AC 2010-1593: A MULTI-FACETED CAPSTONE DESIGN PROJECT IN HVAC

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A Multi-Faceted Capstone Design Project in HVAC

The Beginnings

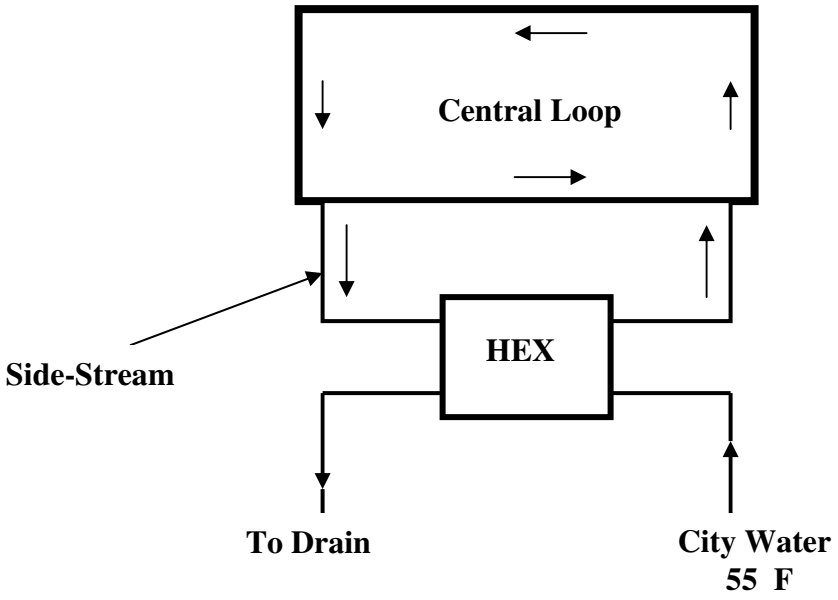
In 2000 I was contacted by a former student[1] working for an engineering firm in the HVAC field. He wanted to discuss a system that he had designed for cooling of a glycol/water solution used in a heating and cooling system for a commercial building. The situation was as follows:

A two-pipe heating and cooling system for a building has a central loop circulating either hot or chilled water. The central loop contains 426 gallons of 30% propylene glycol circulating at 168 gpm. When the system changes from heating to cooling, it is desired to cool the hot water from 180 F to 80 F within two hours. It is proposed to do this by bleeding off a side-stream of water from the central loop, passing this hot water through one side of a heat exchanger, and returning the water to the central loop. Cooling is provided by city water entering the heat exchanger at 55 F. A diagram of the system is shown below.

The problem is to size the heat exchanger and determine the required flow rates of the side-stream and the city water to achieve the desired cooling of the water in the central loop within the specified two-hour period.

After considering the problem, it became apparent that this might be the source of a very worthwhile project for my senior mechanical engineering students in the thermal/fluids capstone design course.

Figure No. 1 - The Proposed Cooling System



The Capstone Design Project

A capstone design project should be one that applies knowledge gained in several courses to the design of a system, process, or device. Ideally, the project should be based on a problem from industry.

Over several years I have observed many capstone projects in our engineering department. These projects were not only in the mechanical engineering area, but included projects in electrical engineering, bio-engineering, industrial engineering and civil engineering. Some of the projects were excellent, but many others (in my opinion) fell short of the mark. Some projects were solely analytical in nature and had little or no design content. Others were pure construction projects and lacked meaningful engineering calculations. It is believed that the project outlined in this paper satisfies the requirements of a worthy capstone design project in the thermal/fluids area of mechanical engineering. It includes analysis, design, and construction aspects, and has a tie to industry.

What makes this project especially attractive is that it requires students to apply theory gained in several courses, including differential equations, thermodynamics, heat transfer, and engineering economics. It requires the students to look at a problem and model it with the appropriate differential equation. This equation, which incorporates heat exchanger theory, must then be solved to size the heat exchanger and determine the necessary water flow rates. After the heat exchanger is sized, the students have to determine the make and model number of an appropriate heat exchanger. This is done by internet searches and through discussions with manufacturers representatives. The interaction with the manufacturers reps is especially worthwhile. The students find that it is usually difficult (at least in our area) to gain information from manufacturers if a specific job and potential sale is not imminent. The interaction gives the students an opportunity to practice and improve their communication and negotiation skills.

An extension of this project could be the design and construction of a lab experiment to verify the analytical solution of the governing differential equation. The experiment could utilize existing heat exchangers in the engineering laboratories or the students could design and build a heat exchanger specifically for the experiment.

The project has many facets to it, and the instructor has a lot of flexibility in his/her specification of the project's requirements and scope.

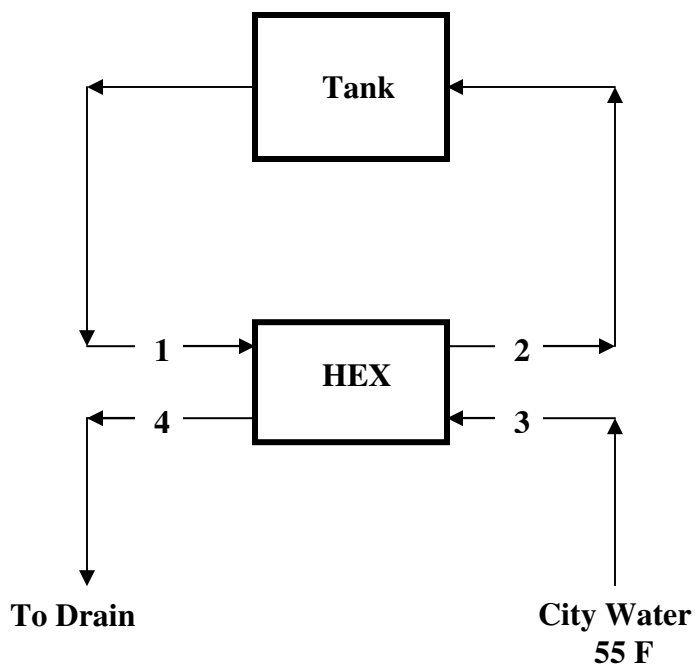
Some details of the project will now be discussed.

Modeling of the Proposed Cooling System

(Note: As mentioned at the beginning of this paper, the fluid in the central cooling loop is 30% propylene glycol. In this paper we will simply call it "hot water". Likewise, the city water used for cooling the propylene glycol will simply be called the "cold water".)

We can consider the central cooling loop as a tank of hot water containing the same amount of water as the cooling loop; i. e., 426 gallons. The water in the tank is initially at 180 F and it is desired to cool it to 80 F within two hours. To do this, a stream of hot water leaves the tank, goes through the heat exchanger, and returns to the tank. The cold water enters the heat exchanger at a constant temperature of 55 F. After cooling the hot water, the cold water is dumped to the drain. A diagram of the situation is as follows:

Figure No. 2 - The Modeled Cooling System



Location 1 is the hot water entering the heat exchanger.

Location 2 is the hot water leaving the heat exchanger.

Location 3 is the cold water entering the heat exchanger.

Location 4 is the cold water leaving the heat exchanger.

The water in the tank is at temperature T_1. The hot water enters the heat exchanger at this temperature.

From the first law of thermodynamics, the rate of heat removed from the hot water, Q, is equal to the rate of decrease of the internal energy of the hot water.

$$Q = -\rho c V \frac{dT_1}{dt} \qquad (1)$$

where:
- Q = the rate of heat transfer
- ρ = density of the water in the tank
- c = specific heat of the water in the tank
- V = volume of water in the tank
- T_1 = temperature of the water in the tank at time t

From heat exchanger theory [2, 3], we have

$$Q = UA\ (LMTD) \qquad (2)$$

where:
- U = overall heat transfer coefficient of the exchanger
- A = heat transfer area of the exchanger
- LMTD = log mean temperature difference of the exchanger

We will assume a counter-flow, double pipe heat exchanger. The LMTD is then

$$LMTD = \frac{(T_1 - T_4) - (T_2 - T_3)}{\ln\left(\frac{T_1 - T_4}{T_2 - T_3}\right)} \qquad (3)$$

It will be assumed that there are no heat losses to the surroundings. Therefore the heat lost from the hot water in the exchanger equals the heat gained by the cold water in the exchanger.

The rate of heat lost by the hot water is

$$Q = m_h c_h \left(T_1 - T_2\right) \qquad (4)$$

The rate of heat gained by the cold water is

$$Q = m_c c_c (T_4 - T_3) \qquad (5)$$

In equations (4) and (5),

m_h = mass flow rate of the hot water = m_1 = m_2
m_c = mass flow rate of the cold water = m_3 = m_4
c_h = average specific heat of the hot water in the exchanger
c_c = average specific heat of the cold water in the exchanger

By combining equations (1) to (5) we obtain the differential equation for the temperature of the water in the tank, T_1, as a function of time, t.

$$Q = -\rho c V \frac{dT_1}{dt} = \frac{(A_1 - 1)(T_1 - T_3)}{\dfrac{A_1}{m_h c_h} - \dfrac{1}{m_c c_c}} \qquad (6)$$

Or,

$$\frac{dT_1}{dt} = -\frac{1}{\rho c V} \frac{(A_1 - 1)(T_1 - T_3)}{\dfrac{A_1}{m_h c_h} - \dfrac{1}{m_c c_c}} \qquad (7)$$

In equations (6) and (7), the parameter A_1 is

$$A_1 = e^{UA\left(\frac{1}{m_h c_h} - \frac{1}{m_c c_c}\right)}$$

Equation (7) is a linear first-order differential equation. The students have to solve it to determine the temperature of the water in the tank as a function of time. The size of the heat exchanger (i.e., its "UA" value) and the flow rates of the hot and cold water must be selected so that the water cools from 180 F to 80 F within 2 hours.

Selection of the Heat Exchanger

With the "UA" value of the exchanger determined, the students must determine the make and model number of a suitable heat exchanger available from a manufacturer's stock. Internet searches will be helpful. For example, some manufacturers have software programs on the web which allow customers to select heat exchangers based on the size and flow rate parameters [4]. However, one can go just so far with internet searches. At some point the students will have to contact a manufacturer's representative for pricing and other information.

The students will have to address the economic aspects of the heat exchanger selection. They will have to take into consideration the cost of the heat exchanger and also the cost of the city water which will be dumped to the drain during the cooling process.

This might also be a good time for the students to investigate the construction aspects of various types of exchangers in more detail than what was covered in the heat transfer course. Students could also become acquainted with ASME (American Society of Mechanical Engineers) and TEMA (Tubular Exchanger Manufacturers Association) standards related to heat exchangers.

Laboratory Experiment

Another possible part of the design project could be the design and construction of a small-scale lab experiment. This would allow comparison of experimental results with the predictions from the solution of the governing differential equation. The experiment could utilize an existing heat exchanger in the engineering laboratories, or the students could design and build a heat exchanger specifically for the experiment.

In our department, we have an existing exchanger which had been constructed many years ago as a student's capstone design project. The exchanger has been used as a permanent experiment in our heat transfer laboratory, and its rating (i. e., UA value) has been experimentally determined for various flow rates. The exchanger is of the double-

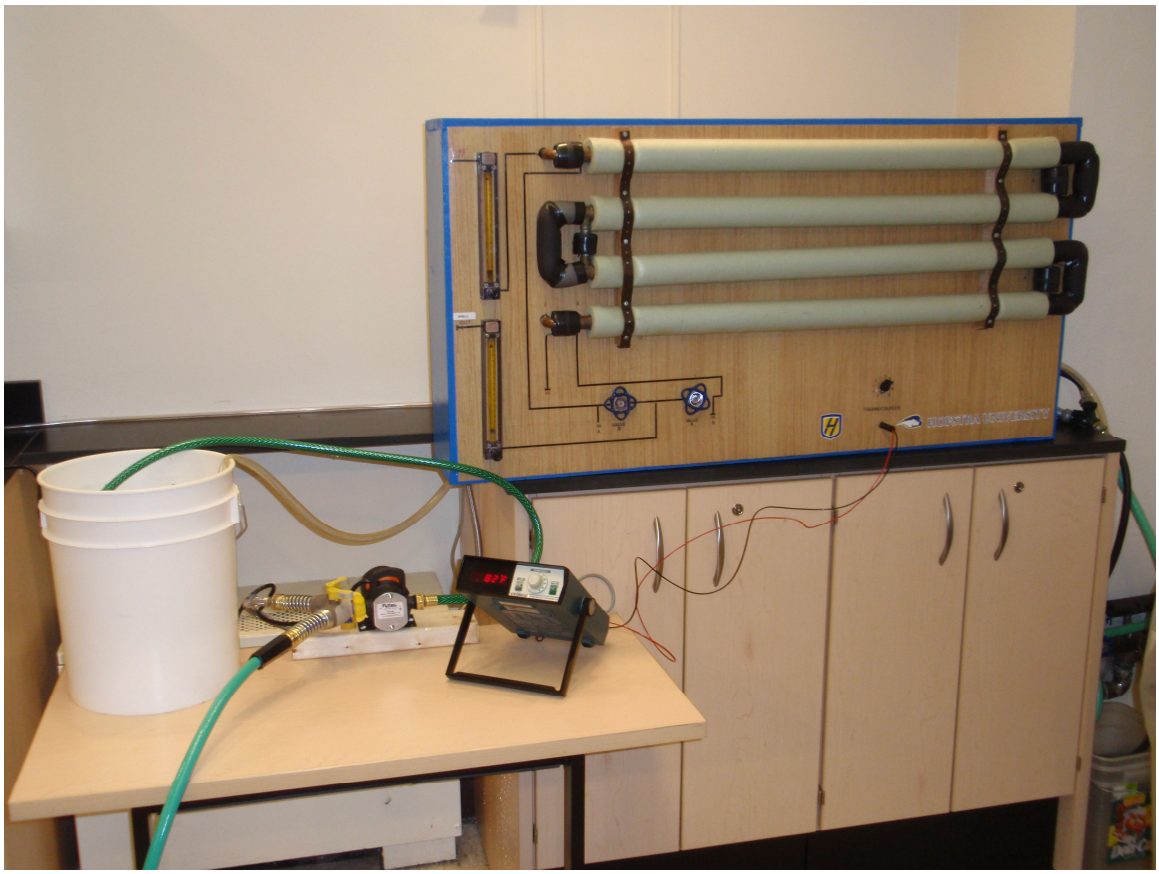
pipe type, and the flow can be configured for either parallel flow or counter flow. The exchanger is shown in Figure 3 below.

We have used the exchanger as part of an experiment demonstrating the cooling of water in a tank as described in this paper. The tank consists of a 5-gallon pail. The pail is filled with 4 gallons of the hottest water available from the building's supply. This is about 110 F. There is a submersible pump in the tank [5] to pump the water through the tube side of the heat exchanger. The hot water is cooled in the exchanger and recirculated back to the tank. Temperature versus time data is taken for the water in the tank and is compared to the theoretical predictions. Cooling is provided by the building's cold water taps. The water enters the exchanger at about 50 F, goes through the annulus side of the exchanger, and is dumped to the drain.

Figure 4 shows the experimental set-up. In addition to the submersed pump in the tank, there is a pump mounted on the table [6]. This pump is used to easily drain the tank to facilitate multiple runs. The tank is filled with hot water from a hose (not shown) from the sink taps.

Figure No. 3 - The Heat Exchanger

Figure No. 4 - The Laboratory Experiment



If a heat exchanger is not available in the engineering laboratories, then a possible additional capstone project would be the design and construction of one. Alternatively, the students could select and purchase a commercially available exchanger from a manufacturer. The students could use the information gained in the theoretical calculation portion of the present project to size the exchanger for the lab experiment.

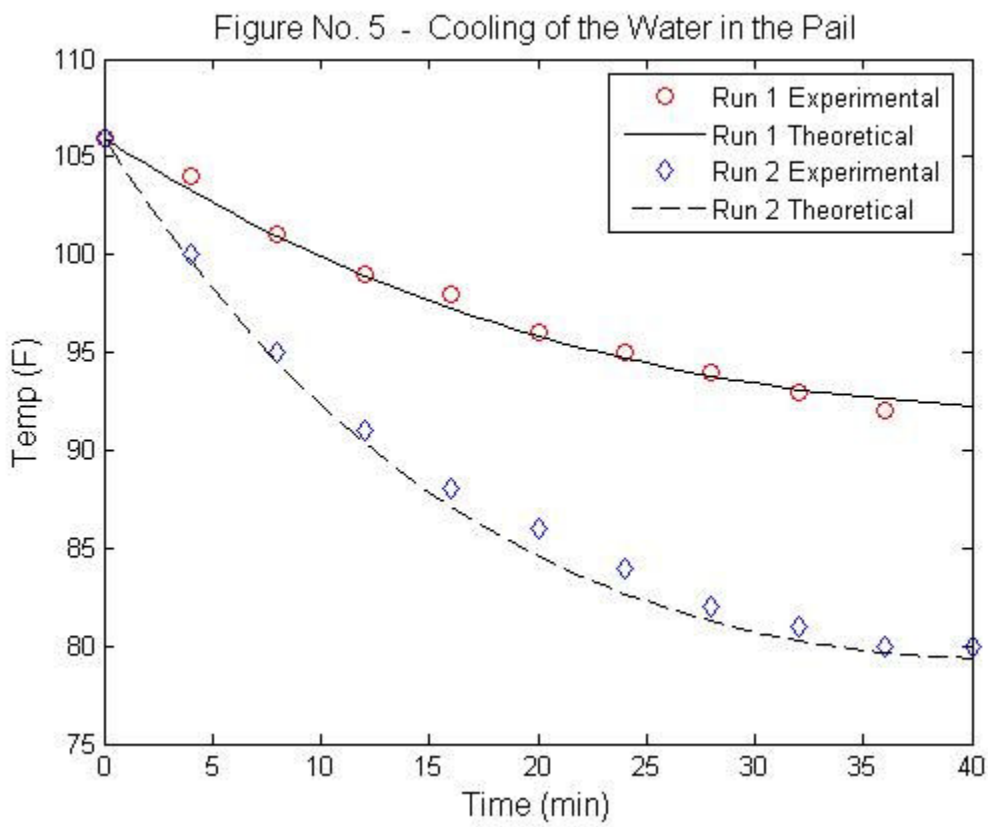
The Author's Experience

The author has used this project with his senior design students on three occasions. One group completed the theoretical work, but only partially completed the experimentation. The second group completed the theoretical work, but decided to build a shell and tube heat exchanger rather than use the existing laboratory heat exchanger. The shell was made of plastic plates glued together. The final assembly was done hurriedly a couple of days prior to the oral presentation, and the glued joints failed upon pressurization. (Luckily this did not happen during the presentation!) The third group did the theoretical work but, like the other groups, did not do thorough experimentation.

The lack of complete success is due to a variety of reasons, as follows: At Hofstra, the senior design course is over only one semester, which makes scheduling very difficult with a multi-faceted project such as this. In particular, it is necessary that the students working on the theoretical calculations do their work expeditiously so their results on the heat exchanger sizing are given to the students selecting the exchanger and designing the experiment as soon as possible. Also, a design and construction project is difficult to complete successfully in a single semester. In addition, this project is in the final semester of the students' program. Many students are more interested in finding jobs and getting accepted to graduate school than in doing a thorough and complete job on their senior projects.

Finally, the author may have been too optimistic regarding the size of the groups. The above groups were groups of two or three. This may have been too small for the scope of the work. The author now believes that perhaps as many as seven (7) students could be involved in this project. Two students could do the theoretical calculations, two on the heat exchanger selection, two on the design, construction and testing of the experiment, and one for project coordination. All of the students would meet together with the instructor on a weekly or biweekly basis to provide progress reports. In this way, all students will be kept informed of all aspects of the projects. The meetings would also provide opportunity for students to participate in areas of the project outside their specific assignment.

The author has done considerable experimentation on this project. The results of two runs are shown in Figure 5 below. It is seen that there is good correlation between the theoretical predictions and the experimental results. For Run No. 1, the hot and cold water flow rates are 88 lbm/h and the UA for the heat exchanger is 105 Btu/h F. Cold water entered the exchanger at 61 F. Run No. 2 is for a larger flow rate (187 lbm/h). At this flow rate, the UA of the heat exchanger is larger (151 Btu/h F). For this run, the cold water entered at 56 F. For both runs, the experimental data was adjusted to correct for water heating due to the submersible pump and for heat lost to the air by convection from the pail.



Conclusion

This paper describes a project which could be used as a senior capstone design project in the thermal/fluids area of mechanical engineering. The project has both theoretical and practical (i. e., construction) aspects. It is industry-based and allows student to apply knowledge gained in several lecture courses. The project has several components, and the instructor has considerable flexibility in determining its scope and scheduling.

Bibliography

1. Daniel C. Greenidge, PE was a student in my heat transfer class. I enjoyed very much having him in my class and having the opportunity to remain in contact with him after the class had finished. Unfortunately, Dan contracted the terrible disease ALS and passed away at a very young age. This paper is dedicated in his honor and to his memory.

2. Holman, J. P., *Heat Transfer, 10th Edition,* McGraw-Hill, 2010, Chapter 10.

3. Cengel, Yunus A., *Heat and Mass Transfer – A Practical Approach, 3rd Edition,* McGraw-Hill, 2007, Chapter 11.

4. Exergy company; exergyllc.com

5. Flotec 1/6 hp submersible pump, FP0S1300X-08 (Available from Home Depot)

6. Flotec 1/12 hp utility pump, FP0F360AC (Available from Home Depot)