performance. One feature of this system is that the central circulating pump is turned off when all of the heat pumps are off. This feature seems to be frequently omitted in central circulating pump systems. Even with this feature, the system as installed had significant room for improvement, as can be seen in Figure 3.

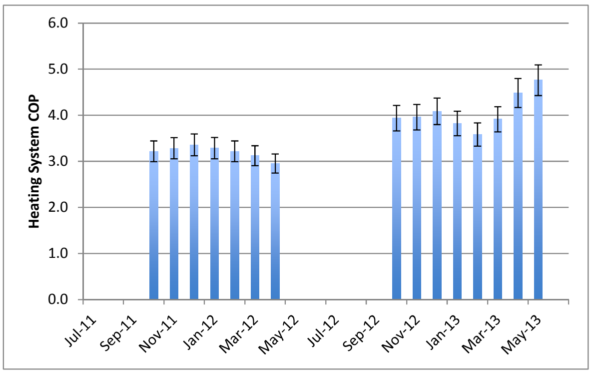

Figure 3: Improved system COP with differential pressure control set-point change.

The monthly heating system COPs increased significantly from one heating system to the next due to one simple change in the building controls– the ΔP setting was reduced from 138kPa to 55kPa. This setting controls the flow rate to each heat pump and has a significant effect on the pumping energy and, hence, the system COP.

It is one thing to observe that too many GSHP systems have pumping energy requirements that are higher than desirable and another thing to change the culture of system design to make these problems rare. Detailed comparisons of GSHP pumping systems that measure both pumping energy and heat pump energy over short time intervals would be useful to better evaluate different hydraulic system designs. More comprehensive design tools that could evaluate the effects of different hydraulic system designs and other design decisions on system COP would also be useful. At present, a minimal first step would be to make sure any system does not violate Mescher's maxim (ASHRAE 2011) that the borefield pressure loss should be no greater than 75 kPa and the total system pressure loss should be no more than 150 kPa.

4. SITE CHARACTERIZATION

G.S. Smith (1951) observed "The introduction of the heat pump in the field of space heating has created a demand for information not generally available." When the second wave of ground-source heat pump development led to design tools in the 1980s, it soon became apparent that a method for determining effective ground thermal conductivity was needed. (Spitler and Gehlin 2015) This led to the development of in situ methods for measuring the ground thermal conductivity in the mid-1990s and it is now common practice to make an in situ measurement (also known as a thermal response test or "TRT") prior to completing the ground heat exchanger design for larger commercial buildings.

Research developments since the mid-1990s have shown that additional information can be garnered from thermal response tests. E.g. multiple injection rate tests (Gustafsson and Westerlund 2010, Witte 2016) and tests involving heat extraction and injection can provide more information about groundwater flow and convection. Distributed thermal response tests (Acuña 2013) can provide additional information about the distribution of thermal conductivity and groundwater flow. At present, design tools cannot make good use of this information, but further developments may allow ground heat exchangers to be reduced in size in geologies with layers of varying thermal conductivities.

The other trend in thermal response testing is the development (Raymond et al. 2015, Verdecchia et al. 2016) of less expensive, more automated and more convenient test rigs.

5. CONTROL AND OPERATION

A typical residential GSHP system may offer little opportunity for improving the controls beyond the internal controls within the heat pump. However, as commercial systems get more complicated, particularly with hybrid GSHP systems including auxiliary heat sinks or sources, there are more opportunities to improve the system performance by optimizing the controls. (Atam and Helsen 2016a, b) have reviewed the literature related to challenges in modeling and optimal control of GSHP systems and the corresponding challenges in design. Optimal controls, optimal operation, and optimal design are all necessarily related, though the interaction between the three is not well understood.

Atam and Helsen (2016a) review approaches to control of hybrid GSHP systems. The chief question is when to operate the auxiliary heat sink device (e.g. a cooling tower). Should it be operated to try and prevent the heat pump entering fluid temperature from exceeding a set-point? Should it attempt to make an annual balance on the heat extraction and heat rejection? These include rule-based approaches, dynamic programming, model predictive control and extremum seeking controls.

Early work (Yavuzturk and Spitler 2000) utilized simulation studies to recommend simple rule-based controls. Hackel et al. (2009) optimized design and control strategies for individual systems. Hamstra (2014) described an adaptive/predictive control that is now commercially-available.

6. NEW APPLICATIONS

Sections 2-5 above address use of GSHP systems in more-or-less conventional buildings. Another category of new developments is related to near-zero-energy buildings (NZEB) and "energy flexible" buildings – buildings that are intended to facilitate use of intermittent renewable energy by making use of storage and alternative heating or cooling systems to allow the load-side demand to be shifted. NZEB may also be energy flexible – if one is relying on electricity produced by building-mounted photovoltaic panels, it is quite useful to have storage. GSHP systems are highly desirable for NZEB – photovoltaic-generated electricity can readily be consumed on-site with a very high efficiency heating/cooling system. And, no combustion air is required, so fewer building envelope perforations are needed.

There are several ongoing projects looking at use of GSHP in near zero energy buildings. Two case studies are underway in Switzerland (Wemhoener 2016) and Sweden (Haglund Stignor 2016), but results are not yet published. Berggren et al. (2012) reported on a case study of a Swedish NZEB with geothermal heat pumps, but the paper did not cover the GSHP system performance.

Two recent papers have looked at the advantages of combining photovoltaic-thermal (PVT) collectors – solar collectors that produce electricity and thermal energy – with GSHP systems. Besides recharging the ground in cold climates, the cooling of the photovoltaic panels improves the efficiency of producing electrical energy. Brischoux and Bernier (2016) report on a simulation-based study which uses double U-tube borehole heat exchangers, with one U being connected to the heat pump and the other U connected to the PVT collector. The single borehole used in the study limited the possibilities for seasonal storage of heat, so further investigation with a larger storage-oriented system was recommended.

Gervind and Benson (2016) report on an actual system installation serving 70 terraced houses on the West coast of Sweden. In this system, the heat from the PVT collectors can be used directly as a heat pump source or to recharge the boreholes. The boreholes are too far apart (15 m) to function effectively as a seasonal storage system, but the summer recharge can prevent any year-to-year decrease in the ground temperature.

Thygesen (2016) reports on a study of GSHP systems combined with photovoltaic or solar thermal collectors with an eye towards maximizing self-consumption (Luthander et al. 2015) of the photovoltaic-generated electricity. Storage of heat generated using excess photovoltaic electricity was a better (more cost-effective) option than battery storage of electricity.

In countries with a high fraction of electrical energy generated by renewable technologies (especially wind and photovoltaics) it is highly desirable to have building systems that can moderate their load through the use of on-site storage. Esfehani et al. (2016) report on a case study of a system in Berlin that incorporates on-site thermal energy storage in the form of a hot water tank. This is part of an ongoing research project aimed at optimizing the system.

7. CONCLUSIONS

There are numerous developments in GSHP system technology around the world. These represent an interesting mix of incremental improvements, more powerful and flexible design tools, and innovative applications. There is significant room for further improvements. A noticeable need is more widespread understanding of best practices that would lead to improved system performance with lower pumping energy consumption.

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ACKNOWLEDGEMENTS

This paper and talk draws on previous collaboration with Dr. Signhild Gehlin of the Svenskt Geoenergicentrum. Her assistance is gratefully acknowledged.