A Project To
DESIGN AND BUILD COMPACT HEAT EXCHANGERS

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Our department initiated a project for students to design and build a compact shell-and-tube heat exchanger in order to address needs defined by our educational goals, by industrial advisors, and by our students and alumni. The needs that fit neatly within the scope of this project include putting theory into practice, developing engineering judgment, and gaining hands-on experience. For our purposes, engineering judgment is defined as the aspect of problem solving and design that balances theory with practice, creativity, and common sense.[1]

Recently, members of our department's industrial advisory board provided us with feedback on their experiences with young chemical engineers in the work place. One theme that emerged was that the modern student has a general lack of practical, hands-on, mechanical skills with basic tools and building materials. One company reported on a workshop they started that offers intern and co-op students (as well as new engineers) instruction on topics such as the use of small tools, fittings, piping, filters, valves, automation and instrumentation, pump basics, heat exchanger knowledge, and basic troubleshooting skills. Our experience, along with that of our industrial partners, echoes Finlayson's observation[2] that

> *We see students who have very little hands-on experience in anything and their practical education begins when they get into our laboratory. These people are more susceptible to accepting whatever comes out of the computer. Now, instead of teaching people how to write programs, we are teaching them how to check the results, to use their heads and evaluate the information. We teach them to be skeptical and some specific steps to use in checking their work.*

The project for students to design and build a compact shell-and-tube heat exchanger was structured to meet several important objectives. First, it was designed to help students become comfortable in industrial environments through exposure to basic hand tools and construction materials; second, it would provide students with an open-ended design problem where they could develop confidence in engineering principles through application; and third, it was meant to develop our students' sense of engineering judgment.

PROJECT DESCRIPTION

The heat-exchanger project was incorporated into a core course on heat transfer, typically taken during the spring semester of the junior year of our program, that covers topics on transport phenomena and unit operations of heat transfer. The assignment was to design and build a compact shell-and-tube heat exchanger for water streams such that the temperature of the tube-side fluid changes by a magnitude of at least 20 °C at the operating conditions listed in Table 1. The design objectives were to minimize cost and size. For this project, the cost was assumed to be directly proportional to weight. The size was taken as the largest dimension (*e.g.,* length of exchanger).

A simple double-pipe heat exchanger was constructed as a prototype for the purpose of demonstrating the concept of the project to the students and to provide them with ideas of materials and construction methods. The shell and tube were made from four feet of one-inch schedule 40 PVC pipe and 1/4-inch copper tubing, respectively.

By intentional design, the prototype exchanger did not perform to the required specifications of the project. The students formed teams of two or three students and were told to

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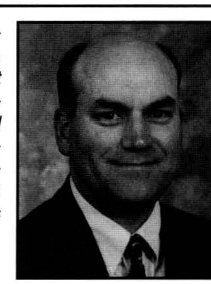

improve the design of the example exchanger to meet or exceed the project performance and design specifications. In order to avoid proposals that simply lengthened the tube, the teams were challenged to consider compact designs that minimized the size and weight of the device. Individual students were required to report their results in a memo report to the instructor. Each team presented its findings to the class.

Materials of Construction • The first objective was to give students hands-on experience with tools and construction materials. The project also served as a learning vehicle to acquaint students with pipe schedules and fittings (such as caps, elbows, unions, reducers, tees, and connectors). Students were limited to materials available in typical hardware stores or home building centers, including standard schedule 40 or schedule 80 PVC pipe and fittings, 1/4-inch copper tubing, compression fittings, and common insulation materials. Compression fittings, PVC cement, and Teflon tape were used to seal the connections. An allocation from the university laboratory fee was used to purchase the materials. The average cost of a heat exchanger was less than \$20, and the department maintained ownership of the materials in order to recycle copper tubing and compression fittings when possible.

TABLE 1
Heat Exchanger Operating Specifications

Feed Streams	*Temperature °C*	*Approximate Flow Rate (L/min)*
Cold Water	<15	0.50±0.05
Hot Water	>55	0.20±0.05
Room Air	20±2	

TABLE 2
Tools Provided for Building Heat Exchangers

Hand Tools	*Power Tools*
• 8- and 10-inch adjustable wrenches and locking pliers	• Skil variable speed 3/8-in drill
• 1/2- to 9/16-in open end and socket wrenches	• Craftsman 9-in drill press
• Cutting shears	• Delta 10-in compound miter saw
• Tube cutter and bender	• Craftsman 9-in band saw
• Miscellaneous files and clamps	• Craftsman 42-in belt, 6-in disk sander/grinder
• Tap threading tools and drills	• Dremel rotary tool, attachments
• Measuring tape and caliper	• Skil variable-speed jig saw

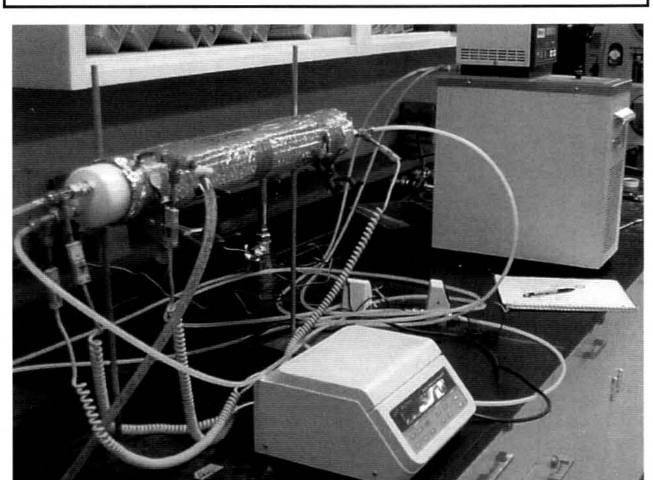

***Figure 1.** Experimental station to measure hot- and cold-stream flow rates and temperatures in student-manufactured heat exchangers.*

Tools and Safety • The project also provided students with experience in using a variety of common hand tools and small power tools—a complete list of tools for the project is given in Table 2. While a few students already had significant practice with many of the tools, several indicated that they had little or no experience. This provided an opportunity for instruction in basic safe practice using tools and materials.

Students were given training on the proper and safe use of each hand and power tool, with the safety guidelines supplied by the manufacturer of each power tool being used as the basis for the training. The university's environmental health and safety officer visited the laboratory to make a presentation and to measure the noise level in the vicinity of the power tools—the conclusion was made that hearing protection was necessary around the power saws. Students were issued leather gloves when using sharp hand tools and latex gloves when using PVC pipe cement. Eye protection and closed-toe shoes were required at all times during the construction phase of the project. Students were not permitted to use tools until they had completed the safety training.

Experimental Station • The student-built heat exchangers were tested on the experimental station shown in Figure 1. The hot-water stream was generated in a constant-temperature circulating bath. Consistently cold tap water (straight from the Minnesota shore of Lake Superior!) was used for the cold-fluid stream. The flow rates were controlled with small ball-and-pinch valves in the flow lines. Flow rates were measured with McMillan 112 electronic flow meters. The temperatures of the inlet and outlet streams were measured with type-K thermocouples mounted in 1/4-inch brass tees placed in line with the fluid streams, located near the points of entry and exit. The temperatures and flow rates were monitored to determine steady-state operating conditions, which were typically achieved in less than twenty minutes. By requiring 1/4-inch connections for the feed and effluent tubes, the same experimental setup was used to test all student-built heat exchangers without significant rearrangement.

DESIGN AND ANALYSIS

The second objective of this project was to enhance student confidence in engineering design principles. They learned the basic principles of heat exchanger design, including mass and energy conservation, overall heat transfer coefficients, and the log-mean temperature difference and effectiveness number of transfer units (ϵ-NTU) methods. They also participated in discussions of nonideal behavior of heat exchangers (such as the potential for heat exchange with the surroundings), orientation and fluid mixing, entrance and transition effects, and temperature dependent properties. Armed with these skills, the teams were capable of designing a compact shell-and-tube heat exchanger subject to the project constraints.

Each team was required to document its design calculations before it was allowed to begin construction. The teams could not change or modify their basic designs once construction began, to avoid a scenario of empirical design by trial-and-error. The teams were also required to set up and solve their design equations in computer spreadsheet applications, such as Excel, or general-purpose mathematics software such as Mathcad, Polymath, or Matlab. An example of student design calculations for a multipass heat exchanger using Mathcad is available for download at <http://www.d.umn.edu/~rdavis/htxr>.

Computer software tools allow students to quickly and efficiently perform a sensitivity analysis on their design equations and to investigate potential effects of uncertainty in parameters such as operating conditions, material properties, and heat transfer coefficients. For example, an analysis of the overall heat transfer coefficient revealed that the conduction resistance through the wall of the copper tube was insignificant for this project. It was also determined that heat exchange with the surroundings was negligible. The "design first, build later" feature of the project was important for students to develop their sense of engineering judgment and transformed their skill set from the academic "learning by doing" to the competitive edge of "learning before doing."[3]

A range of creative designs emerged from the various teams. The most common designs, illustrated in Figure 2, were variations on multipass heat exchangers imitating industrial configurations. Students quickly discovered that correlations for heat transfer coefficients specific to their design concepts were not readily available in the literature, so they adapted general-purpose correlations to their geometries and flow conditions. For example, one team decided to coil the tube in the shell and used a heat transfer coefficient correlation for cross flow over a cylinder for the fluid in the shell.

All of the groups designed their exchangers for operation with the hot stream on the tube side and the cold stream on the shell side, to minimize heat transfer to the surroundings. They also noted from manufacturer's recommendations that PVC pipe is not suitable for hot-water plumbing service for temperatures exceeding 100°F. Other design considerations were tube spacing to allow the fluid to flow over the available surface area for heat transfer and allowances for tube length to include the designed heat transfer area requirement plus accommodating the additional length required by the pipe connections and tube fittings.

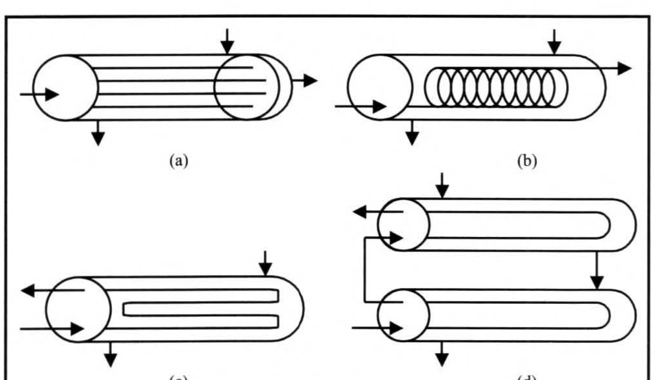

Figure 2. *Schematics of common heat exchanger configurations: (a) single shell-and-tube bundle, countercurrent flow pattern; (b) single shell with coiled tube, cross-flow pattern; (c) single shell, multiple-tube pass; (d) two-shell pass with multiple-tube pass.*

RESULTS AND DISCUSSION

A selection of student-built heat exchangers is shown in Figure 3. In two cases, the shells were cut away to reveal the interior tube configurations. The exchangers in Figure 3 are representative of the construction materials used for the project. PVC pipe and end caps were used for the shell, and brass pipe and compression fittings were used for the copper tube connections. The locations of the feed and effluent ports were determined by the student teams to adapt their performance and design calculations.

Teams that came to the laboratory well prepared were able to construct their devices in approximately one hour. Appropriate preparation included team-member assignments for an equal division of labor, a simple schematic with dimensions, and an idea of where to cut, drill, and tap. Thirty more minutes were needed on a following day to test the performance of the device. A few teams arrived at the laboratory ill-prepared to begin construction and found that a considerable amount of additional time was required to implement the fabrication process when they had only a general idea of how the final product might look. In the future, teams will be required to present specific plans and a schematic for manufacturing their device, in addition to the basic design calculations, to avoid unusual laboratory time commitments.

At the end of the course, each student team had successfully designed and built a compact shell-and-tube heat exchanger that met the required performance specifications and size objectives relative to the prototype. The most successful exchanger in terms of minimizing size and weight used a single copper tube making four passes through the length of a 2-inch pipe. The success of the designs promoted student confidence in the principles of engineering design. The students also gained an appreciation for the limitations of common assumptions (such as steady-state operation, constant temperature or heat flux, perfect mixing, and constant properties) typically required to solve textbook problems.

Some interesting questions were posed by the teams during the construction phase of the project. For example, where should the fluid inlets and outlets be located on the shell to preserve the heat transfer area determined by the design calculations? Students realized that their choice of feed and effluent port locations might have an effect on the fluid residence time in contact with the working heat transfer area.

Some other questions were posed regarding issues of fluid mixing, stagnation, and entrance effects, as well as insulation requirements and containing leaks. The best start-up procedure to eliminate pockets of air in the exchanger was also considered. One team was particularly less careful than others when assembling its exchanger. This team built a single-pass shell-and-tube heat exchanger and found they could not achieve steady-state operation. The team made the following observations: the circulating bath reservoir was slowly draining, while the outside surface temperature of the shell was increasing. They correctly deduced that the hot water was leaking from the header into the shell side. This experience fostered class discussions about how to improve the design and further developed the students' troubleshooting skills.

Students reported that they enjoyed the project and appreciated the opportunity to apply principles of heat transfer. The teams were proud of their devices, gave them names, and took them home to show friends and family. Much of the learning came from interactions between the different teams. Students were curious about the various designs that emerged from the project and freely shared ideas for design and manufacturing tips during the construction phase. A friendly atmosphere of competition existed throughout the project and lasted through the oral presentations. All of this combined to generate enthusiasm for the subject matter of the course.

An informal discussion with several students revealed that the project advanced their understanding of film theory, heat transfer coefficients, and heat exchanger performance and design methods. The students were also given a heat-exchanger design problem on the final exam in order to assess the effectiveness of the project on student learning. The students involved in the heat exchanger design project outperformed the classes from the previous three semesters on a similar exam question, indicating that this project enhanced their understanding of the material.

Figure 3. *Examples of student-built heat exchangers and construction materials. At the left are examples with the shell cut away to reveal a multipass and coiled-tube design. At the right are double-pipe and shell-and-tube heat exchangers.*

A few students claimed extensive experience with common hand tools from summer work experience, living on a farm, or tinkering with engines. We worried that they might find this project trivial and become disinterested, but were pleased to find that they were equally enthusiastic about the project and willingly shared their skills with the other students. The mixture of students with a range of previous experience enhanced the overall learning experience for all students in the class.

One drawback of this project was the additional time required of the students to be in a laboratory outside of lecture periods. Reducing the lectures or including this project in the unit operations laboratory may minimize the impact on students' time demands. Another disadvantage was limited access to tools. Currently, our department has only one set of power tools, but there are plans to increase the availability of tools to permit multiple teams working simultaneously.

CONCLUSIONS

A simple, inexpensive, hands-on learning project for students to design and build compact shell-and-tube heat exchangers was assigned as part of a course on heat transfer. Students worked in small teams of two or three, using the basic principles of engineering design to propose a heat exchanger that would perform according to predetermined specifications. The teams were required to manufacture their heat exchangers according to their basic design calculations as an integral part of the learning experience to encourage confidence in the engineering principles and to develop their sense of engineering judgment. The students gained mechanical experience with basic tools and common building materials, as well as lessons in safety. They were pleased with the outcome of this exercise and recommended the project to students that followed them.

ACKNOWLEDGMENT

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