AC 2007-2153: DESIGN AND CONSTRUCTION OF A LAB-SCALE GROUND SOURCE HEAT PUMP

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Design and Construction of a Lab-Scale Ground Source Heat Pump

Abstract

Undergraduate engineering and engineering technology students are in need of rigorous and multi-faceted hands-on activities to enhance their self-confidence and technical skills. Very few courses give students the opportunity to approach practical design and production problems in a holistic manner. Senior design courses or capstone projects frequently give students the opportunity to design complex or multi-component systems in a timely effective manner. However, most capstone design projects are only concerned with the design itself and not with production, construction, or implementation of the design outcomes because of time restriction or lack of resources.

In this paper, a case study is presented which shows how two groups of students undertook the design and construction of a lab-scale ground source heat pump (GSHP). The first group was responsible for the design and component selection of the GSHP. As part of the design process, the students derived and specified an appropriate performance metric based on the first law of thermodynamics which was then used to guide the design optimization process. As a result, size, weight and cost of the system were determined and optimized computationally. A second group of students built a GSHP taking into account the established design attributes and a limited budget. After successful construction and installation of the lab-scale GSHP, undergraduate students in engineering technology are now able to experimentally measure its performance under various experimental conditions.

Introduction and Motivation

Senior design courses and capstone projects give senior-level students the opportunity to manage multi-faceted projects. However, very few projects involved the design and construction of multi-component systems such as advanced thermal systems. The design and construction of advanced thermal systems involves the application of basic thermodynamic principles. The first and second laws of thermodynamics as well as other physical principles including continuity and energy equations for fluids need to be considered in the design process. Design of complex system compels engineering and engineering technology students to set up the design problem in a simple but effective mathematical form so the right design solution set or outcomes can be obtained with ease. Other motivating factors that each engineering and engineering technology student taking capstone courses should strive for are as follows:

- Ability to design multiple-component systems taking into account the interconnections among all the subsystems
- Ability to take is into account dynamic or transient behavior of complex system
- Ability to design and build systems within a limited budget
- Ability to integrate and use multiple engineering and science disciplines in an expeditious and easy manner
- Ability to learn about the latest trends in thermal management or pertinent field of study

- Ability to design and build laboratory equipment, and high value-added or high end products
- Ability to learn how to assemble equipment and components from different suppliers at low cost

In the case of advanced thermal systems, students, engineers and plant managers should also possess or acquire the necessary technical skills to meet future energy-related challenges including energy conservation in a competitive global economy. Students should have the ability to specify fluid mechanics and heat transfer equipment based on availability, size, quality and cost with confidence. Students should also know how to propose and formulate novel ideas for advanced thermal systems. Students should be able to explore, research and test cost effective energy solutions so they can be implemented in the near future.

Background

In recent years, several investigators have reported on the need to improve senior design or capstone courses so the students can be better prepared for jobs in industry[1-5]. Specifically, recent publications have even suggested and shown that senior design courses can be enhanced by incorporating hands-on and prototype building activities into the courses requirements[6-9]. In the case of designing, building and testing (DBT) thermal equipment for laboratory courses, Choate and Schmaltz[10] showed that such activities encourage students to be successful in independent research activities and promote lifelong learning. More recently, Post[11] presented the results of a fairly complex solar thermal pump which indicates that students can tackle challenging tasks with the right guidance.

These publications show that design and construction activities can be a formal and regular part of any capstone design course. In this paper, design and construction activities undertaken by students as part of a capstone course are described in detail. The activities show that students were successful in meeting the technical challenges posed by the project.

Implemented Model for Senior Design Course or Capstone Project

The first part of the case study was to devise the appropriate course model to be able to involve students in the design, development and construction of a lab-scale ground source heat pump (GSHP). Figure 1 shows the traditional or conventional approach frequently used in most senior design courses. It basically shows a course coordinator as the main point of contact for all major activities including project selection and assignment, and student group selection. Even though such a model has been used effectively for years, it may not be well suited for more advanced or complex projects because of the lack of resources, technical expertise or even time. Given the nature of complex thermal systems, a more appropriate model should be considered[12]. Figure 2 shows the senior design course model used for the design, development and construction of a lab-scale GSHP. As in the conventional case, Figure 1, it also shows a course coordinator as the main point of contact for project selection and assignment, and student group selection. However, the implemented course model takes advantage of a specific and well-qualified expert or technical advisor in the field of interest that is also responsible for securing funding for the project[12]. The technical advisor supervises the students' technical progress during the semester to make sure the stated goals are achieved and the project remains within the approved budget. In the case of the lab-scale GSHP, the technical advisor secured $5,000 from ASHRAE (American Society of Heating, Refrigerating, and Air Conditioning Engineers) to design and build the advanced thermal system.

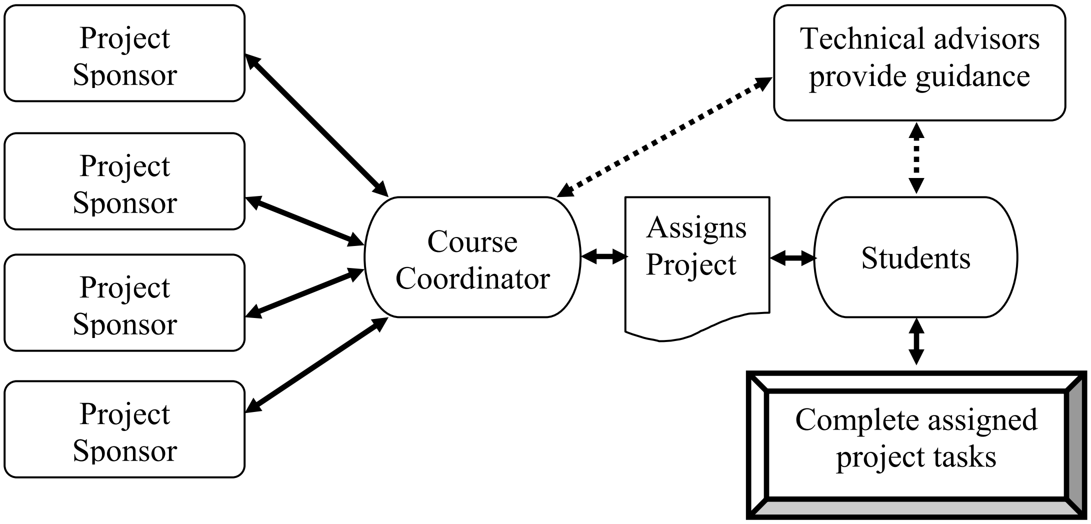


Figure 1. Conventional senior design course structure

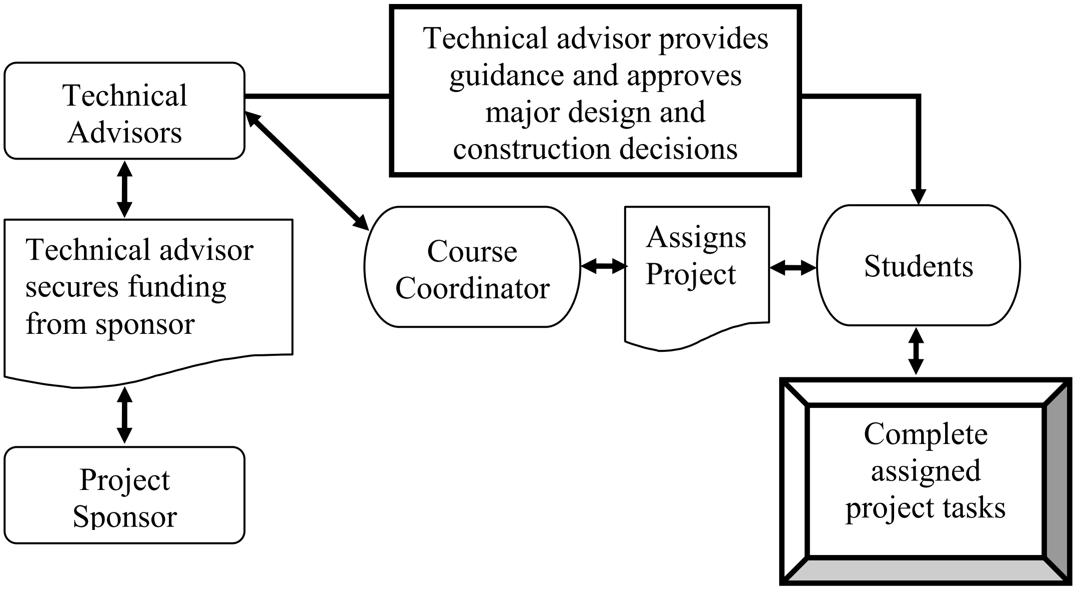


Figure 2. Implemented senior design course structure

Case Study: Design and Construction of Lab-Scale Ground Source Heat Pump

Brief introduction of GSHP

A ground source heat pump (GSHP) exchanges heat with the ground to heat or cool a building, as depicted in Figure 3. It uses a secondary heat transfer fluid like water or a water-antifreeze solution which it is pumped through a closed or u-tube in the ground. The ground acts as a heat sink or heat source depending on the time of the year and location. GSHP make use of the abundant thermal energy or thermal inertia of the ground due to its massive size. The ground below any residential unit or building could stay at a relatively steady temperature below a certain depth[13]**.** GSHPs are becoming more popular because of their simplicity and low operating cost. However, initial equipment and installation costs, unknown long-term performance, and lack of familiarity are the major obstacles in their intended widespread use.

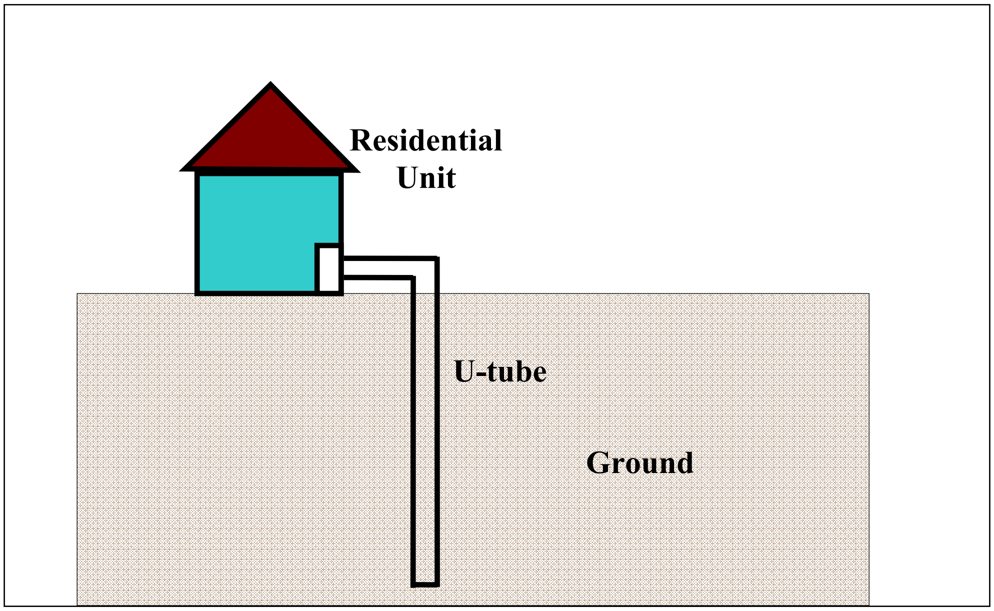


Figure 3. A ground source heat pump exchanges heat with the ground

Project scope and objectives

The scope and objectives of the project was to research, design and build a modern lab-scale version of a ground source heat pump. The lab-scale GSHP will be used in the thermal sciences laboratory as part of an applied thermodynamics course. Students taking the course will have the opportunity to learn about GSHPs and how they perform in the long term. The project objectives were broken down into two main categories: Research and Design, and Construction. Two groups of undergraduate students taking the senior design course in our department were responsible for achieving the project's objectives.

Research and Design of lab-scale GSHP

The first senior design team was responsible for setting the design objectives and criteria for designing a lab-scale GSHP for the thermodynamics laboratory. As the first task, the group had to consider the long-term effects of using a ground source heat pump on the surrounding environment while being limited to volume size constraints in the laboratory. Long-term effects include undesirable changes in soil temperature and moisture level, which can have a negative impact on GSHP performance. The students considered different GSHP configuration to determine the one most suitable for the thermodynamics lab. After looking at all the configuration possibilities, the students, under the supervision of the author, selected a vertical configuration because it can take advantage of ample vertical space available in the lab. The first group of students also researched which components are necessary for a complete GSHP system. The components included a large plastic container, a water tank, pumps, heater (to simulate thermal loads), u-tube, soil, flowmeter, thermocouples, soil moisture sensors, insulation, data acquisition system and sufficient piping. A preliminary configuration is shown in Figure 4.

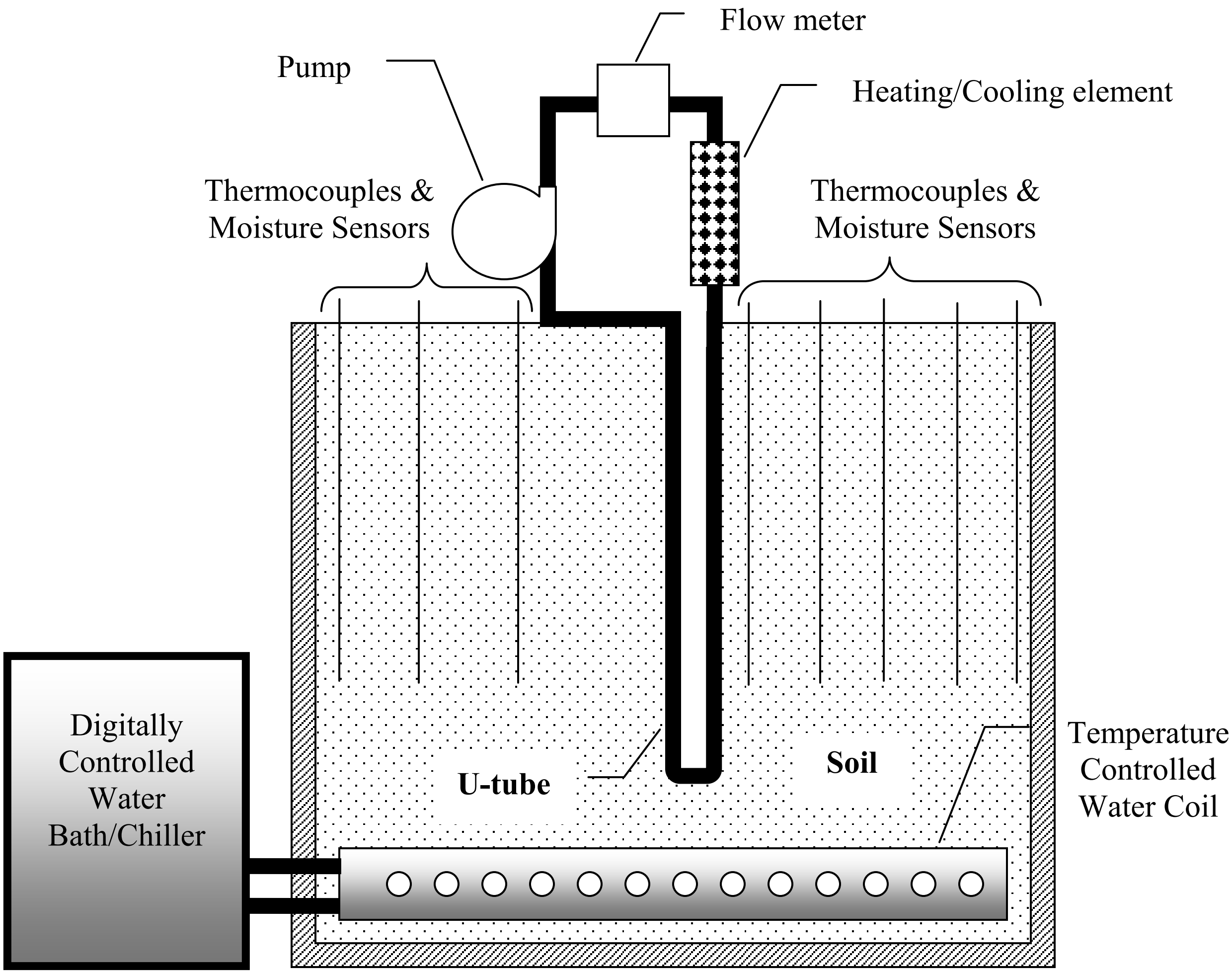


Figure 4. Preliminary lab-scale GSHP system

As seen in Figure 4, a large plastic container is needed to store a considerable amount of soil so its temperature can remain relatively constant during any GSHP experiment. The u-tube acts as a heat exchanger where the heat transfer fluid (water) can transfer energy to the ground. A pump can be used to pump the fluid from the water tank through the u-tube or through a heater. Thermocouples are placed in the soil container and along the u-tube external surface to measure temperature changes during the cooling or heating process. The experiments will determine how effective the u-tube, flowing fluid and soil are in transferring heat. The experimental data will also be used to measure the effective coefficient of performance (COP) of the lab-scale GSHPs[13].

The next phase of the design process was to size each component based on the conservation of energy principle and flow equations. Using Engineering Equation Solver (EES), the students were able to size each component with relative ease. The first step was to determine the optimal size of the container so an average soil temperature rise could be minimized. The student performed first-law analysis for the GSHP which was modeled as a closed system with a line source of heat as shown in Figure 5. From the first law of thermodynamics, the energy balance is as:

$$\dot{E}_{in} - \dot{E}_{out} = \Delta\dot{E}_{system} = \Delta\dot{U}_{system} \tag{1}$$

For the GSHP shown in Figure 5, Equation 1 can be expressed as:

$$\dot{Q}_{in} = m \cdot c_p \frac{\Delta T}{\Delta t} \tag{2}$$

Where, $\dot{Q}_{in}$, m, c_p, and $\frac{\Delta T}{\Delta t}$ are the *heat rate in*, *mass of soil*, *specific heat of soil*, and *temperature rise per unit time*, respectively. To determine the size or volume of the container, Equation 2 was solved for m (mass) and volume as shown in Equation 3.

$$m = \frac{\dot{Q}_{in}}{c_p \frac{\Delta T}{\Delta t}} \rightarrow V = \frac{m}{\rho} = \frac{\dot{Q}_{in}}{\rho \cdot c_p \frac{\Delta T}{\Delta t}} \tag{3}$$

where, ρ and V are the *soil density* and *container volume*, respectively. The soil density and specific heat used for the calculations were 1500 kg/m^3 and 800 J/kg-K, respectively. The soil properties were based on information provided by the soil supplier. Thermal characterization experiments were conducted to validate the soil properties and the supplier's claim. The results are consistent with recent published data[13]. The resulting design variables and their selected ranges are shown in Table 1.

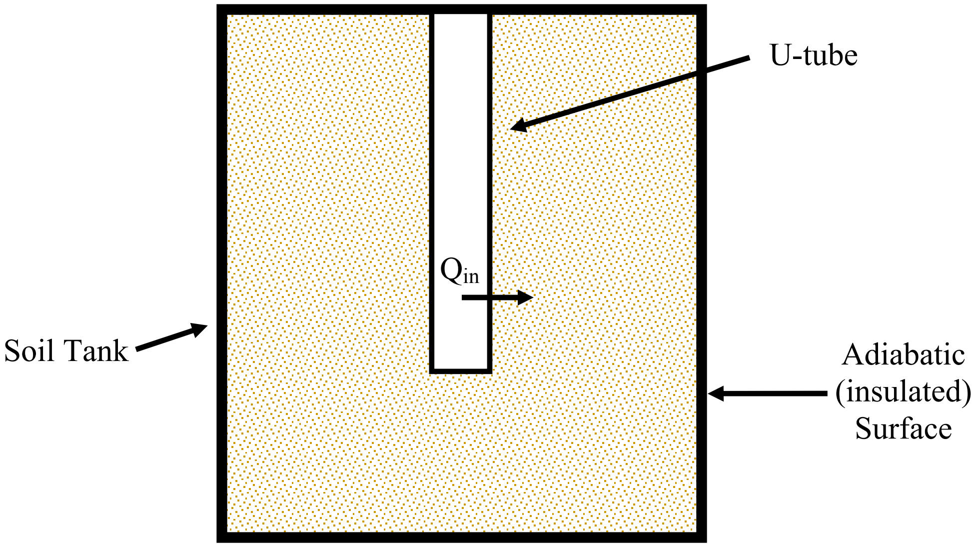


Figure 5. Schematic representation for first-law analysis

Table 1. GSHP System Design Variables

Variable	**Range**	**Fixed Value**
Heat rate in, $\dot{Q}_{in}$ in Watts	10 - 100	25
Temperature rise, ΔT in ° C	1 - 10	5
Time for temperature rise, Δt in days	1 - 5	3

Table 1 shows those design variables that have a direct impact on the size of the soil container. The heat rate is also used to determine the flowing fluid flowrate necessary to transfer the amount of heat listed in Table 1. To determine what should be the maximum container size, each variable was allowed to float or vary while the other two variables remained fixed as prescribed in Table 1. The students used EES to run several simulations to determine the required amount of soil for the GSHP. The simulation results are shown in Figures 6 through 8, as provided by the students.

Density = 1500 kg/m^3 Cp = 800 J/(kg-k)
ΔT = 1 TO 10 K
Q = 25 W
Δtime = 3 days

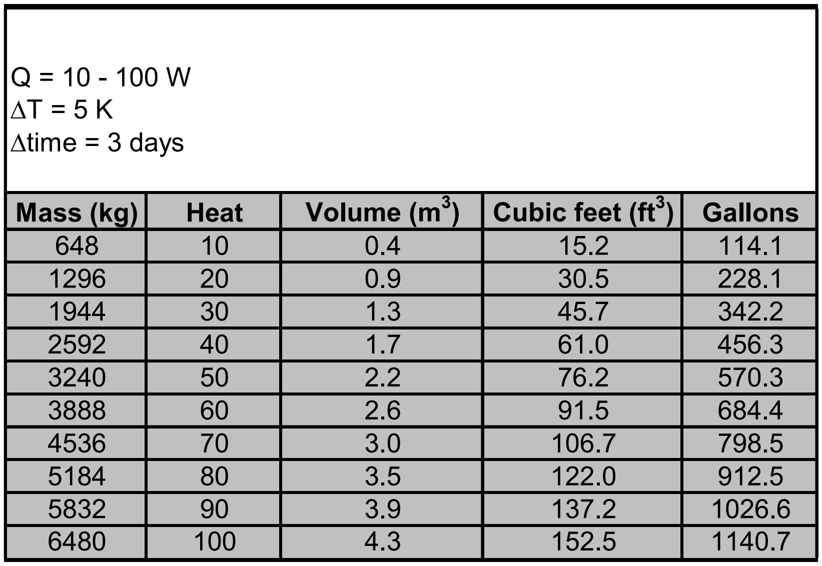
Run	Mass (kg)	Temp (K)	Volume (m^3)	Cubic feet (ft^3)	Gallons
1	8100	1	5.4	190.6	1425.8
2	4050	2	2.7	95.3	712.9
3	2700	3	1.8	63.5	475.3
4	2025	4	1.4	47.7	356.5
5	1620	5	1.1	38.1	285.2
6	1350	6	0.9	31.8	237.6
7	1157	7	0.8	27.2	203.7
8	1013	8	0.7	23.8	178.3
9	900	9	0.6	21.2	158.4
10	810	10	0.5	19.1	142.6

Figure 6. GSHP simulation result for several temperature rises

Δtime = 1 - 5 days
ΔT = 5 K
Q = 25 W

Mass (kg)	Time (sec)	Time (day)	Volume (m^3)	Cubic feet (ft^3)	Gallons
540	86400	1.00	0.4	12.7	95.1
780	124800	1.44	0.5	18.4	137.3
1020	163200	1.89	0.7	24.0	179.5
1260	201600	2.33	0.8	29.7	221.8
1500	240000	2.78	1.0	35.3	264.0
1740	278400	3.22	1.2	40.9	306.3
1980	316800	3.67	1.3	46.6	348.5
2220	355200	4.11	1.5	52.2	390.8
2460	393600	4.56	1.6	57.9	433.0
2700	432000	5.00	1.8	63.5	475.3

Figure 7. GSHP simulation result for several time periods (days)



Q = 10 - 100 W
$\Delta T = 5$ K
Δtime = 3 days

Mass (kg)	Heat	Volume (m^3)	Cubic feet (ft^3)	Gallons
648	10	0.4	15.2	114.1
1296	20	0.9	30.5	228.1
1944	30	1.3	45.7	342.2
2592	40	1.7	61.0	456.3
3240	50	2.2	76.2	570.3
3888	60	2.6	91.5	684.4
4536	70	3.0	106.7	798.5
5184	80	3.5	122.0	912.5
5832	90	3.9	137.2	1026.6
6480	100	4.3	152.5	1140.7

Figure 8. GSHP simulation result for heat rate values

From the simulation studies, it is evident that *heat rate* has the greatest impact on *container size* and *soil mass*. A design value of 700 gallons or about 2.65 m^3 for the *container volume* was selected due to the availability of a plastic container of that size and to avoid extremely high normal stresses on the lab's floor.

The students also specified soil type and supplier, pumps, heater, flowmeter, soil moisture sensor, thermocouple wire, and insulation. The heater was sized for a 10.9 mm copper tubing section with a maximum load of 100 W. The U-tube is about 10 ft or 3.05 m in length and 10.9 mm in diameter with a 200 µm helical enhancement at 18° to enhance heat transfer. Centrifugal pumps were selected because the flowrate can be easily adjusted by controlling the electric motor speed. The students selected a ½ hp pump which has enough capacity to transfer heat from the water tank to the soil tank, and for the specified tubing length. A combination of downstream valve and frequency controller (silicon-controlled rectifier or SCR) was used to control the flow and speed of the pump, respectively. The soil moisture sensor selected is specifically designed for soil moisture sensing applications. Type T thermocouples with water resistant coatings were chosen because they have high accuracy and readability compared with other thermocouple types. The thermocouples will be connected to an Agilent data acquisition system for data logging. Thermocouples and soil moisture sensors will be used to determine how the heat transfer rate affects and is impacted by soil temperature and soil moisture levels. The students also selected standard air conditioning duct insulation (fiberglass) to insulate the soil tank and ensure adiabatic conditions at the container's surface. Adiabatic conditions were prevalent during all the experimental runs indicating the effectiveness of the insulation system. Cooling will be achieved by using a secondary heat transfer fluid such as an ice-water mixture in the flowing fluid's tank as shown in Figure 4.

This bench-scale GSHP will certainly give students the opportunity to learn about GSHP in general, and how thermal experiments should be run.

Construction and Assembly of lab-scale GSHP

A second senior design team was responsible for the construction and assembly of the lab-scale GSHP. As the first task, the second group reviewed the design put together by the first group a semester earlier. They started contacting suppliers to request the necessary quotes. Once all the quotes were received and scrutinized, the students made final material and equipment decisions based on conversation held with the faculty technical advisor. The decisions were based and driven by budget constraint, space availability and the appropriate design criteria. The students were asked to limit all purchases to no greater than $4000.

The second group of students also made necessary computer-based drawings to make sure they had a good understanding how to assemble and connect all the components of the GSHP as shown in Figure 9.

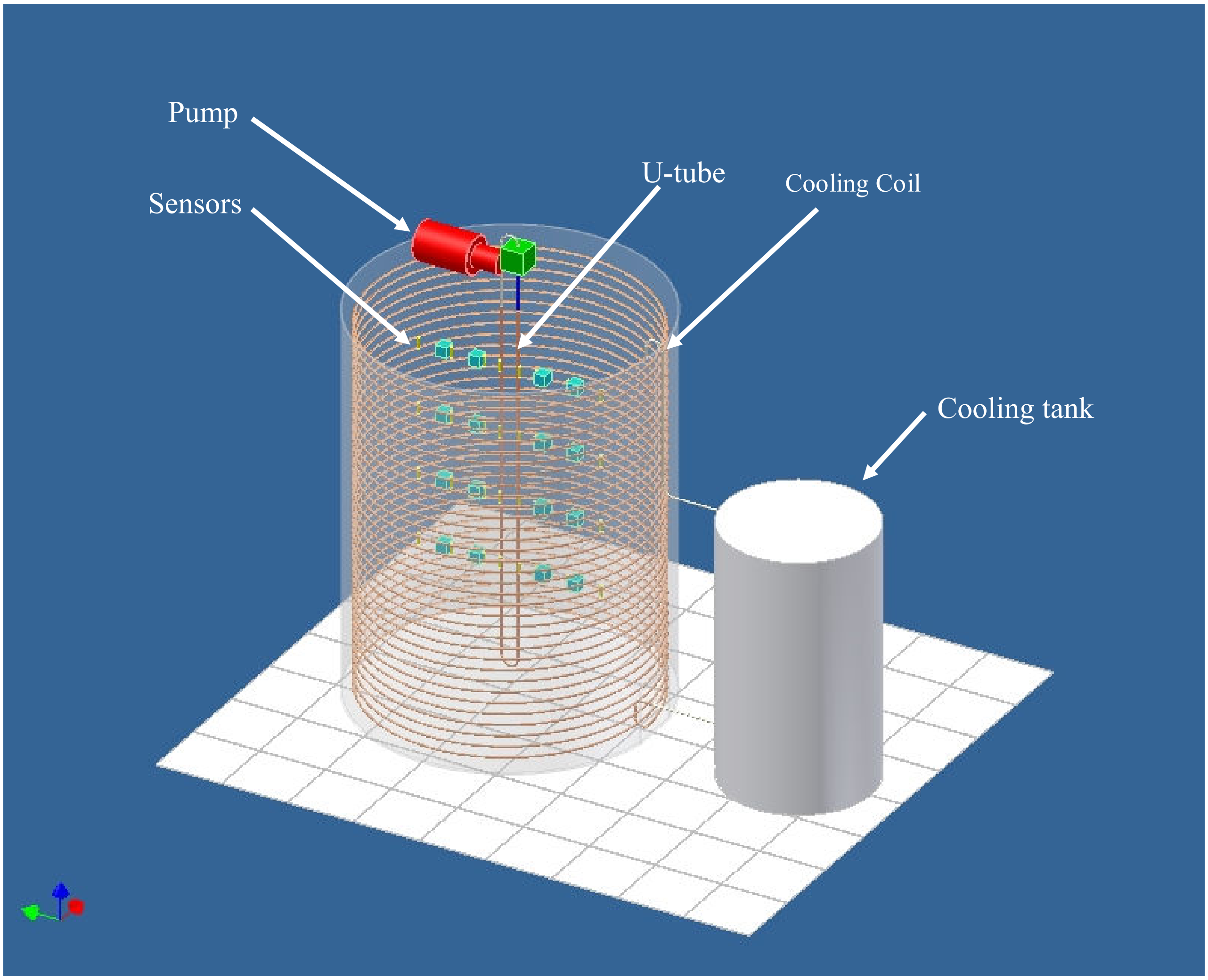


Figure 9. GSHP construction drawings

The students also modified the existing design in an effort to make the lab-scale GSHP better. One of the main modifications was to install a 450-ft (or about 138 m) of 6.4 mm soft copper tubing around the internal periphery of the tank to be used as a cooling coil inside the soil container. The cooling coil which is connected to a pump and water tank can provide enough cooling necessary to ensure specified soil temperatures at the beginning of each experiment. The temperature of the cooling tank is maintained by using the right amount of ice and water, and a temperature-controlled heater. Another major design modification was to devise a structure able to holding in place all the thermocouple connections and soil moisture sensors. The students designed and built a 3-D frame made of PVC as shown in Figure 10.

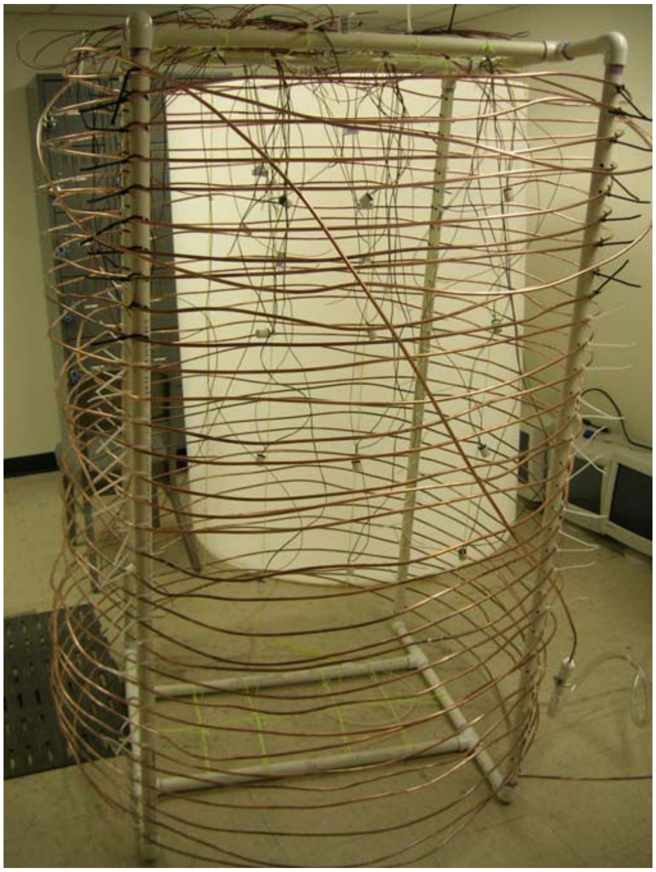


Figure 10. PVC Frame for thermocouples, soil moisture sensors and cooling coil

The location of the thermocouples and soil moisture sensors was based on a drawing made by the students as seen in Figure 11. The location of the u-tube was based on another drawing made by the students as seen in Figure 12. A picture of the complete lab-scale GSHP can be seen in Figure 13.

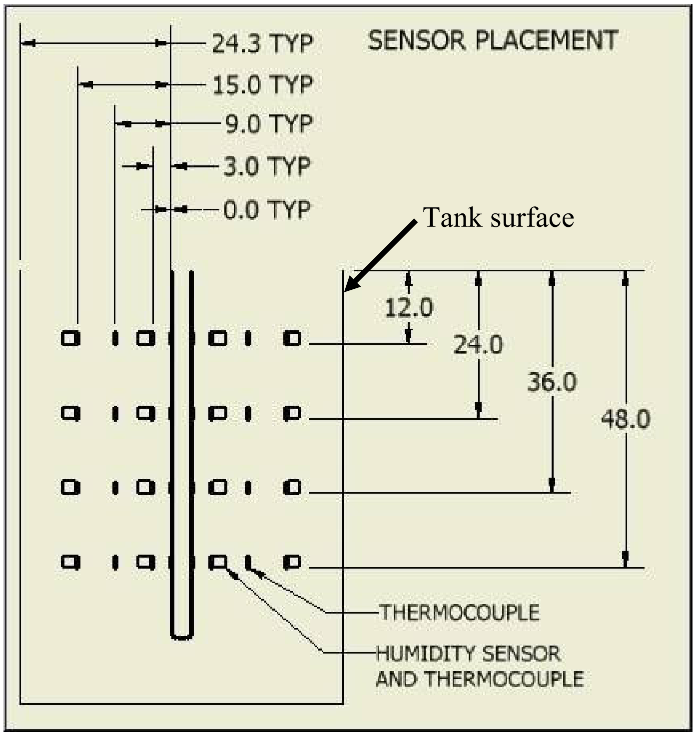


Figure 11: Vertical view of sensor location plan (all dimensions are inches)

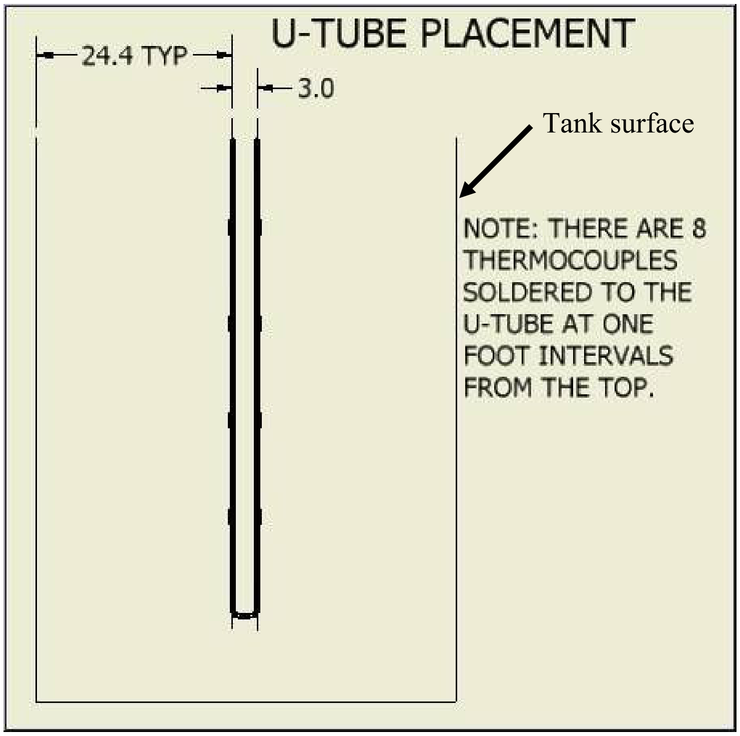


Figure 12: Vertical view of U-tube plan (all dimensions are inches)

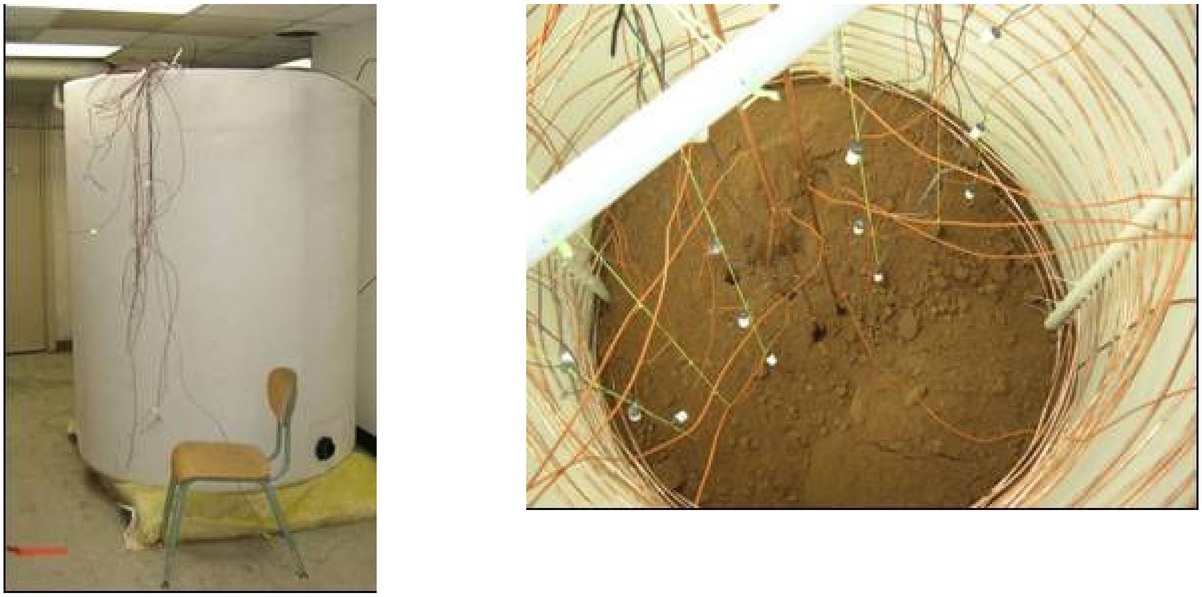


Figure 13. Lab-scale GSHP in the lab

Testing of lab-scale GSHP

The lab-scale GSHP still is being tested under various conditions to determine the impact of thermal load on the soil. Soil temperature and moisture content are being analyzed to draw appropriate conclusions. So far, the results from the first round of experiments have been positive. The soil can be used to dissipate a significant amount of thermal energy. An optimal combination of flow and heating rates is still being searched experimentally to find the best operating conditions. A report detailing the outcomes of all the experiments will appear in a Journal publication to be published soon.

Case Study Assessment

Each group of senior design students was evaluated based the project objectives and stated goals. Other aspects that were part of the evaluation are as follows:

- Ability to perform successfully the required calculations
- Ability to control the cost of the project
- Ability to complete tasks in a timely fashion
- Ability to perform each task with little supervision

Table 2 shows the results of technical advisor (faculty member) evaluation of both design groups based on the evaluation criteria shown above. The legend below shows and explains the meaning of each designated letter.

Table 2. Evaluation of design and construction activities

Group Description	**Met Objectives**	**Calculations**	**Cost Control**	**Timely Execution**	**Ability to perform with little supervision**	**Overall Score**
Design group	**E**	**E**	**G**	**G**	**G**	**G**
Construction group	**E**	**E**	**E**	**G**	**E**	**E**

Legend:

E-Excellent
G-Good
S-Satisfactory
NI-Needs improvement
U-Unacceptable

Based on the qualitative assessment of both groups as shown in Table 2, it is evident that the students were able to satisfactorily meet the stated objectives. The second group obtained a better rating because they showed a higher commitment to the project and took the initiative to propose design modifications. The design and construction of the GSHP showed the students' ability to deal with a relatively-complex real-life application with little supervision. From the students' point of view, they gave the project and course good ratings and rave reviews. Many favorable comments were made by the students during the exit interview including the fact that they had the opportunity to design and build something completely new.

Other observations worth noting include the students' ability to think independently and to conduct research with little help in a new area. The students were also able to use appropriate computer graphics packages and analytical tool to design and construct the lab-scale GSHP.

Conclusion

In this paper, a case study is presented which shows how two groups of students taking a capstone design course were able to design and construct a lab-scale ground source heat pump (GSHP) successfully. The first group successfully designed and selected the components necessary for the lab-scale GSHP. The students were able to apply first principles and speficied appropriate performance metric to guide the design optimization process. As a result, size, weight and cost of the system were determined and optimized computationally. A second group of students successfully built a GSHP taking into account the established design attributes and a limited budget. After successful construction and installation of the lab-scale GSHP, undergraduate students in engineering and engineering technology are now able to experimentally measure performance of a lab-scale GSHP under various experimental conditions.

The case study also shows that engineering and engineering technology students can enhance their self-confidence and technical skills by pursuing a senior design project that includes design and construction activities. The case study shows that those activities help students to make the best use of several disciplines including economics, thermodynamics, machine design, manufacturing processes and fluid mechanics.

Acknowledgments

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