A Student-Centered Senior Capstone Project in Heat Exchanger Design

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Overview

Hofstra University recently received a grant from the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) for students to design and build a heat exchanger demonstration unit for the mechanical engineering laboratories. The grant was awarded through ASHRAE's Undergraduate Senior Project Grant Program. Senior mechanical engineering students designed and built the heat exchanger unit as their capstone design project in the thermal/fluids area - one of two such required design projects.

The objective of the project was to design and construct a demonstration unit which included three different types of heat exchangers - a double pipe heat exchanger capable of both parallel and counterflow operation, a shell-and-tube heat exchanger, and a cross-flow heat exchanger. The heat exchangers, along with sufficient instrumentation to measure fluid temperatures and flow rates, were mounted on a portable cart so that the unit could be used in various locations in the laboratories.

The project gave the students a meaningful design experience which made use of knowledge gained in previous lecture courses in heat transfer, fluid mechanics, and instrumentation. It gave the students practical construction experience. It provided the students with substantial experience in working as a team. Although the instructor was available to help the students over stumbling blocks, the effort was team-centered, with team members making the major decisions and assisting and learning from each other. And, as a result of the project, a major experiment was added to the mechanical engineering laboratories.

In addition to providing details of the heat exchanger design, the paper describes non-technical aspects such as: organization and scheduling; interactions between faculty, students, and lab technicians; equipment procurement; division of work among the students; and the students' abilities and motivation. The paper discusses problems which were encountered in this and other capstone projects supervised by the author. It includes suggestions for avoiding, or at least minimizing, such problems in future similar activities. The information should be very useful to faculty in planning and directing capstone design courses, regardless of topic.

The student-centered approach followed in this project is consistent with actions being taken by many educators to change the educational experience from a teacher-centered approach to a team-based and student-centered approach. [1, 2 , 3, 4] The heat exchanger project also provides the students with a design-build test experience that greatly enhances their educational experience. Other schools have also found the design-build-test approach to be beneficial for students. [5, 6, 7, 8]

This is the second major design-build-test project overseen in recent years by the writer. The prior project dealt with design and construction of a pump system. [9] Comparing the first project with this one, the writer has noted considerable improvement in the students' performance. At least some of this improvement is due to the writer's increased experience and improved skills in directing student projects. A third project, currently underway, is the design and construction, by students, of a heat pump experiment for the mechanical engineering labs. The intent is to make this project even more student-centered than the two previous projects. This should serve to even further enhance the students' learning experience.

I. Objectives

There were two main objectives for the project: To provide a meaningful design and teamwork experience for the students, and To construct a demonstration unit to be used in the mechanical engineering labs as a heat exchanger experiment.

II. Design and Construction of the Heat Exchanger Demonstration Unit

A. Design Criteria

The following design criteria were given to the students at the first class session:

1) The demonstration unit shall have three heat exchanger modules: A double-pipe heat exchanger capable of being operated in both the parallel and counterflow modes, a shell-and-tube heat exchanger, and a cross-flow heat exchanger.

2) The demonstration unit shall be portable and mounted on a cart so that it can be moved to different locations in the laboratories.

3) The unit shall be self-contained, except for the necessary connections to the cold water supply and the electrical service.

4) The unit shall have a large hot water tank capable of being readily filled from the hot water tap and also capable of being readily drained. The hot water shall be recirculated through use of a submersible pump in the tank. Cold water is supplied directly from the cold water supply tap in the lab. The cold water is not

recirculated, but goes directly to the drain.

5) The heat exchanger modules shall have plastic, transparent shells so that the internals of the exchangers can be seen.

6) The instrumentation shall be sufficient to measure the temperatures of the entering and exiting hot and cold water streams and to measure the flow rates of both streams.

7) Valving and piping shall be provided so that water flows can be directed to and from the particular heat exchanger module in use at a given time. Valves shall also be provided for flow control.

8) The demonstration unit shall be aesthetically pleasing and shall be an attractive addition to the mechanical engineering laboratories.

9) The instrumentation shall be modern, with digital readout.

10) Due to the limited time period available, parts to be used shall be, as much as possible, stock, readily-available items. (Of course this excludes the heat exchanger modules, which require custom construction by the students.)

After setting forth the design criteria, the professor reviewed heat transfer calculations related to heat exchanger design. He presented some sample heat exchanger problems. He discussed the selection of instrumentation and the determination of the ranges for the various sensors. Students met with the professor weekly to submit progress reports, discuss problems encountered, and obtain guidance and suggestions. At other times during the week, the students met together without the professor, working as a team and learning from each other.

B. The Final Design

After considerable heat transfer calculations, the students arrived at a final design for the heat exchanger modules. They also determined the layout of the components on the portable cart.

This section discusses the final design in detail. An overall view of the demonstration unit is shown in **Figure 1**.

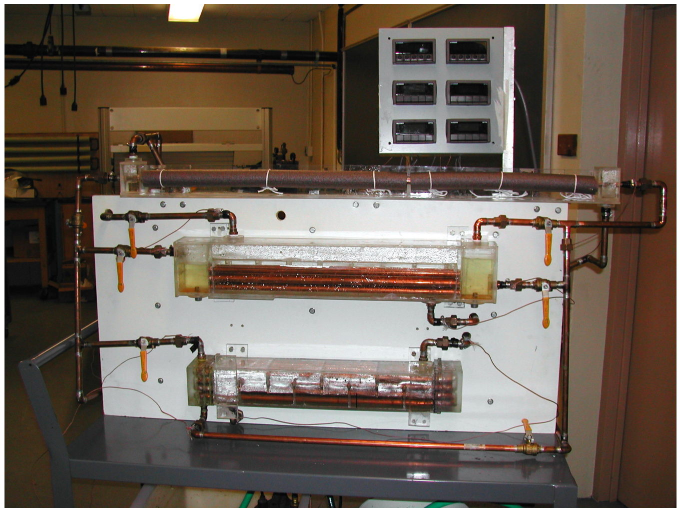

Figure 1 - The Demonstration Unit

The heat exchanger demonstration unit includes three heat exchanger modules:

The first module is a double-pipe exchanger consisting of an inner copper tube (1/2 inch outside diameter and 0.065 inch wall thickness) and an outer rigid plastic tube (5/8 inch inside diameter). The exchanger is about 44 inches long. Hot water flows through the copper tube and cold water flows through the annulus between the outside of the copper tube and the inside of the plastic tube. Valving is provided to allow both parallel flow and counterflow operation. **Figure 1** shows the double-pipe exchanger covered with a foam insulating jacket.

The cross-flow heat exchanger is located under the double-pipe exchanger. Hot water enters the exchanger in the left water box, flows from left-to-right through seven (7) 1/2 inch Type M copper tubes, and exits through the right water box. Cold water enters the exchanger on the top and is distributed over the outside of the tubes by means of distribution baffle consisting of a 1/4 inch thick plastic plate with distribution holes. The cold water leaves through a pipe at the bottom of the exchanger. The heat transfer length of the exchanger is about 24 inches.

The bottom module in **Figure 1** is a shell-and-tube heat exchanger. It is a four-pass exchanger, with four (4) 1/2 inch Type M copper tubes passing four times through the length of the exchanger. The hot water flows through the tubes. It enters at the top left of the exchanger and leaves at the bottom left of the exchanger. The cold water enters at the upper right and leaves at the bottom left. The heat transfer length of the exchanger is about 24 inches.

Figure 1 also shows the six (6) meters at the top right of the figure (2 flow meters and 4 temperature meters). The hot water tank, with its submersible pump is on the lower shelf of the portable cart. There is also a bucket and submersible pump on the lower shelf used for circulation of the cold water. (As mentioned in the design criteria, the original intention was to not recirculate the cold water. This proved to be an unfortunate design criterion, as the students operated the crossflow exchanger without having the exit valves open. This caused the high water pressure of the supply main to be applied to the plastic shell of the exchanger, thereby blowing-out a section of the exchanger wall. A repair was made, but it was decided to change the design and recirculate the cold water as well as the hot water, thereby avoiding potential future destruction.)

Figure 2 is a view of the back of the unit, showing the piping and components.

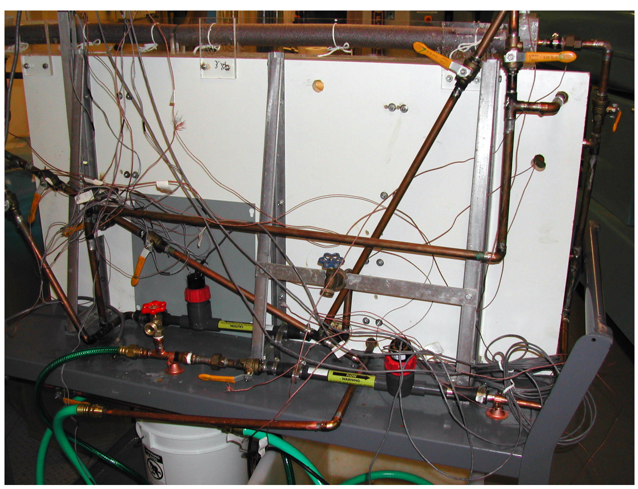

Figure 2 – The Back of the Demonstration Unit

Finally, **Figure 3** shows details of the three heat exchanger modules. The shell-and-tube and cross-flow exchangers have piping unions so the modules can easily be removed for servicing.

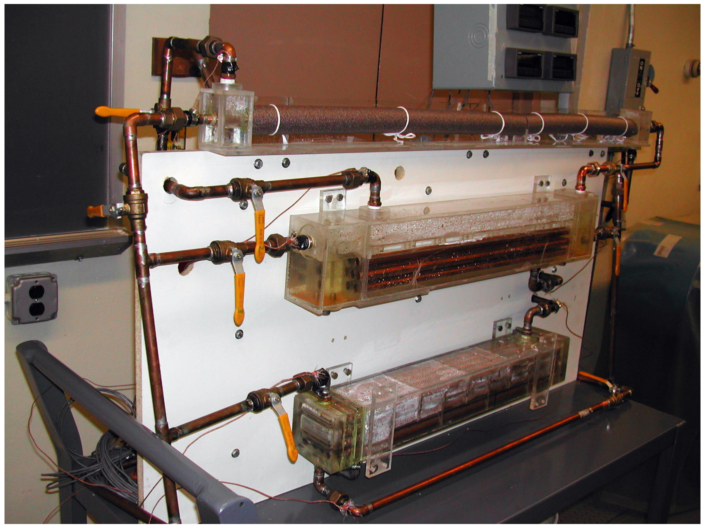

Figure 3 - The Heat Exchanger Modules

The following table lists the major equipment items, including costs. (Costs are not given for the heat exchanger modules, which were custom-made in the engineering machine shop by the students under the supervision of the laboratory supervisor.)

EQUIPMENT ITEMS

QTY.	DESCRIPTION	PRICE
Cart		
1	Stock Truck (48" x 24"; 2000 lb. Capacity) (Grainger #4YW65)	$ 265
Tank		
1	20 gallon, high density polyethylene Rectangular Tank (McMaster-Carr #4420K55)	$ 200
Valves		
15	Brass ball valves; ½", full port	$ 75

1	½" Drain Valve for Hot Water	$ 5

Electrical

1	Electrical Steel Service Box (for mounting meters)	$ 35

Temperature Instrumentation

4	Temperature Meters (Omega Engineering #DPF119-TF2)	$ 900

Flow Sensors

2	Paddle Wheel Sensors (Omega Engineering #FP-5300)	$ 500
2	Fittings for Flow Sensors (Omega Engineering #FP-5305)	$ 300
2	6-digit Rate Meters (Omega Engineering #DPF-701)	$ 520

Submersible Pumps

2	Flotec 1/6 Horsepower (from Home Depot)	$ 150

Miscellaneous $ 300
Material for the heat exchanger modules
Type T thermocouple wire
½" Copper Type M pipe and fittings
Drain and fill rubber hoses
Electrical wiring
Bucket for cold water system

Total Cost = $ 3,250

As much as possible, construction of the demonstration unit was done by the students. The lab supervisor helped the students greatly and performed operations beyond the skills of the students (e. g., machining of the plastic parts of the heat exchanger modules). The students gained significant construction skills during the project, including the use of various tools and brazing of the copper tubing.

III. Sample Experimental Results

This section presents sample experimental results for the double pipe and crossflow heat exchangers.

In both exchangers, heat is transferred from hot water in the tubes to cold water in the shell.

All undergraduate heat transfer texts include sections covering heat exchanger theory. [10] The rate of heat transfer from one fluid to the other is given by the equation

$$\mathbf{Q = U\ A\ F\ (LMTD)}$$

where Q is the rate of heat transfer (watts)

U is the overall heat transfer coefficient of the exchanger (w / m^2 C)

A is the heat transfer area of the exchanger (m^2)

F is a correction factor. For the double pipe exchanger F = 1. For the crossflow exchanger, F = 0.98 per the experimental data.

LMTD is the log mean temperature difference between the two heat transfer fluids. It is calculated from the fluids' entering and exiting temperatures at the exchanger. (C)

Table No. 1 gives a sample of experimental data obtained from the double pipe heat exchanger, in both the parallel flow and counter flow modes of operation. **Table No. 2** gives data for the crossflow heat exchanger.

Table No. 1
Experimental Data for the Double Pipe Heat Exchanger

Parallel Flow

Flow Rates		In/Out Temperatures		
Hot Water	Cold Water	Hot Water	Cold Water	UA
(kg/s)	(kg/s)	(C)	(C)	(w / C)
0.0697	0.0201	50.6/47.4	23.3/37.0	30
0.0753	0.0446	50.4/46.0	24.9/34.5	44
0.0753	0.0653	50.2/45.2	25.4/33.1	49
0.0772	0.0848	49.9/44.7	26.5/32.7	54
0.1074	0.0848	49.5/45.7	27.4/34.1	59
0.1067	0.0496	48.9/46.4	29.2/37.4	45
0.1080	0.0659	49.2/46.0	28.4/35.7	54

Counter Flow

Flow Rates		In/Out Temperatures		
Hot Water	Cold Water	Hot Water	Cold Water	UA
(kg/s)	(kg/s)	(C)	(C)`	(w / C)
0.0659	0.1036	45.2/39.2	17.5/23.9	77
0.0979	0.1105	46.2/41.3	19.7/26.7	96
0.1256	0.1117	46.4/42.5	21.6/28.7	107
0.1620	0.1105	46.4/43.4	23.2/30.3	112
0.1883	0.1117	46.3/43.8	24.7/31.6	116

Table No. 2
Experimental Data for the Crossflow Heat Exchanger

Flow Rates		In/Out Temperatures		
Hot Water	Cold Water	Hot Water	Cold Water	UA
(kg/s)	(kg/s)	(C)	(C)	(w / C)
0.0669	0.0559	45.8/41.1	29.6/32.4	108
0.0894	0.0553	46.1/42.1	28.9/32.6	115
0.1212	0.0546	46.4/42.7	28.4/32.6	136
0.1605	0.0521	46.7/43.2	27.7/32.8	163
0.1962	0.0502	47.1/43.7	27.0/33.1	186
0.2436	0.0458	47.6/43.8	26.0/32.5	240

For the data samples presented, the UA values for the double pipe exchanger ranged from 30 to 59 w / C for parallel flow operation and from 77 to 116 w / C for counter flow operation. The UA values for the crossflow exchanger ranged from 108 to 240 w / C.

IV. Interactions of Team Members and the Team-Centered Approach

The student team consisted of four students, each bringing to the group his own background and experience. One team member was a part-time student with considerable full-time industrial experience. Another had part-time experience as an intern in an engineering company. The remaining two students had no industrial experience. The educational achievement of the students varied considerably; with grade point averages being respectively 2.1, 2.5, 3.1, and 3.2.

At the first class session, after introduction of the project and the design criteria, the professor assessed the students' retention of heat transfer material by asking a number of questions about heat exchanger design. The student response was minimal and discouraging, so it was decided to spend some time reviewing calculations related to heat exchangers. The professor also reviewed selection of instrumentation and determination of the ranges for the various sensors.

After the initial review lectures, the professor's interaction with the students was minimized so that the course would be team-centered and students could develop their own leadership capabilities. At first, no student took a leadership role and there was some floundering and lack of progress. Then the part-time student became the leader of the group and work progressed more rapidly. The students with industrial experience were able to mentor and help the two other students in keeping on track, making timely decisions, and getting the work done. Students with tool and construction experience shared their skills with the other students, and by the end of the course, all the students had significantly increased their construction abilities.

The professor met weekly with the students to receive progress reports, encourage the students, and assist in problem solving, if needed. At other times of the week, the students worked by themselves, as a team, gaining and improving skills through interaction with each other.

At the end of the semester, an assessment was made of the success of the course in meeting the course objectives. The assessment was made by both submittal of a formal design report by the students and through an oral presentation given by the students to members of the faculty and students not on the team. A review of the design report showed that the students had made significant advancement in their design capabilities. The report contained considerable information on heat exchanger design beyond that which they had received in the professor's lectures. The oral presentation showed that the students had achieved significant presentation skills and were able to readily and appropriately respond to questions posed by the audience members.

Finally, with their greatly improved construction skills, the students were able to produce a major experiment for the mechanical engineering laboratories.

V. Non-Technical Aspects of the Project, Including Suggestions.

Several non-technical problems were encountered during this project and other similar projects supervised by the author. This section discusses these problems and makes suggestions for their avoidance or minimization.

A. Project Organization and Scheduling

Being a one-semester project, it is necessary to get going immediately at the beginning of the semester and continue at a fast pace. The project got off to a somewhat slow start due to the necessary review of heat transfer topics. The review was needed for the system design aspects of the course, but too much time was spent on it. In the future, notes will be handed-out and only minimal class time will be devoted to review of previously learned theory.

A complete overview of the course schedule should be presented at the first class meeting. This schedule should indicate definite dates for major action items and milestones such as conceptual design, determination of final design, release of purchase orders for equipment, construction of the system, testing of the system, initial draft of the project report, etc. This will emphasize to the students the limited time available for the various items, and hopefully prod them to keep moving.

B. Interactions Between Faculty, Students, and Lab Technicians

The objective is to have the students work as a team with minimal supervision. However, it is necessary for the professor to keep track of the students' progress or lack thereof. Weekly written and oral progress reports are necessary, and the professor should not hesitate to take a more active role in project direction if he/she sees that students are proceeding too slowly or have encountered major obstacles. It may be even by necessary, at certain times, for the professor to assign specific tasks for the students to accomplish before the next progress report meeting. This direction by the professor is to be avoided as much as possible since the goal is to maximize decision making by the students. However, professor intervention is sometimes necessary.

In such a construction project there is considerable interaction between the students and the lab technician(s). The lab supervisor and technicians play a significant role in the successful construction of the project, and the students should recognize and appreciate this role. The students should tactfully request the laboratory personnel's help and should not have unrealistic demands during the hectic final weeks of the semester.

C. Students' Motivation and Abilities

The professor looked upon this project as being exciting, real, and practical. The significant ASHRAE funding gave the students the opportunity to design and build a major system illustrating the heat exchanger theory discussed in lecture class. Despite the professor's enthusiasm, some students at the outset of the project exhibited very little interest and motivation. Fortunately, there was considerable improvement in attitude and activity as the project progressed. This improvement was most likely due to the team organization and peer pressure.

The professor was surprised to observe the lack of manual construction skills on the part of some of the students. It was observed that the skill level increased significantly as the project progressed and the students assisted each other.

D. Division of Work Among Students

As often happens, it appeared that certain students were working considerably more on the project than others. It is necessary for the professor to know as early as possible which tasks the team has assigned to the various team members. This will enable the professor to review the assignments and suggest modifications if it seems that the workload is uneven among the team members. Knowledge of the assignments is also necessary for grading purposes.

E. Equipment Procurement

Delays were experienced in the procurement of equipment. The purchase order procedure is tedious, with approvals required from many individuals even though the grant money is in the bank. Approvals are needed from the department head, the associate dean, and the grants office. The purchasing department places the purchase order. When the equipment has arrived, it goes to receiving and stores where it may remain for a considerable time until union personnel can deliver it to the lab. Each step involves a delay, and it is definitely necessary to keep a constant watch on the progress of purchase requests. It is often better, if the system permits, for the professor to avoid the hassle and place orders for equipment directly with the vendors. This can be done if the cost of the item is small enough and multiple bids are not required. Of course, it is usually necessary for the professor to use his/her own credit card and receive reimbursement from the university. Despite this drawback, the author uses this approach as much as possible to avoid hassles and minimize delay.

VI. Conclusion

This project has provided a very significant design/construction experience for the students. It gave the students an opportunity to work as a team, with minimal direction from the professor, to accomplish a specific goal. It enhanced the leadership and interactive skills of the students, and resulted in a major heat exchanger experiment being added to the mechanical engineering laboratories. The experiment will be regularly used in the senior level laboratory course ENGG 170, “Mechanical Engineering Laboratory II”.

VII. Acknowledgments

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