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1. Executive Summary

ClimateMaster, the applicant, was the lead for a group of world known experts from ClimateMaster (CM), James J. Hirsch and Associates (JJH) and Oak Ridge National Laboratory (ORNL) to enhance the simulation capacity of eQUEST and make it a more powerful tool for performing energy analysis and optimizing the design of geothermal heat pump (GSHP) systems.

In 2006, as a cooperative effort between CM and JJH (the developer of eQUEST), eQUEST capabilities were expanded to include simulation of conventional GSHP systems comprised of water-to-air heat pump units, horizontal or vertical ground loop heat exchangers (GLHX), and lakes or wells. However, eQUEST did not model hybrid systems, such as the combination of a fluid cooler in series with a GLHX. Nor was it capable of simulating water-to-water heat pumps coupled to a horizontal or vertical GLHX. As a result, significant opportunities were being missed, as hybrid and/or water-to-water GSHP system applications may prove to be a cost effective solution in many situations.

The objective of this project was to expand eQUEST to simulate the most common hybrid and/or water-to-water geothermal heat pump configurations. With the addition of these new capabilities, eQUEST can better enable prospective GSHP system customers to analyze the cost and performance of a variety of GSHP system applications. As such, it will serve as a powerful tool for use in purchasing and design decisions. It will thus be very helpful to meet the objectives of DOE to expand the commercialization of GSHP technologies.

Project activities were initially led by Dr. Xiaobing Liu, PI, ClimateMaster (Systems Engineering Manager). Mid-project, Dr. Liu took a new position at Oak Ridge National Laboratory, and was replaced by Shaojie Wang at ClimateMaster. Wang, Liu, and their project partners at JHH and ORNL implemented the following highly desired features into eQUEST:

- Simulation of ground coupled water-to-water heat pump systems
- Full multi-year simulations for conventional GSHP and hybrid GSHP systems
- Models of common hybrid GSHP system configurations

The enhanced eQUEST, training materials, and manuals are provided to the public free of charge and will thus support increased deployment of GSHP systems to all consumers. These enhancements support the goals of the DOE and the ARRA to engage American engineers, technicians, customers, and installers in the increased implementation of energy efficient geothermal technologies. All goals and objectives of the project were met, as described in section 3.

2. Background

eQUEST is a widely accepted building and HVAC system energy analysis tool that is powered with the latest implementation of the DOE-2.2 building energy simulation program. Approximately 20 years ago, the DOE-2 simulation engine was enhanced to simulate conventional geothermal heat pump (GSHP) systems. The systems supported consisted of:

- Water-to-air heat pump units,
- A water loop distribution system consisting of piping, pumps, and controls

- Horizontal or vertical ground loop heat exchangers (GLHX) to accept or reject the heat imbalance that arises between those heat pump units operating in the heating mode vs. those operating in the cooling mode.
- As an alternative to a ground loop heat exchanger, the water loop could be coupled to a lake or well

The original implementation of the GLHX simulation capability (horizontal trenches and vertical well fields) was based on algorithms developed by R. Merriam of Arthur D. Little, and ported into DOE-2 by James Hirsch and Steven Gates in 1995. In 2006, the vertical well field model was replaced with a more accurate model based on G-functions. The G-function formulation is based upon work by Claesson (1987), Eskilson (1987), Hellstrom, .et.al. (1978) at the University of Lund in Sweden, and Spitler, .et.al. (1999) at Oklahoma State University. Their algorithm was enhanced and adapted to DOE-2 by Xiaobing Liu of ClimateMaster.

While powerful, the DOE-2 GLHX algorithms were missing several features that limited their usefulness:

- <u>Simulation of water-to-water heat pumps</u> – While water-to-air heat pumps (zonal DX units coupled to a water loop) are the most common configuration, many systems utilize water-to-water heat pumps supplying 2-pipe fan coils. In DOE-2, water-to-water heat pumps existed, but were restricted to lakes or wells; coupling to ground loop heat exchangers was not supported.
- <u>Multi-year simulation of GLHX systems</u> – While DOE-2 could simulate a building and its HVAC systems on an hourly basis for an entire year, it was not capable of multi-year

simulations. However, the thermal performance of a GLHX can vary drastically over the course of its lifetime, as a net annual heating/cooling imbalance may build up over the years. DOE-2 incorporated an approximate method to account for the history of the prior years' thermal imbalances, but the approach used had major shortcomings.

- Simulation of hybrid systems – As the GLHX industry has matured, it has become increasingly evident that many projects have a net annual heating/cooling imbalance sufficiently large that it can severely impact GLHX performance over its lifetime. Either the GLHX must be sized considerably larger (possibly at considerable expense), or supplemental cooling towers and/or boilers must be incorporated to mitigate the net annual thermal imbalance. The use of supplemental equipment in conjunction with a GLHX is termed a hybrid system. DOE-2 did not have the capability of simulating hybrid GLHX systems.

The objective of this project was to expand eQUEST to simulate the most common hybrid and water-to-water geothermal heat pump configurations. With the addition of the proposed new capabilities, eQUEST is now an integrated modeling tool that enables prospective GSHP system customers to analyze the cost and performance of a variety of GSHP system applications. As such, it should serve as a powerful tool for use in purchasing and design decisions.

3. eQUEST Tasks

The enhancements enumerated in the following tasks were made to the eQUEST user interface and the DOE-2 simulation engine in this project.

DOE-2.3 Implementation Comments:

- The eQUEST graphical user interface and its DOE-2 simulation engine are computer programs comprising hundreds of thousands of lines of code. The DOE-2 engine has been in continuous development over the last 40 years, starting with the original CalERDA program, and progressing through DOE-1.0 to DOE-2.2, and now DOE-2.3. The tasks in this project were implemented in the newest version, DOE-2.3, which is being released as a beta on the DOE2.com website. DOE-2.3 is still in development, with additional non-GLHX features still being added at this time. A new version of eQUEST has been developed to work with DOE-2.3, eQUEST-3.70 (eQUEST-3.65 is the current standard release and utilizes DOE-2.2).
- All DOE-2.3 source code is available on the DOE-2 website. Not surprisingly, while much of this code is necessary for the new GLHX algorithms to run, most of the existing algorithms are not directly related to GLHX systems, and so are not relevant to this report. To document work done as part of this project, or in support of this project as co-funding, we have extracted the most relevant DOE-2.3 source code algorithms and have consolidated them into the Appendix. Some of these algorithms serve more than one purpose. To aid in the algorithm review, we have highlighted in blue any code directly related to the GLHX capabilities implemented in this project.
- A major difference between DOE-2.2 and DOE-2.3 is the ability to iteratively solve for solutions. It is this iterative approach in DOE-2.3 that made this HGSHP implementation possible. For example, when simulating the interaction of a GLHX with a cooling tower,

the performance of the cooling tower depends on the performance GLHX, but the converse is also true. The solution of the circulation loop supply temperature vs. the net cooling loads requires an iterative method. Two of the algorithms crucial for successfully solving iteration solutions were custom developed for DOE-2.3, and are included in the appendix. They are:

- "Subroutine CnvgCheck" – Iteratively solving for the converged solution of a complex system utilizing multiple algorithms is challenging. At the beginning of the time step, assumptions must be made about variables that are not yet known, the systems are then simulated and calculations made to solve for the assumed variables, and then the assumptions updated to reflect the latest result. The process is repeated until the initial assumptions match the calculated result. Oftentimes, a "harmonic" can result, where assumption "A" produces result "B". But, when the calculations are repeated using "B" as the initial assumption, the calculations yield result "A". As a result, convergence is never achieved. It is also possible for more complex harmonics to develop, such as assumption "A" yielding "B", which in turn results in "C", which results in "A". "Subroutine CnvgCheck" was developed to check to determine when convergence is achieved. If convergence has not yet achieved, the algorithm checks to see if any harmonic has developed, and if so calculates that damping factor that gets the calculations to settle down and converge.
- "Function PredictX" – This algorithm allows for a non-linear solution to be iteratively solved by using a parabolic function fit to successive guesses of the

solution, and the error associated with each successive guess. This function is used in several of the GLHX algorithms. For example, when simulating a hybrid system consisting of a ground-loop heat exchanger and a cooling tower and solving for the resulting supply temperature, the performance of the cooling tower depends on the performance of the GLHX, which in turn depends on the performance of the cooling tower. This relationship is non-linear and cannot be directly solved. However the supply temperature error in each iteration, together with the deviation in supply temperature between iterations (the error), can be used to develop a parabolic equations that can be solved for the temperature at which the error is zero. PredictX automates this process.

Task 1.0 Simulation of ground coupled water-to-water heat pump systems

The most common configuration for a GSHP system is a well field directly coupled to direct-expansion (DX) water-to-air heat pump units. An alternative configuration that may be more desirable in some situations is the use of a water-to-water heat pump. Like a water-to-air heat pump, a water-to-water heat pump is coupled to a well field. But, rather than directly delivering cold or hot air to spaces as the DX water-to-air heat pump does, a water-to-water heat pump is coupled to a 2-pipe circulation loop that delivers chilled or hot water to various types of 2-pipe zone terminals (fan coil, air handling unit, etc.). And, while water-to-air heat pumps are typically distributed throughout the building (one unit for each zone), water-to-water heat pumps are typically bigger and are located in a central plant.

The DOE-2 simulation engine has supported the water-to-air configuration since the original implementation of GLHX systems in 1995. Water-to-water systems were implemented several years later, and were coupled to lakes or water wells only; coupling to ground loop heat exchangers was not supported.

This JJH task added the following capabilities to eQUEST and/or DOE-2:

a. <u>Allow coupling of the water-to-water heat pump to horizontal and vertical well fields</u> – The existing water-to-water heat pump coupled only to lakes or wells where the temperature of the heat source/sink is independent of the load; it did not couple to a geothermal heat exchanger. This restriction was due to the interaction of the heat pump with the well field; the load and power consumption of the heat pump affects the well field temperature, which in turn affects the capacity and power consumption of the heat pump.

   This task modified the circulation loop and heat-pump components so that coupling to a geothermal heat exchanger could be modeled. The hourly calculation was modified to iterate multiple times between the heat pump, the circulation loop, and the well field. This allows the temperature of the well field to be determined simultaneously with the capacity and power consumption of the heat pump.

   <u>DOE-2 implementation comments:</u>

   - The water-to-water heat pump algorithm as originally implemented in DOE-2.2 was found to have major shortcomings. As a result, the water-to-water heat pump algorithm was rewritten for DOE-2.3 as part of the co-funding for this project. The source code is included in the appendix in "Subroutine Chiller_HP".

- The iteration between the heat pump, the circulation loop, and the well field as described above involves multiple algorithms coordinated together, and is not specifically highlighted in the included source code.

b. Implement new hot-water coil algorithm for fan coils - The hot-water coil algorithm in DOE-2.2 utilized performance curves that were derived assuming a 180F hot-water supply temperature. These curves are not suitable for the lower temperature water (100°F – 120°F) commonly generated by a water-to-water heat pump. Coils with variable air flow and/or variable water flow were also not well-supported, although this is becoming increasingly common. The curves can generate significant errors in calculating both coil capacity, flow at low loads, and required hot-water temperature for load reset control strategies.

In DOE-2.3, the hot-water coil algorithm was replaced with an NTU/effectiveness model that provides accurate modeling for a wide variety of hot-water temperatures and flows. This algorithm was implemented in all eQUEST system types, so that a water-to-water heat pump will not be restricted to just fan coils.

DOE-2 implementation comments:

- The source code for the hot water coil is found in "Subroutine Coil_HW". This routine relies upon "Subroutine HeatExchanger" for the NTU/effectiveness calculations, which in turn relys upon "Subroutine PredictX" which solves for the non-linear heat exchanger relationships.

c. <u>Extend enhancements to the 3-loop chiller</u> – In addition to a water-to-water heat pump that utilizes a 2-pipe heating/cooling circulation loop, eQUEST also models a 3-loop chiller. The 3-loop chiller is a heat-recovery device that provides cooling to a chilled-water loop, simultaneously with heating to a hot-water loop. As heating/cooling loads are virtually never balanced, a third loop is used to add/reject heat from the chiller. The third loop was previously limited to coupling to a lake or well, not a geothermal heat exchanger, for the same reasons as the water-to-water heat pump.

The 3-loop chiller was modified to allow coupling to horizontal and vertical well fields, in the same manner as the water-to-water heat pump. (Note that, as per the original proposal, the 3-loop system is accessible via the eQUEST “Detailed Data Edit” mode, it cannot be generated via the Wizard.)

<u>DOE-2 implementation comments:</u>

- The 3-loop heat pump algorithm as originally implemented in DOE-2.2 was found to have major shortcomings. As a result, the 3-loop heat pump algorithm was rewritten for DOE-2.3 as part of the co-funding for this project. The listing is included in the appendix in "Subroutine Chiller_LoopHP".

d. Library entries for water-to-water heat pumps – Performance characteristics developed by Shaojie Wang of ClimateMaster for selected water-to-water heat pumps have been reviewed by JJH and added to the library.

DOE-2 implementation comments:

- The CURVE-FITs are included in the BDLLIB.dat file, and are appended to the end of the appendix.

e. eQUEST Wizard enhancements – The existing capabilities of the eQUEST Wizard for simulation of ground-loop heat pumps has been expanded to model 2-pipe fan coils coupled to a 2-pipe loop served by a water-to-water heat pump and well field. The wizard accesses the water-to-water heat pump equipment added to the library in the above task. Because of the complexity of a water-to-water heat pump system, this implementation is restricted to the Wizard's "Detailed Data Edit" mode only.

Task 2.0 Improved multi-year simulations for conventional and hybrid GSHP systems

As described in the introduction, the performance of ground-loop heat exchangers is affected by the loading history of the ground heat exchanger, especially when there is an imbalance between the annual heat rejection to the ground and the heat extraction from the ground. Previously, the loading history of a GLHX was approximated in eQUEST/DOE-2.2 with a simplified algorithm, which estimated an annual load profile using the estimated peak winter heating load vs. the peak summer cooling load, and assuming a sinusoidal variation between the two peaks to develop the yearly profile.

In reality, *annual* heating and cooling load profiles are usually not proportionate to the *peak* heating and cooling loads. For office buildings, annual heating loads are typically overestimated using this technique, and act to reduce the thermal imbalance of a well field serving a cooling-dominated building.

Initially, there was a discussion as to whether to implement a full multi-year simulation (possibly 30 years or more) to develop the history, or to implement a single year of history and assume that year would be typical for all of the years in the history. A detailed analysis was undertaken, which concluded that a single year of history would not be sufficiently accurate in all cases, and could be severely inaccurate for a hybrid system having a supplemental cooling tower and/or boiler.

A hybrid system complicates the history because of the way the cooling tower interacts with the GLHX over the years. In the initial year of operation, the GLHX temperature is close to the undisturbed ground temperature, and for that reason the cooling tower may run relatively little. But, if the building is cooling dominated (typical of most office buildings), then as the years pass the GLHX temperature rises due to the annual heating/cooling thermal imbalance, and the cooling tower picks up more of the load. In other words, in the first year of operation the cooling tower may pick up only 10% of the cooling load, while in year 20 the tower may pick up 50+% of the load. For this reason, a single "typical" year of history cannot suffice.

Two versions of a multi-year history simulation were implemented:

a. Simulate every year in the history – Each successive year in the history is simulated utilizing the actual loading history calculated in the simulation of the previous years. This approach allows the first-year performance to be distinguished from later years when the ground has progressively become more saturated with the annual heating/cooling load imbalance. In this approach, if the actual simulation is for the 30th year of operation, then all 29 previous years of operation are also simulated; resulting in a potentially long run period.

b. Simulate a Fibonacci sequence of years- This is similar to the simulation described above, but instead of simulating every year in the history, only the years corresponding to the Fibonacci sequence {1, 2, 3, 5, 8, 13, 21, …} are simulated. Where years are skipped, the ground history of the next simulated year is weighted by the number of years skipped. This method recognizes that the ground temperature changes the most rapidly during the early years, and changes more slowly in later years as the ground approaches thermal equilibrium.

The advantage of Option (a) is that it fully captures the variation in well field temperature over successive years, and is the most accurate. Option (b) may be somewhat less accurate, but can result in significantly faster run times. Tests comparing Option (a) to Option (b) show very little difference between the two methods. For histories of 20 to 30 years, results showed the variation in well field temperature to be typically less than 1°F. Both modes of generating the history are supported, with the Fibonacci sequence being the default.

Reports are suppressed in eQUEST for all years of the history generation. Reports are generated for the final year simulation, and represent only the final year.

eQUEST Wizard enhancements – The eQUEST Wizard was modified to support the above. The existing eQUEST detailed mode input entry for "Design day load profile in ground" and the Julian heating and cooling design days have been removed as they were relevant only for the old method of initializing the load history.

DOE-2 implementation comments:

- The simulation of all years in the history or the Fibonacci sequence is controlled by "Subroutine System" and its sub-subroutine "SimulateHVAC"; found in the Appendix.
- The consolidation of each year in the history simulation is done in "Subroutine GLHX_Vertical", in the section titled "BEGINNING OF RUN INITIALIZATION". This section is called at the start of each year of the history, and at the beginning of the final annual simulation.
- Shaojie Wang of ClimateMaster and Xiaobing Liu of ORNL did extensive testing of this new feature in order to understand the differences between the new detailed method of developing the history versus the previous approximate method, as the two methods could produce substantially different temperature responses in the final year. As part of their testing, a constant-load model was developed and results compared to that predicted by GLHXpro, which is used to design the vertical borehole-type ground loop heat exchangers. For the cases tested, DOE-2.3 and GLHXpro results agreed to within approximately 1°F.

Task 3.0 Models of various hybrid GSHP system configurations

As noted above, geothermal heat pump systems typically have an imbalance between annual heating and cooling loads. This imbalance typically degrades the ability of the geothermal heat exchanger to absorb or provide heat, except at more extreme temperatures. This imbalance may be minimized via the use of a supplemental boiler and/or cooling tower. The supplemental equipment is usually placed in series with the geothermal heat exchanger, and the control configured to maximize usage of the geothermal capacity, with the supplemental equipment making up the remainder. The combination of a geothermal well field with a supplemental boiler or cooling tower is termed a "hybrid" system.

As part of this project, Xiaobing Liu of ORNL conducted a survey of engineers who have designed hybrid GSHP systems, and also reviewed three research projects on HGSHP system design and simulation (Spitler et al. 2000, TESS/ORNL 2005, Hackel et al. 2009). Based on these data, the team developed the following description of the most common and cost effective hybrid GSHP system, which was implemented into eQUEST by JJH with support from Xiaobing Liu of ORNL:

a. DOE-2.3 model enhancements

- The supplemental heat rejection device (cooling tower, fluid cooler, or dry cooler) and/or the supplemental heat addition device (boiler) is connected to the ground loop heat exchanger in series configuration with bypass to the supplemental devices and the GLHX when they are not called for.
- While the above configuration shows the supplemental heat rejection device upstream of the GLHX, the supplemental heat rejection device as implemented in DOE-2.3 is downstream of the GLHX, as this is considered to be the most common configuration

of hybrid GLHX systems. This configuration maximizes the summertime charging of the GLHX by having the warm return water enter the GLHX first, while allowing the cooling tower to then reduce the supply temperature fed back into the building; maximizing heat pump efficiency.

- The supplemental heat addition device is always placed downstream of GLHX. Otherwise, it could act to heat the GLHX.
- Supplemental devices normally have their own circulation pump to avoid sudden change of flow rate in each heat pump unit when the supplemental devices are turned on. DOE-2.3 was configured to allow either option.
- The capacity of supplemental devices can be staged or modulated, although fixed capacity offered by one-speed fan and pump is still an option.
- Control strategies
    - The set-point temperature is the supply fluid temperature leaving the loop, entering the building. The cooling and heating modes have separate set-points. The set-points will normally be fixed, but may be varied by schedule or by outdoor wetbulb temperature reset.
    - By default, the GLHX is preferentially loaded over the supplemental devices, which means the GLHX will be loaded prior to the operation of the cooling tower or boiler. If the GLHX can satisfy the cooling or heating load without the loop temperature exceeding the cooling or heating set-points, then the loop temperature will float.

- If the supply temperature exceeds the cooling setpoint and a cooling tower exists, then the tower will start and control to the cooling set-point temperature.
- Similarly, if the supply temperature drops below the heating setpoint and a boiler exists, then the boiler will start and control to the heating setpoint temperature.
- When supplemental equipment is running concurrently with the GLHX, it is possible that the continued operation of the GLHX may be counterproductive in some circumstances. For example, if a cooling tower is running, the cooling set-point is sufficiently low, and the ambient wetbulb temperature is low, then it is possible that the loop return temperature entering the GLHX may cooler than the GLHX temperature. In this case, the GLHX will heat the loop while the tower is cooling the loop. This behavior may or may not be desirable, and a provision is provided to allow or disallow the GLHX to be bypassed when counterproductive.

- The existing algorithms for the GLHX were extensively rewritten so that GLHX operation could be coordinated with supplemental hybrid equipment. Previously, the algorithms would calculate the output temperature for a given load. This mode is still supported for times when the supplemental equipment is inactive. However, when supplemental equipment is active, then a new mode is required where the GLHX must respond to the temperature imposed on it by the supplemental equipment, and calculate the resulting load; the converse of the original formulation. The performance of the GLHX is dependent on the load and the performance of the cooling tower; the converse is also true. Therefore a non-linear iterative solution is required that relies on the PredictX function described previously to achieve convergence. The revised algorithms are included in the appendix in "Subroutine GLHX_Vertical" in the sections "OPERATING CAPACITY" and "EQUIPMENT SIMULATION". (The horizontal GLHX algorithm was modified in a similar fashion.)

- Previously, DOE-2.2 did not attempt to size the geothermal well field. Instead, the user had to completely specify the characteristics of the well field, such as the number and configuration of the boreholes, the depth of each borehole, etc., and then run the program to determine whether the temperature performance of the GLHX was acceptable. As part of this project, DOE-2.3 was modified to better assist the user in sizing the well field. The user can specify the approximate configuration of the well field (or allow it to default), and indicate whether the program should autosize the well field. If so, then the program calculates the field multiplier of the GLHX based on the peak cooling or heating load from the design sizing runs, and assuming 250' of bore per peak ton. This sizing method is still only approximate, as it does not take into account the ground characteristics of the site, nor does it take into account the thermal imbalance between heating and cooling loads that have accumulated in the prior years of operation. However, it is a good starting point.
- For sizing purposes for equipment in series, it is necessary to specify the fraction of the peak load that is to be picked up by the upstream vs. downstream equipment. An input is provided for this purpose.

- To help the user understand the temperature performance of the GLHX, a new report was implemented that summarizes the distribution of temperatures found during GLHX operation. Report PS-O is included in the appendix.
- The central plant control logic was extensively rewritten to allow equipment to operate in series, and to coordinate the operation of the GLHX with supplemental hybrid equipment. The revised algorithm is included in the appendix in "Subroutine CircLoopPlant". These revisions included items specifically added for the GLHX (highlighted in blue), as well as co-funded work necessary to simulate equipment configured in series (not highlighted). Note that an iterative solution is required, as the performance of the GLHX depends on the performance of the cooling tower, which in turn depends on the performance of the GLHX.

b. <u>eQUEST Wizard enhancements</u> – The eQUEST wizard was modified to allow a cooling tower or fluid cooler or boiler to be created and modeled in series with a well field.

<u>DOE-2 implementation comments:</u>

- Shaojie Wang of ClimateMaster and Xiaobing Liu of ORNL tested the hybrid GSHP system with various capacity ratios and control strategies including fixed setpoint, outside air reset, scheduled setpoint, load reset, and wetbulb reset to understand the impact of these design parameters on the annual HVAC energy consumptions, Electric Peak demands and unmet cooling/heating hours. The simulation results show that the capacity ratios depend on the weather conditions, peak cooling/heating loads, and net thermal loads on the ground loop. The optimized control strategies also can dramatically reduce the annual HVAC energy savings and Electric Peak demands in the different climate zones.

Task 4.0 Software launch and training material

eQUEST-3.70 has been made available to public as freeware via the DOE2.com website.

The JJH tasks included:

a. Program documentation – The existing *DOE-2 Dictionary* and *New Features* documents have been updated to include the hybrid GLHX implementation. An excerpt of the *New Features* document is included in the Appendix.

b. eQUEST on-line help – The on-line help feature of eQUEST has been expanded to include the documentation developed within the *Dictionary* and *New Features* documents. Tool tips have been included for eQUEST fields.

c. Program release on DOE2.com – eQUEST-3.70 is available to public as freeware via the DOE2.com website.

d. ClimateMaster training – Training on the new program has been provided to ClimateMaster personnel.

4. Conclusions

The new enhancements were incorporated into a developmental version of DOE-2.2 released as DOE-2.3-49c. The ground coupled water-to-water heat pump system was successfully added as an alternative configuration of the GSHP system. Rather than using an approximate loading history generated using a sinusoidal loading function between peak heating and cooling loads, the program now allows for either full multi-year simulations, or simulation of previous years using a weighted sample of the years. The program also can simulate a GROUND-LOOP-HX together with supplemental heat rejection device and/or boiler to reduce the size of the well field and drilling cost. The eQUEST graphical user interface was modified to include these enhancements and released as eQUEST-3.70.

While the hybrid GLHX enhancements have been extensively tested by ClimateMaster, the program is considered a beta, as this version of DOE-2 is still under development with other extensive enhancements underway or still planned as part of James J. Hirsch's ongoing program support and development.

Program documentation modified as part of this project includes the eQUEST-3.70 on-line help and the following DOE-2 Manuals:

- DOE-2.3 Volume 2: Dictionary
- DOE-2.3 Volume 4: Libraries and Reports
- DOE-2.3 Volume 6: New Features

The program and all documentation have been posted on the DOE2.com website.

5. References

[1] Claesson J, Eftring B, Hellström G and P Olanders (1978). Theoretical analysis and computer simulation of solid-fluid heat storage systems in the ground.

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[4] Hackel, S., Nellis, G. F., & Klein, S. A. (2009). Optimization of Cooling Dominated Hybrid Ground Coupled Heat Pump Systems RP#1384.

[5] DOE-2.3 Volume 2: Dictionary, 2014

6. Appendix

The model of hybrid GSHP system in eQUEST 3.7 was extensively tested by Dr. Shaojie Wang from ClimateMaster and Dr. Xiaobing Liu from ORNL. Below are the simulation results for the Comparative Study of Control Strategies for Hybrid GSHP System in the Cooling Dominated Climate.

Abstract

The ground source heat pump (GSHP) system is one of the most energy efficient HVAC technologies in the current market. However, the heat imbalance may degrade the ability of the

ground loop heat exchanger (GLHX) to absorb or reject heat. The hybrid GSHP system, which combines a geothermal well field with a supplemental boiler or cooling tower, can balance the loads imposed on the ground loop heat exchangers to minimize its size while retaining superior energy efficiency. This paper presents a recent simulation-based study with an intention to compare multiple common control strategies used in hybrid GSHP systems, including fixed setpoint, outside air reset, load reset, and wetbulb reset. A small office in Oklahoma City conditioned by a hybrid GSHP system was simulated with the latest version of eQUEST 3.7[1]. The simulation results reveal that the hybrid GSHP system has the excellent capability to meet the cooling and heating setpoints during the occupied hours, balance thermal loads on the ground loop, as well as improve the thermal comfort of the occupants with the undersized well field.

Introduction

As addressed in Buildings Energy Data Book [1, 2], the buildings sector consumes about 40% of US primary energy including 74% of electricity consumption, 56% of natural gas consumption, and significant oil consumption in the Northeastern in 2010. Over the long term, buildings are expected to continue to be a significant component of increasing energy demand and a major source of carbon emissions, driven in large part by the continuing trends of urbanization, population and GDP growth, as well as the longevity of building stocks. The increasing importance of building energy efficiency generally, as well as EERE's programmatic focus on net zero energy homes and net zero energy commercial buildings brings tremendous challenges and opportunities to the Heating, Ventilation, Air-Conditioning, and Refrigeration (HVAC&R) industry. Many new, or relatively new, HVAC&R technologies [3] are promoted with emphasis on their superior energy efficiency. Among these, the ground source heat pump is one of the most energy efficient HVAC technologies in the current market.

As shown in Fig.1, the GSHP system rejects the heat to the ground (in the cooling mode) or extracts the heat from the ground (in the heating mode). It takes the advantages of the moderate ground temperatures to increase the efficiency and reduce the operating cost of the HVAC system. It usually comprises of multiple water-to-air heat pump indoor units, which are parallel connected with the GLHX through a common two-pipe water loop. The GLHX consists of multiple boreholes connected in parallel. Depending on the operation mode of the GSHP system, the fluid is circulated through the boreholes to either reject the heat to the ground or absorb the heat from the ground before returning to the water-to-air heat pump indoor units. Since each of the water-to-air heat pump indoor units can run in either cooling or heating mode independently, the GSHP system can provide simultaneous cooling and heating for different zones of the building. As of 2004, Lund et al. [4] reported that over a million GSHP units were installed worldwide to provide 100 MWt of thermal capacity, with an annual growth rate of 10% [5].

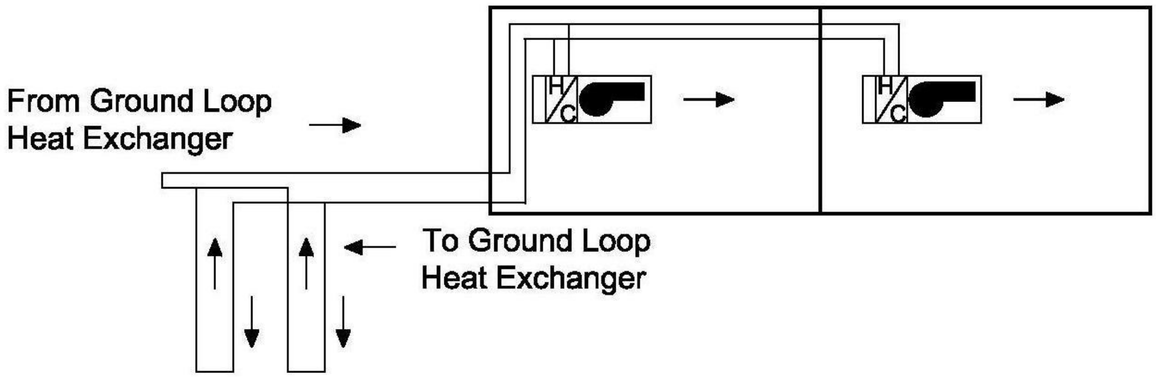


Fig. 1 Schematic of GSHP system

However, the space cooling and heating loads in the cooling dominated climate such as Oklahoma City are not balanced on an annual basis. This imbalance may degrade the ability of the GLHX to absorb or provide heat. This imbalance may be minimized via the use of a supplemental boiler and/or cooling tower. The supplemental device is usually placed in series with the geothermal heat exchanger, and the control is configured to maximize usage of the geothermal capacity, with the supplemental equipment making up the remainder. The combination of a geothermal well field with a supplemental boiler or cooling tower is termed a “hybrid” GSHP system as presented in Fig. 2.

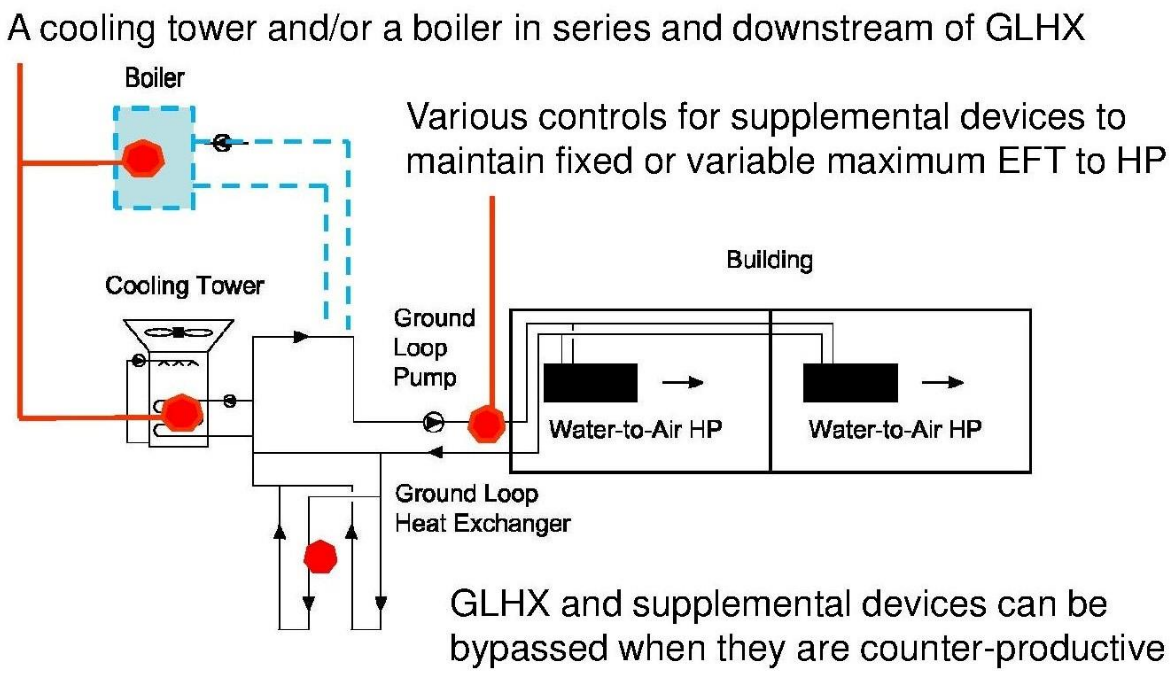


Fig. 2 Schematic of Hybrid GSHP system

ASHRAE [6] published an engineer manual on how to size the capacity of the cooling tower. Instead of using the building peak loads, the capacity of the cooling tower is determined based on the difference between the monthly average building cooling and heating loads. The ground loop is sized to meet the building heating loads, while the cooling load in excess of the heating load is met through supplemental heat rejection.

Kavanaugh and Rafferty [7] discussed hybrid ground source heat pump systems within the framework of ground loop heat exchanger design alternatives. The sizing of the cooling tower is based on peak block load at the design condition. The nominal capacity is calculated based on the difference between the ground-loop heat exchanger lengths required for cooling and heating.

Kavanaugh [8] recommended calculating the operation hours of the cooling tower based on the cooling setpoint of the ground loop. This revised method can reduce the thermal load aggregation on the ground loop and improve the performance of heat pump unit. The author concludes that the economic value of hybrid systems is most apparent in warm and hot climates where cooling loads are the highest. Although hybrid systems with heat recovery options are deemed somewhat attractive for regions of moderate climate, no economic value could be justified for cold climates even with heat recovery.

Yavutzurk and Spitler [9] conducted a comparative study investigating several control strategies for Hybrid GSHP systems. The strategies investigated include full sized GLHX, undersized GLHX with no supplementary heat rejecter, fixed set point control (heat pump entering or exiting fluid temperatures), differential temperature control (the difference between heat pump entering or exiting fluid temperatures and the ambient wet-bulb temperature), and operation of the supplemental rejecter to remove heat from the GLHX field during nighttime hours. The simulate results indicate that the hybrid GSHP system is more cost effective than the conventional GSHP system for 20 year operation period. The differential temperature control is the most beneficial choice as compared with other control strategies.

eQUEST is a widely used, time-proven whole building energy performance design tool. Its wizards, dynamic defaults, interactive graphics, parametric analysis, and rapid execution make eQUEST uniquely able to conduct whole-building performance simulation analysis throughout the entire design process, from the earliest conceptual stages to the final stages of design. While powerful, eQUEST development team still continuously makes improvements and adds new features. Three new enhancements recently have been implemented into eQUEST 3.7 to expand its modeling capacity. These enhancements includes: (1) Simulation of ground coupled water-to-water heat pump systems; (2) Improved multi-year simulations for conventional and hybrid GSHP systems; (3) Models of various hybrid GSHP system configurations. Therefore, eQUEST 3.7 was chosen for this comparative study.

Description of simulated building

As shown in Fig. 3, a 2-story small office was selected for this comparison study. Each floor of the office has a square footprint and total conditioned space of 1161 m2, which has four thermal zones in the perimeter and one core zone in the interior. The floor to floor height is 3.66 m with 0.91 m high return plenum.

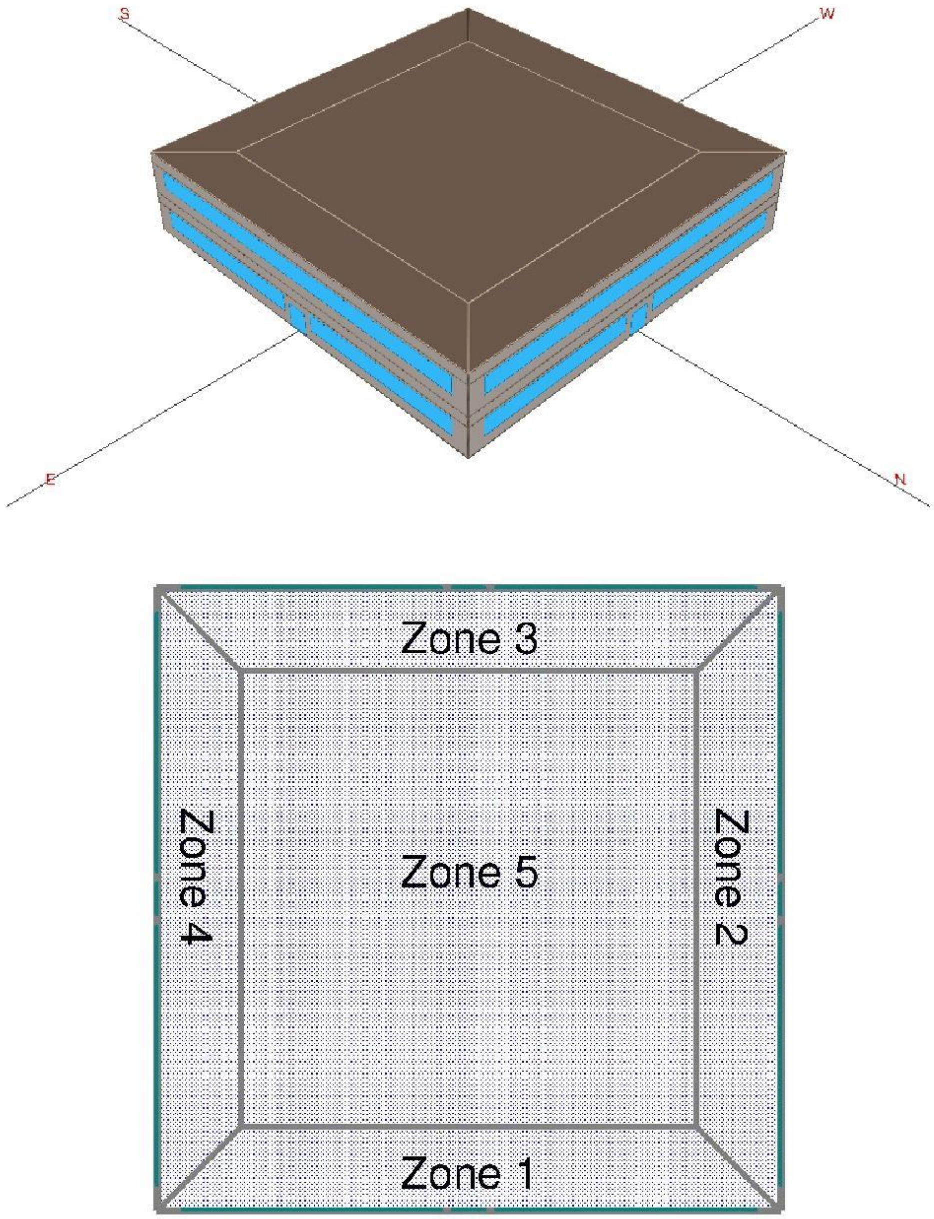


Fig. 3 3D view and floor plan of the simulated small office building

The small office building was assumed to be located in Oklahoma City, OK which lies in Warm – Humid Climate zone 3A as described in the ASHRAE standard 90.1-2010. The exterior wall has the 2 in. (5.1 cm) by 6 in. (15.2 cm) metal studs framing at 24 in. (61.0 cm) on center with cavities filled with R-18 batt insulation. The exterior insulation was ¾ in. (1.9 cm) fiber board sheathing with the plywood finishing. The roof was constructed by using the metal frame at 24 in. spacing with 3 in. (7.6 cm) polyurethane (R-18) exterior insulation. The slab was built with 6 in. concrete and interior vinyl tile. Two types of the double pane glazing were installed on the building. The single clear/tint glazing was selected for the exterior door. Table 1 lists the construction details of the small office building. The corresponding internal loads are shown in Table 2 including lighting power density, equipment load and occupant density.

Table 1 Construction of the small office building

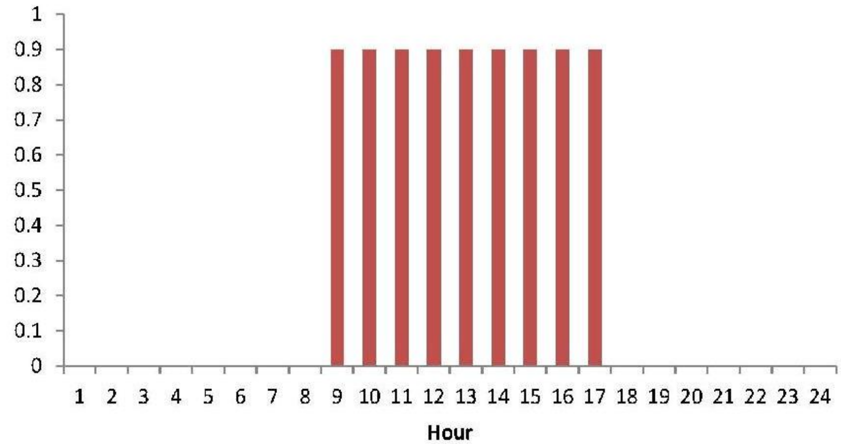
Building Envelope	**Construction Detail**
Exterior wall	Metal frame, 2x6, 24 in o.c. with plywood, ¾ in fiber board sheathing (R-2) and R-19 batt insulation, U value=0.08 Btu/hr.ft^2(0.25 W/m^2)
Roof	Metal frame, 24 in. o.c. built-up roof with R-18 3 in. polyurethane insulation U value=0.042 Btu/hr.ft^2 (0.13 W/m^2)
Floor	Slab-on-grade with 6 in concrete and vinyl tile
Windows	1) Double pane clear,1/2 in glass, 1/2 in air gap

	U=0.47 Btu/hr.ft^2 (1.48 W/m^2) 2) Double pane clear,1/2 in glass, 1/4 in air gap U=0.54 Btu/hr.ft^2 (1.69 W/m^2)
Door	Single clear/tint U=0.98 Btu/hr.ft^2 (3.1 W/m^2)

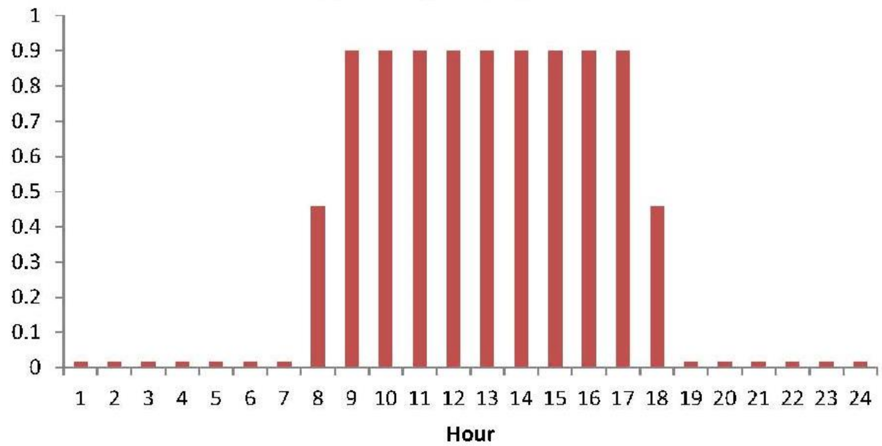
Table 2 Internal loads of the small office building

Internal Load	**Unit**
Light power density	16.1 w/m^2
Equipment load	10.8 w/m^2
Occupant density	11 people/100 m^2

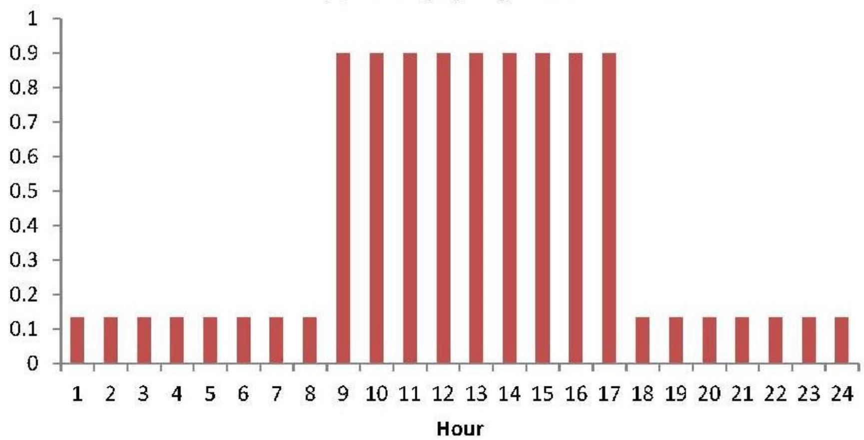
The office operated from 8 am to 5 pm (Monday to Friday) and was closed on Saturday, Sunday and holiday. The HVAC system ran between 7 am and 6 pm. In the cooling mode, the thermostat setpoints were 24°C when occupied and 28°C when unoccupied. In the heating mode, 21°C was selected as occupied room temperature and 18°C was used in the unoccupied hours. The indoor fan was assumed to run intermittently with the constant air flow rate during the occupied hours and stay off when unoccupied. The fan efficiency and motor efficiency were 0.62 and 0.77 with 249 Pa pressure rise. Fig.4 shows the daily building occupancy, lighting and equipment schedules.



(a) Building occupancy schedule



(b) Building lighting schedule



(c) Building equipment schedule

Fig. 4 Building occupancy, lighting, and equipment schedules

Hybrid GSHP system model description

As a key part of HGSHP system, the GLHX was used as a heat source and sink to cool or heat the condenser water. The entering fluid temperature (EFT) to the heat pump from the loop is used to determine the size of the well field. The sizing criterion is that the min EFT is above 7.2°C and the max EFT is below 35°C during the period of 30 year operation. It can limit the degradation of the performance of the heat pump in the heating and cooling seasons. The GLHX was constructed with 32 (4x8 array) boreholes placed in a rectangular configuration. The borehole depth is 76 m with the radius of 0.08 m. The U-tube spacing and leg separation are 6 m and 0.1 m. The pipe thermal conductivity is 0.4 W/m.K with the inside and outside diameters of 0.022 m and 0.027 m. The ground thermal conductivity and diffusivity are 2.9 W/m.K and 1.11×10-6m^2/s. The undisturbed ground temperature is 18°C.

The fluid cooler is attached to the same water loop with a ground loop heat exchanger. It is in series with the well field, and downstream of the well field. If the outlet loop temperature is within the circulation loop's cooling/heating setpoint, then the loop temperature floats with the well temperature without running the fluid cooler. If the temperature exceeds the loop's cooling setpoint, then the fluid cooler will operate to maintain the loop temperature at setpoint. The downstream split ratio determines the design heating or cooling load to be picked up by the fluid cooler. For the fluid cooler, the sizing method is to balance the annual heat rejection with heat extraction and reduce the load aggregation on the ground loop. Because the building is highly cooling dominated, the downstream split ratio is 0.8, which means the fluid cooler is designated to satisfy 80% of peak cooling load. The fluid cooler is always assumed to be bypassed when inactive. A variable speed fan modulates the air flow to maintain the tower setpoint. The fluid cooler spray pump can run as "STAY-ON". "Stay-on" enables the fluid cooler to have two stages of cooling. On the first stage of cooling, the spray pump operates whenever a heat-rejection load exists. If the load can be met using the spray pump and natural convection, then the fan will stay off. Otherwise, the fan will cycle on as required, and when cycled off, the pump will remain on.

Each zone of the small office is served with one packaged water-to-air heat pump unit and controlled independently. The indoor fans run under intermittent mode. The intermittent mode enables the indoor fan to only operate for that fraction of the hour required for space heating or cooling. All the heat pump units are connected to a close-loop vertical ground loop heat exchanger through a common 2-pipe loop.

The central pump station has the variable speed pump. According to their zone thermostats, individual heat pump units extracted heat from or rejected heat to a common water loop. The water loop connected the heat pump units with the GLHX. The water pump attached to the water loop and circulated the water between the GLHX, fluid cooler, and the condenser. It ran intermittently with the rated pump head of 31.9 ft and the motor efficiency of 0.885. The water flow rate was 16.5 L/s which was autosized by eQUEST 3.7.

Loop temperature control strategy

The set-point temperature is the entering fluid temperature to the heat pump from the loop. The heating and cooling modes have separate set-points. The set-points normally are fixed, but may be varied by load reset, outdoor temperature reset and wetbulb reset.

The GLHX is preferentially loaded over the fluid cooler. However, if the GLHX is counterproductive (i.e., warming the water when heat pumps are in cooling mode), and a fluid cooler is also enabled, then the GLHX will be bypassed (to save pump energy) and the fluid cooler used exclusively.

The fluid cooler will be enabled when the EFT from the GLHX is higher than the cooling setpoint. When enabled, the fluid cooler will modulate a variable-speed cycling fan to maintain the cooling temperature set-point. When the fluid cooler is disabled, the flow will bypass the fluid cooler.

Description of simulation scenarios

The multiple control strategies [10] including fixed setpoint, outside air reset, load reset, and wetbulb reset were adopted to optimize the performance of the hybrid GSHP system in term of annual HVAC energy consumptions and unmet cooling/heating hours. The fixed temperature control specifies the EFT to the heat pumps at a fixed value. The OA-RESET specifies that the EFT to the heat pumps is reset on outdoor air according to the COOL-RESET-SCH. LOAD-RESET specifies that the EFT to the heat pumps is reset so that the valve of the worst-case coil is fully open. LOAD-RESET is applicable to the heat-rejection side of the water loop. It does not apply, however, to the heating setpoint of the water loop. The fluid cooler temperature floats with the load and wet-bulb temperature. This mode maximizes the efficiency of the primary equipment and minimizes the loop's thermal losses (but at the expense of pumping energy in a variable-flow loop). WETBULB-RESET specifies that the EFT to the heat pumps is reset according to the outdoor wetbulb temperature, plus an offset. The offset may be either fixed, or may vary with the wetbulb.

Conventional GSHHP system

The conventional GSHP system was simulated as a base case to compare with the hybrid GSHP system. The simulation for this case only includes the GLHX, the circulation pump, and the heat pump indoor units. The GLHX was designated without the use of any supplementary heat rejection equipment. The GSHP system fully depends on the GLHX to meet the building heat and cooling loads. The sizing method of the GLHX uses the same max and min EFTs as addressed above with a 30-year operation period. Therefore, the well field is comprised of 72 boreholes in an 8 x 9 rectangular configuration. Other related design parameters of the GLHX are identical to those specified for the hybrid GSHP system.

Fixed Cooling Setpoint

Table 3 lists the simulation scenarios with fixed cooling setpoint control. The fixed cooling setpoints are 23.9ºC, 26.7 ºC, and 29.4 ºC while the fixed heating setpoint is -0.6 ºC.

Table 3 Simulation scenarios with fixed cooling setpoint control

Case No.	Loop Temp. Heating Setpoint	Loop Temp. Cooling Setpoint
1	-0.6ºC	23.9ºC
2	-0.6ºC	26.7ºC
3	-0.6ºC	29.4ºC

OA-RESET

Three OA-Reset temperature schedules are listed in Table 4. OA-Reset schedule defines the relationship between the cooling setpoint and the outdoor drybulb temperature for each hour of the run period. RESET-SCHEDULE specifies four required keywords including Outdoor-Low, Outdoor-Hi, Cooling-Hi, and Cooling-Low. The cooling setpoint "Cooling-Low" keeps at 15.6ºC while the outdoor drybulb low temperature "Outdoor-Low" is 12.8ºC. Corresponding to Outdoor-Hi at 29.4ºC, the cooling setpoint "Cooling-Hi" increases from 23.9ºC up to 29.4ºC with 2.8 degree increment. Fig. 5 shows the curves of cooling setpoint at various outdoor drybulb temperatures.

Table 4 Simulation scenarios with OA-Reset cooling setpoint control

Case No.	Outdoor-Hi	Outdoor-Low	Cooling-Hi	Cooling-Low
OA-1	29.4ºC	12.8ºC	23.9ºC	15.6ºC
OA-2	29.4ºC	12.8ºC	26.7ºC	15.6ºC
OA-3	29.4ºC	12.8ºC	29.4ºC	15.6ºC

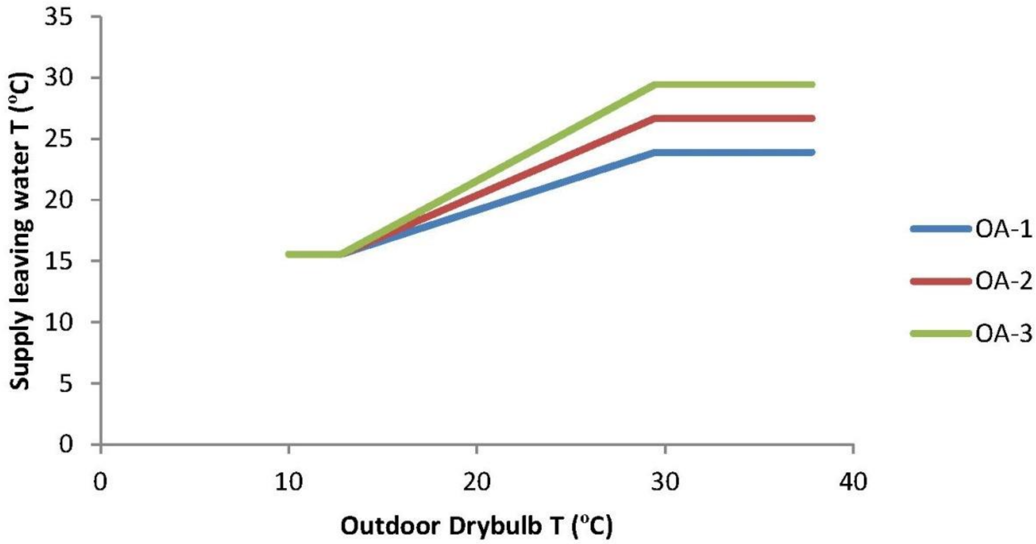


Fig. 5 Cooling setpoint at various outdoor drybulb temperatures

Wetbulb-RESET

Three Wetbulb-Reset temperature schedules were listed in Table 6. The hourly cooling setpoint T_1 is calculated in the following equation. As shown in Table 5, the differential between the cooling setpoint and outdoor wetbulb temperature are 0.6, 2.8, and 5.6 ºC.

$T_1 = T_2 + \Delta T$

Where

T_2: hourly outdoor wetbulb temperature

ΔT: differential between the hourly cooling setpoint and hourly outdoor wetbulb temperature

Table 5 Simulation scenarios with wet-bulb reset cooling control

Case No.	MAX-RESET-T	MIN-RESET-T
LD-1	23.9ºC	15.6ºC
LD-2	26.7ºC	15.6ºC
LD-3	29.4ºC	15.6ºC

Load-RESET

Using LOAD-RESET, the program does not calculate a loop setpoint temperature. Instead, the fluid cooler fan speed is reset directly on the tower load. The tower leaving temperature floats with the wetbulb temperature, load, and resulting fan speed. The MAX-RESET-T of the circulation loop specifies the upper limit of the floating tower temperature, and MIN-RESET-T specifies the lower limit. If either of these limits is exceeded, then the fan will modulate to not exceed the limit. When a variable-speed fan is used, this is the minimum fraction of nominal fan speed at which the fan can operate. If the load is such that the component will overcool the fluid at this minimum speed, then the fan will cycle between off and minimum speed. For current study, the minimum fan speed is 0.4 while minimum reset part load ratio is 0.3. The maximum reset speed is 0.8. The correlation of the fan speed and part load ratios is depicted in Fig. 6.

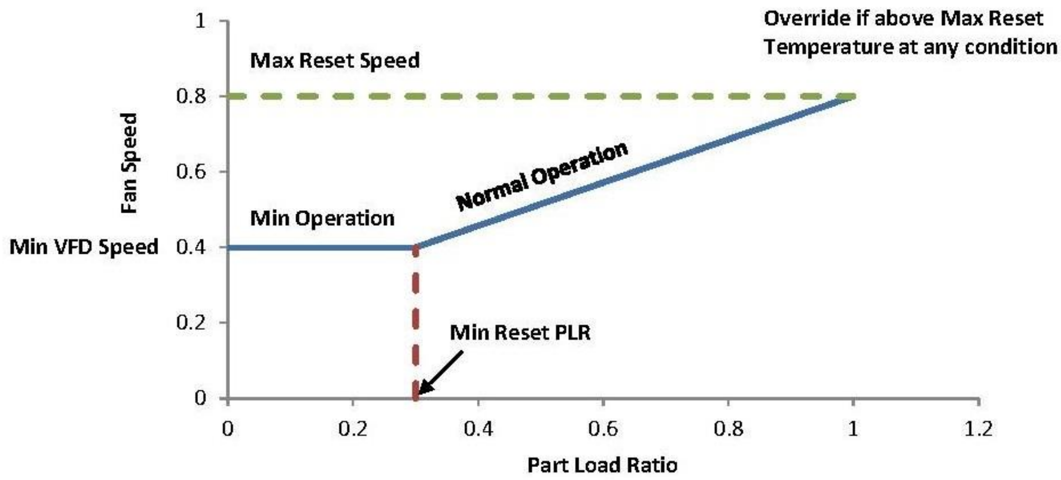


Fig. 6 Correlation of fan speed and part load ratio

Three Load-Reset temperature schedules are listed in Table 6. The MAX-RESET-T and the MIN-RESET-T are the upper and lower limits on the supply temperature. The actual setpoint will be reset, based on coil demand, between the MAX-RESET-T and the MIN-RESET-T. The MAX-RESET-T is between 23.9ºC and 29.4ºC while MIN-RESET-T is 15.6ºC.

Table 6 Simulation scenarios with load-Reset cooling control

Case No.	ΔT
WB-1	0.6°C
WB-2	2.8°C
WB-3	5.6°C

Result and Discussion

The simulation results are analyzed in this section including annual HVAC electric consumption, heat rejections, average entering fluid temperatures to heat pump and unmet hours.

Conventional GSHP

For the base case, the GLHX was sized without any supplemental heat rejection equipment. Then, the well field is more than twice as large as what the hybrid GSHP needs by applying the same sizing criterion. As shown in Table 7, the conventional GSHP system consumes the lowest HVAC electric consumption in year 1 as compared with the hybrid GSHP system. The peak heating and cooling loads on the ground loop are 225 kw and 392 kw. Annually, the heat rejection to the ground is 233 MHW and 243 MHW in year 1 and year 30. The GSHP system only absorbs 6 MWH heat from the ground in the heating mode. So, the max and min EFTs are 33.8 ºC and 23.6 ºC in year 30. The average EFTs are 19.7 ºC in year 1 and 27.6 ºC in year 30, respectively. As a result of the heat imbalance on the ground loop, the average EFT rises 7.9 ºC with a 30 year operation.

Table 7 HVAC electric consumptions (kWh) in Year 1 (conventional GSHP system)

Case No.	GSHP
Space Cool	27196
Tower Fan	0
Spray Pump	0
Space Heat	1344
Vent. Fans	5660
Loop pump	2187
HVAC Total	36387

Annual HVAC Electric Consumption

The HVAV electric consumption is the most important factor to compare the different control strategies analyzed in this study. Besides the annual HVAC electric consumption, six categories of energy end uses are also listed for each control strategies including space cool, tower fan, spray pump, space heat, vent. fans, and loop pump.

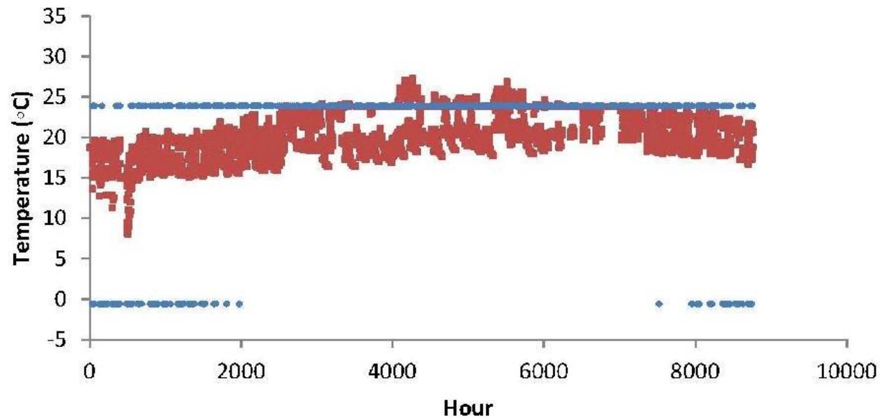
Fixed Cooling Setpoint

As shown in Table 7, Fixed-2 and Fixed-3 reduce the annual HVAC electric consumption by 12.7% and 12.3% as compared with Fixed-1 due to the higher cooling setpoint. The major electric savings come from the reduction of the electric usage of the fluid cooler fan, which are 5616 kWh and 6130 kWh. In addition, the energy end uses for spray pump also drop from 2274 kWh to 1655 kWh and 1103 kWh, as well as the loop pump with the energy savings of 1345kWh and 1429 kWh. The space cooling end use gradually increases from 29097 kWh to 30463 kWh and 31703 kWh because the higher EFTs from the ground loop degrades the performance of the heat pump in the cooling mode. The energy end uses for space heat and indoor fan don't change significantly among three case studies. However, an interesting phenomenon observed here is that Fixed-3 uses more energy than Fixed-2. This result indicates that the higher cooling setpoint cannot guarantee the energy savings of the HVAC system. When the energy end use of the fluid cooler is only a small portion (5.2%) of the annual HVAC energy consumption for Fixed-2, the benefit to further lower the operation duration/frequency of the fluid cooler associated with the higher cooling setpoint is very limited as addressed in Table 7. At the meantime, the penalty of increasing the energy end use for the heat pump offsets the energy savings in Fixed-3.

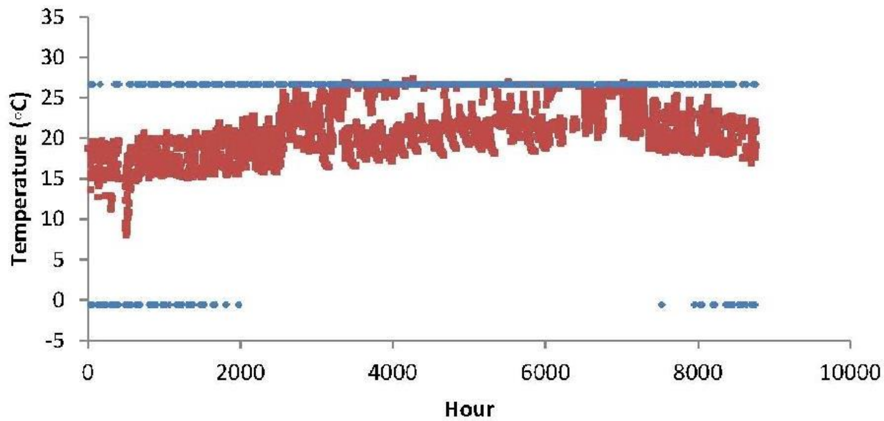
Table 8 HVAC electric consumptions (kWh) in Year 1 (Fixed Cooling Setpoint)

Case No.	Fixed-1	Fixed-2	Fixed-3
Space Cool	29097	30463	31703
Tower Fan	6158	542	28
Spray Pump	2274	1655	1103
Space Heat	1388	1387	1386
Vent. Fans	5764	5836	5906
Loop Pump	3899	2545	2470
HVAC Total	48579	42428	42595

Fig.7 shows the hourly loop control setpoints and EFTs to the heat pumps. As the cooling control setpoint increases from 23.9ºC to 29.4ºC, the EFT to the heat pumps increases accordingly. For Fixed-1, there are some hours when the EFTs to the heat pump exceed 23.9ºC. Then, the hours decrease with the higher cooling setpoints accordingly.



(a) Fixed-1



(b) Fixed-2

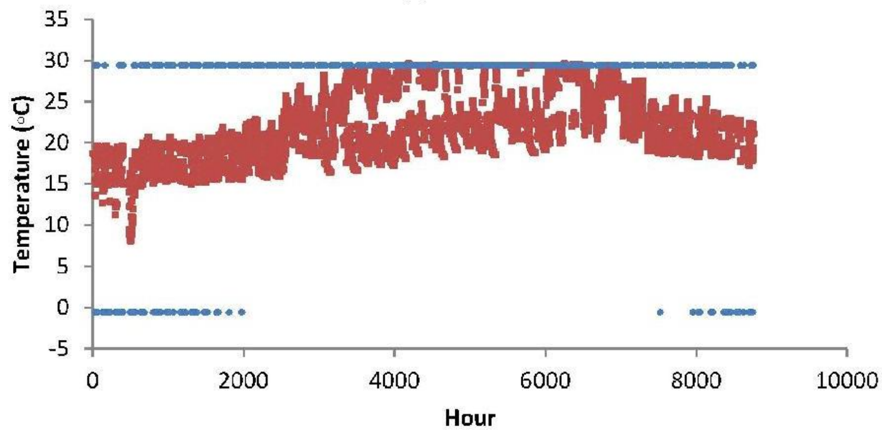


Fig. 7 Hourly cooling control setpoint and EFT to the heat pump for Fixed-1, Fixed-2 and Fixed-3

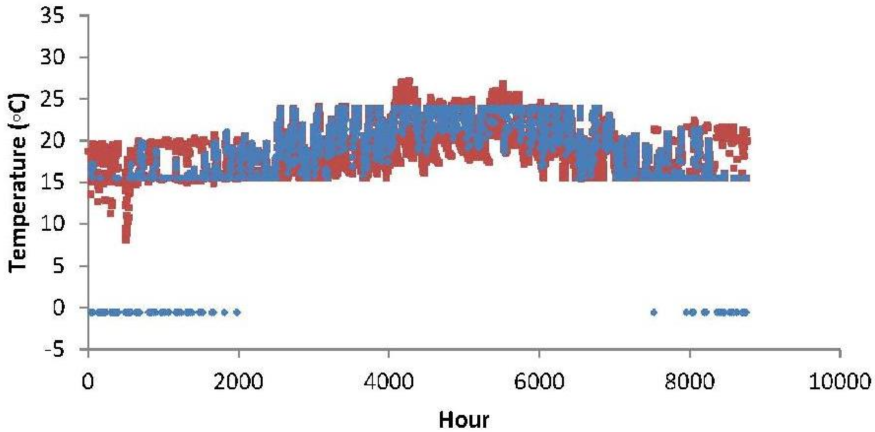
OA-Reset Cooling Setpoint

As shown in Table 9, the HVAC electric consumptions reduce from 55082 kWh to 44198 kWh and 43740 kWh as the supply leaving temperature at the outdoor drybulb high increases every 2.8 degree C The energy end use for space cooling keeps increasing due to the higher temperature of the supply water from the circulation loop into the condenser. Compared with OA-1, the energy end uses for the fluid cooler fan drop 86.4% for OA-2 and 98.0% for OA-3, respectively. Similarly, the spray pump and loop pump totally saves 2795 kWh and 3423 kWh.

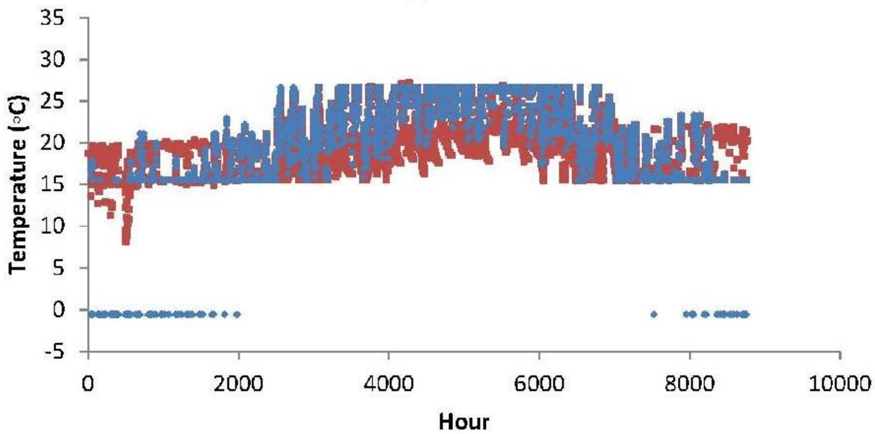
Table 9 HVAC Electric consumptions (kWh) in year 1 (OA-RESET)

Case No.	OA-1	OA-2	OA-3
Space Cool	27783	29010	30370
Fluid Cooler Fan	10858	1479	216
Spray Pump	4034	3841	3293
Space Heat	1390	1389	1388
Vent. Fans	5702	5766	5840
Loop Pump	5316	2713	2634
HVAC Total	55082	44198	43740

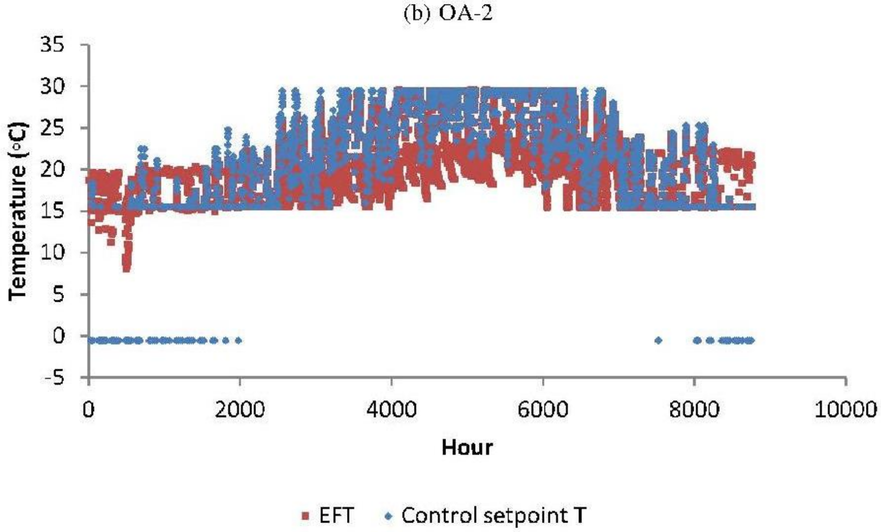
Unlike fixed cooling setpoint control, the cooling setpoint for OA-Reset has a linear relationship with the outdoor drybulb temperature. Fig.8 shows that the EFT to the heat pumps varies between the upper (23.9ºC, 26.7ºC, and 29.4ºC) and lower (15.6ºC) limits of OA reset schedules. The hours exceeding the upper limits are gradually reduced as these upper limits increase.



(a) OA-1



(b) OA-2



(c) OA-3

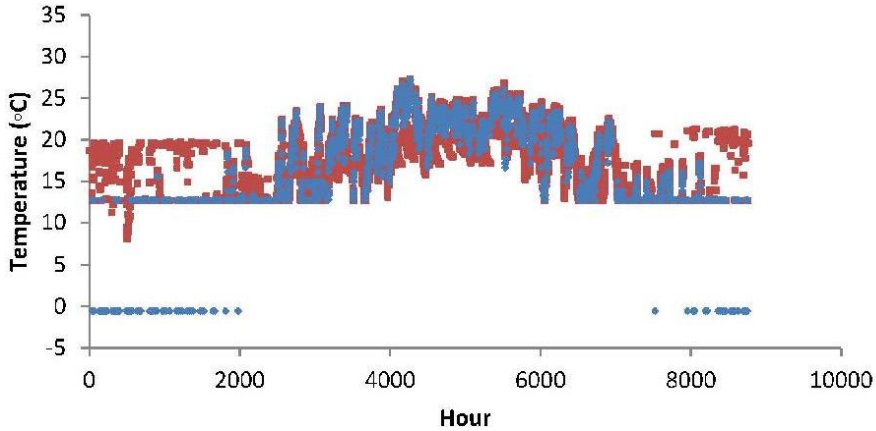
Fig. 8 Hourly cooling control setpoint and EFT to the heat pump for OA-1, OA-2, and OA-3

Wetbulb Reset Cooling Setpoint

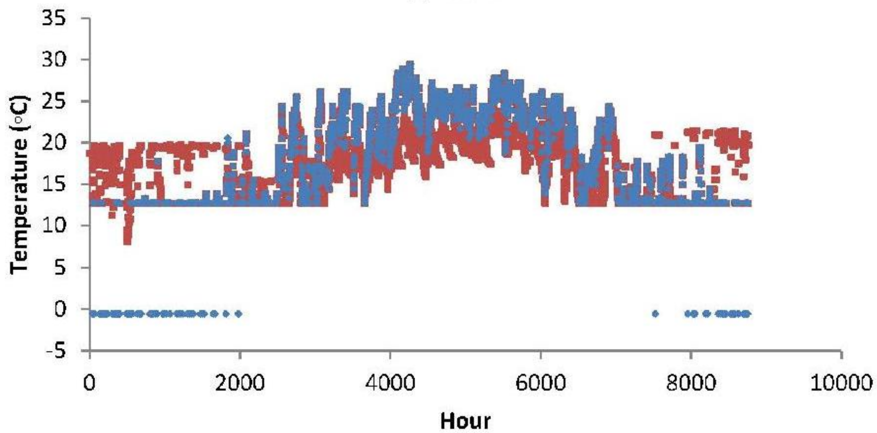
In order to investigate the impact of WETBULB-RESET DT on the HVAC electric consumption, cases WB-1 to WB-3 were simulated with WETBULB-RESET DT at 0.6°C, 2.8°C, and 5.6°C. Table 10 presents that total HVAC electric consumption decreases from 77955 kWh to 45518 kWh when WETBULB-RESET DT increases from 0.6°C up to 2.8°C. As addressed before, the electric end uses for fan and space heat are quite stable for three case scenarios. Further increasing DT to 5.6°C only reduces the HVAC electric consumption by1957 kWh. Fig.9 presents that the EFT to the heat pumps is quite stable when the outdoor wetbulb temperature is quite below the ground temperature. This occurs in the heating season when the building occasionally requires cooling. In the cooling season, the EFT continuously changes with the outdoor wetbulb temperature.

Table 10 HVAC electric consumptions (kWh) in Year 1 (WB-RESET)

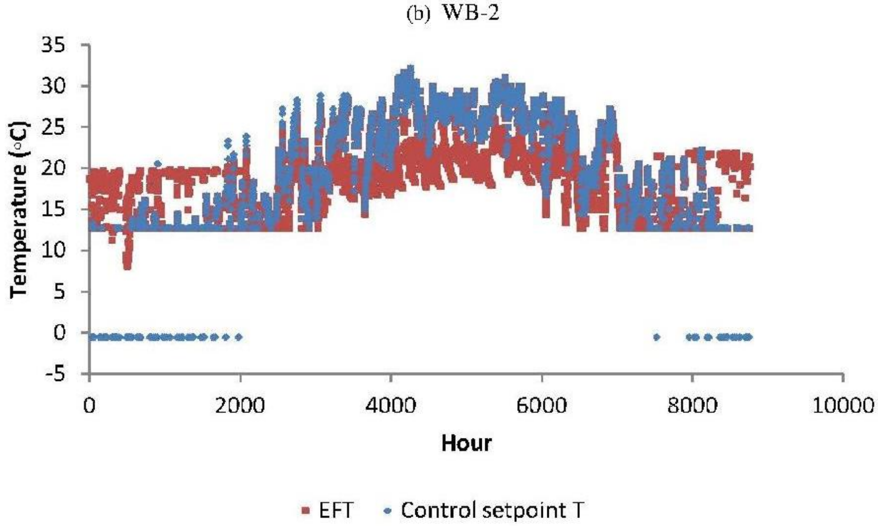
Case No.	WB-1	WB-2	WB-3
Space Cool	26936	27779	29557
Fluid Cooler Fan	28983	3316	300
Spray Pump	4249	4199	3790
Space Heat	1396	1396	1394
Vent. Fans	5663	5707	5800
Loop Pump	10727	3122	2725
HVAC Total	77955	45518	43567



(a) WB-1



(b) WB-2



(c) WB-3

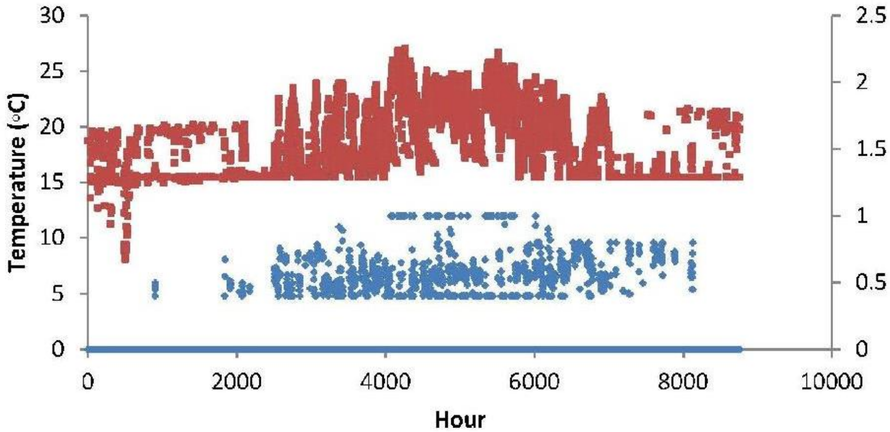
Fig. 9 Hourly cooling control setpoint and EFT to the heat pump for WB-1, WB-2, and WB-3

Load Reset Cooling Setpoint

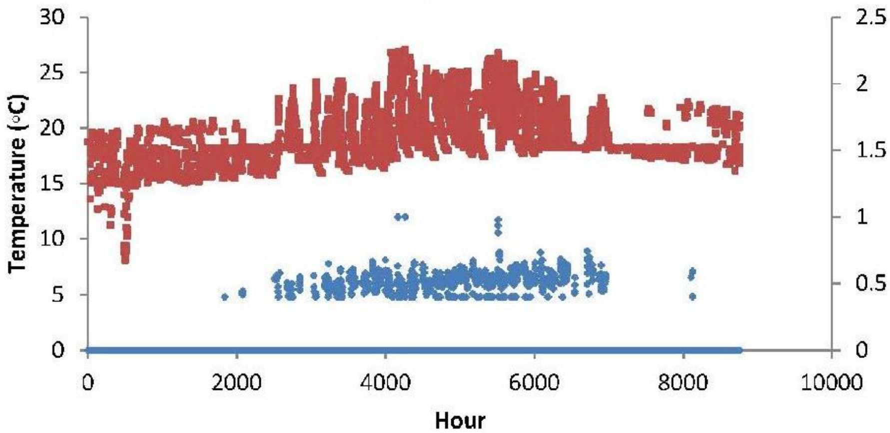
Load-Reset actually shows quickly similar trend as OA-Reset as presented in Tables 11. The higher MAX-RESET-T can drop the energy end use for fluid cooler including fan and spray pump but increase the energy end use for space cooling. Overall, the total HVAC energy can be saved with this cooling control strategy. Fig. 10 shows that the fan runs less frequently when MAX-RESET-T increases. The EFT to heat pumps increases accordingly.

Table 11 HVAC Electric Consumptions (kWh) in Year 1 (LD-RESET)

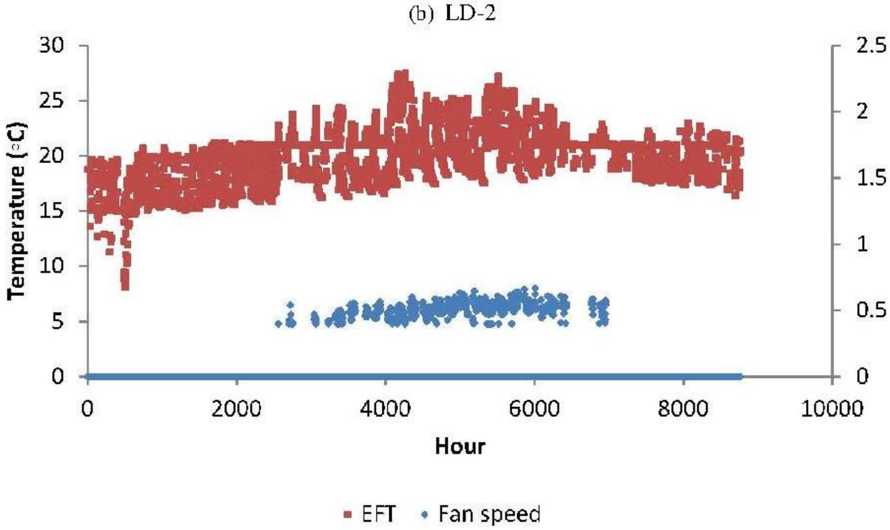
Case No.	LD-1	LD-2	LD-3
Space Cool	27070	27617	28253
Heat Reject.	9498	3631	2364
Space Heat	1391	1389	1388
Vent. Fans	5668	5693	5722
Pumps & Aux.	13891	11778	9273
HVAC Total	57518	50108	47001



(a) LD-1



(b) LD-2



(c) LD-3

Fig. 10 Hourly fan speed and EFT to the heat pump for LD-1, LD-2, and LD-3

Heat rejection and EFT rise

Table 12 summarizes fluid cooler rejection loads, GLHX heating/cooling loads, and max/min entering fluid temperatures to the heat pump for various control strategies in year 1 and year 30. On an annual basis, the heat rejection to the ground is much higher than the heat extraction from the ground. So, even with the supplementary heat rejecter like the fluid cooler, the heat still is built up in the ground. The increment of the max and min EFTs proves the load aggregation in the ground during the 30 year operation. In year 30, the GLHX rejects less heat than the amount of the heat rejected in year 1 due to the temperature rise in the ground. Conversely, the fluid cooler runs somewhat longer to main the cooling setpoint by rejecting more heat to the air. Basically, the heat rejection load just shifts from the GLHX to the fluid cooler. A comparison among twelve control strategies shows that due to the higher cooling setpoint, a general increase in the heat rejection to the ground via the GLHX is observed in year 1 and year 30. Accordingly, the fluid cooler is activated less with the reduced heat rejection to the air.

Table 12 Heat rejections by GLHX/fluid cooler and EFT rise in Year 1 and Year 30

Case No.	Year	Fluid cooler Heat Rejection Load (MWH)	GLHX Cool Load (MWH)	GLHX Heat Load (MWH)	Max EFT (ºC)	Min EFT (ºC)
Fixed-1	Year 1	63	173	-6	29.4	8.9
	Year 30	137	101	-6	30.7	15.2
Fixed-2	Year 1	38	199	-6	29.6	8.9
	Year 30	117	122	-6	31.2	16.6
Fixed-3	Year 1	19	219	-6	31.6	8.9
	Year 30	96	144	-6	33.0	17.9
OA-1	Year 1	99	138	-6	29.3	8.9
	Year 30	161	77	-6	30.2	13.5
OA-2	Year 1	76	159	-6	29.5	8.9

	Year 30	148	89	-6	30.6	14.3
OA-3	Year 1	54	183	-6	31.4	8.9
	Year 30	134	104	-6	32.4	15.3
WB-1	Year 1	130	110	-6	29.2	8.8
	Year 30	170	71	-6	30.1	12.9
WB-2	Year 1	111	124	-6	30.4	8.8
	Year 30	159	76	-6	31.3	13.3
WB-3	Year 1	76	161	-6	32.7	8.8
	Year 30	142	95	-6	33.7	14.6
LD-1	Year 1	120	121	-6	29.2	8.9
	Year 30	169	71	-6	30.1	13.1
LD-2	Year 1	102	137	-6	29.3	8.9
	Year 30	164	75	-6	30.2	13.5
LD-3	Year 1	84	154	-6	29.6	8.9
	Year 30	152	86	-6	30.7	14.3

Average entering fluid temperature to heat pump

The average entering fluid temperature is key parameter that affects the performance of the heat pump. Table 13 lists average EFTs in year 1 and year 30, and average EFT rises. The average EFT in year 1 is in the range of 17.9°C and 23.6°C. In year 30, the average EFT to heat pumps varies between 18.2°C and 28.3°C. Because the heat rejection to the ground is much larger than the heat extraction from the ground even with the supplemental fluid cooler, the ground temperature gradually increases during the course of the 30 year operation. For the current study, the average EFT rise from 0.2°C up to 4.2°C, respectively.

Table 13 Average entering fluid temperatures in the cooling mode

Case No.	Average EFT (˚C) in Year 1	Average EFT (˚C) in Year 30	ΔT (˚C) in Year 30
Fixed-1	21.9	23.8	1.8
Fixed-2	23.2	26.0	2.8
Fixed-3	24.1	28.3	4.2
OA-1	19.8	20.2	0.3
OA-2	20.9	21.2	0.3
OA-3	22.1	22.6	0.5
WB-1	17.9	18.2	0.3
WB-2	18.7	18.8	0.2
WB-3	20.6	20.9	0.3
LD-1	18.9	19.2	0.2
LD-2	20.0	20.5	0.5
LD-3	20.9	22.1	1.1

Based on the simulation result, the loop cooling control strategies can be divided into four categories as follows. In category 1, Fixed-2 and Fixed-3 have the lowest HVAC electric consumption but highest EFT rise. OA-2, OA-3, WB-2, and WB-3 have relative high HVAC electric consumption as compared with Fixed-2 and Fixed-3. However, they also have the lowest EFT rise among four categories. Category 3 including Fixed-1 and LD-3 show higher HVAC electric consumption and EFT rise as compared with second category. The last category includes

LD-1, LD-2, OA-1, and WB-1, which have the highest HVAC electric consumption but the lowest EFT rise. So, OA-2, OA-3, WB-2, and WB-3 can successfully balances the thermal load on the ground loop. While the undersized well field is combined with the supplemental heat rejection device, the heat pump units still can run at the relative high efficiency.

Loop cooling control strategy:

1. Fixed-2 and Fixed-3
2. OA-2,OA-3, WB-2, and WB-3
3. Fixed-1 and LD-3
4. LD-1, LD-2, OA-1, and WB-1

Unmet hour

Besides the annual HVAC electric consumptions and max/min EFTs, the unmet hours also can be used to evaluate the performance of the hybrid GSHP system. The thermostat throttling range is 0.28°C. If the zone temperature is away from the cooling/heating setpoint by more than this value, the cooling/heating unmet hours will increment as appropriate. As required by LEED, the unmet hours are within 300 hours. For this study, the unmet hours are between 10 and 11 hours. This indicates that the room temperature was well controlled by the hybrid GSHP system.

Table 14 Unmet hours of any zone above cooling/heating throttling range

Case No.	Cooling unmet hour	Heating unmet hour	Total Unmet hour
Fixed-1	8	2	10
Fixed-2	8	2	10
Fixed-3	9	2	11
OA-1	8	2	10
OA2	8	2	10
OA-3	9	2	11
WB-1	8	2	10
WB-2	8	2	10
WB-3	8	2	10
LD-1	8	2	10
LD-2	8	2	10
LD-3	8	2	10

Conclusions

The newly released eQUEST 3.7 was selected to simulate a ground loop heat exchanger together with supplemental heat rejection device to reduce the size of the well field from 72 (8 × 9 array) boreholes to 32 (4 × 8 array) boreholes. The multiple control strategies including fixed setpoint, outside air reset, load reset, and wetbulb reset were adopted to optimize the performance of the hybrid GSHP system. For the first year of operation, the conventional GSHP system uses less electric energy than the hybrid GSHP system by taking the advantage of much larger well field (8 x 9 array). However, due to the heat imbalance on the ground loop, the EFT rises much faster than any case scenarios simulated for the hybrid GSHP system.

For the hybrid GSHP system, Fixed-2 has the lowest HVAC energy consumption in year 1. It takes advantage of moderate ground temperature to reject the heat load to the ground and balances the energy end uses between heat pump and cooling tower. However, it has the second highest average EFT rise in year 30 among all 12 case scenarios.

In general, the control strategies that reject more heat through the GLHX give more benefit than those that reject less heat through the GLHX. However, the simulation results also indicate that the higher cooling setpoint cannot guarantee the energy savings of the HVAC system. When the energy end use of the fluid cooler is only a small portion (5.2%) of the annual HVAC energy consumption, the benefit to further lower the operation duration/frequency of the fluid cooler associated with the higher cooling setpoint is very limited. At the meantime, the penalty of increasing the energy end use for the heat pump can offset the energy savings from the fluid cooler.

For 67% of case studies, the average EFT to heat pumps is quite constable as the rise of EFT is less than 0.6ºC during the 30 year operation period. So, the indoor unit can run at the relative high efficiency during the cooling season. From the heating side, the hybrid GSHP can benefit from the increasing of minimum EFTs to the heat pumps. As indicated by the rise of average EFTs, the thermal load is well balanced on the ground loop in the cooling dominated climate zone such as Oklahoma City with the loop cooling control strategies such as OA-2, OA-3, WB-2, and WB-3.

The unmet hours are around 10 hours during the course of the first year operation. With properly loop cooling control strategies, the hybrid GSHP system shows the excellent capability to meet the cooling and heating setpoints during the occupied hours, balance thermal loads on the ground loop, as well as improve the thermal comfort of the occupants with the undersized well field.

Nomenclature

Outdoor-Hi: upper limit of outdoor drybulb temperaturre

Outdoor-Low: lower limit of outdoor drybulb temeprature

Cooling-Hi: cooling setpoint corresponding to the upper limit of outdoor drybulb temperaturre

Cooling-Low: cooling setpoint corresponding to the lower limit of outdoor drybulb temeprature

MAX-RESET-T: upper limit of the floating tower temperature

MIN-RESET-T: lower limit of the floating tower temperature

T_1: hourly cooling temperature setpoint

T_2: hourly outdoor wetbulb temperature

ΔT: differential between the hourly cooling setpoint and ambient wetbulb

EFT: entering fluid temperature to the heat pump, °F (°C)

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