

Optimal Design of a Thermal Recuperator

Gilbert L. Wedekind, Christopher J. Kobus
Department of Mechanical Engineering
Oakland University, Rochester, MI 48309

Abstract

This paper describes the final design project for the senior level *Fluid and Thermal System Design* course, which is a precursor to the *Capstone Design Project* at Oakland University. The *Fluid and Thermal System Design* course is geared to taking students through the entire taxonomy of the design process; from knowledge, comprehension and application, to analysis, synthesis and finally evaluation. The recuperator design is the final design project of the course, and involves all of the aforementioned steps of the design process. The project is carried out during the last five weeks of the semester, working in teams made up of three to four students, with one being the team leader. Results of the students' design experiences will be presented in this paper.

I. Introduction

It has become increasingly obvious in recent years that graduating seniors from accredited institutions have been lacking in exposure to the totality of the design process. Although some aspects of the design process have been intensively covered piecewise in senior-level courses, there was a need to integrate all of the design steps together into a cohesive learning experience. This has prompted ABET to require institutions to offer, and for students to take, a capstone design course, which would expose students to the totality of the design process without the addition of new material in a lecture-style setting.

In the Mechanical Engineering curriculum at Oakland University, students are required to take a capstone design course in their senior year. In addition, however, the curriculum has required for many years that all mechanical engineering students take two senior level precursor design oriented courses, one associated with solid mechanics, the other with the fluid and thermal sciences. The mechanics parallel of the *Fluid and Thermal System Design* course is the *Mechanical System Design* course. Neither course introduces any new fundamental principles but are instead geared to the design process. Lectures are given, but mainly as a review, or, the application of fundamental principles such as the formulation of theoretical models for the purpose of obtaining design insight. The focus of both courses is design. The present paper details the final design project in the Group B required course entitled *Fluid and Thermal System Design*.

The objective of the *Fluid and Thermal System Design* course is to experientially nurture students in various aspects of the design process, focusing on the entire taxonomy¹ of the design process, from knowledge and comprehension through synthesis and evaluation. The final design project in this course is the design, construction and experimental testing of a thermal recuperator—a concentric-tube heat exchanger designed to minimize combined capital equipment and operating costs.

Student teams, consisting of three to four individuals each, consider themselves to be design-engineering teams working for fictitious competing companies that specialize in customized heat exchanger design, testing, and installation. A fictitious chemical company is soliciting bids for the design of a thermal recuperator to save energy costs for a chemical process that requires fresh make-up water be heated in a water heater to a specified temperature. The waste-water is biodegradable, and exits the process at a known temperature above that of the incoming make-up water.

The teams are expected to formulate a theoretical model that will provide insight into the optimal design of the recuperator module, taking into consideration both the capital equipment costs and the energy operating costs. Material costs for copper tubing, tees and bushings for a variety of diameters are given, as are energy costs related to the water heater. The optimum design will be that design which will meet operating specifications, costing the least amount of money over a specified operating time. Heat transfer augmentation is encouraged as a means of being more competitive.

In addition to the responsibility for design, teams are provided with the raw material and tools to build and test the performance of a prototype module of their recuperator design. In addition, along with a cover letter to the chemical company requesting the bid, each team submits a technical report documenting their company's proposed recuperator design.

II. Background of the Class Body

The *Fluid and Thermal System Design* class mainly consists of senior-level undergraduate students with a minority of graduate students. The course is a four-credit class, and involves both a lecture and a laboratory component. The lectures, however, do not introduce any new fundamental principles in the fluid and thermal sciences. Instead, the lectures serve to review and apply principles that have already been taught in introductory classes in thermodynamics, fluid mechanics and thermal energy transport. The laboratory component is strictly geared toward design, synthesis and evaluation, utilizing knowledge, and comprehension learned in previous courses.

The *Fluid and Thermal System Design* course was instituted in the 1970's to be the primary fluid and thermal design experience for graduating seniors. As a four-credit course, the class meets twice a week for approximately an hour and a half. The lectures consist of a variety of design-oriented applications. The lecture is broken up to include regular breakout sessions involving active learning techniques, student-centered learning and collaborative learning. Homework is assigned regularly to keep skills sharp and up-to-date.

The laboratory component is designed to nurture visualization and stimulate creativity. Rather than rely purely on simulation, the laboratory experience was made to be a hands-on experience. In fact, as part of the recuperator design project, the student groups actually build a thermal recuperator prototype, to be tested the day the project is due. Many students appear to be initially intimidated by cutting copper tubing, picking out appropriate fittings and sweat soldering a heat exchanger together, simply because they lack experience. At the end of the course, however, these same students are typically the ones most proud of their accomplishment, and the most excited about their design experience.

III. Overview of Course Goals and Objectives

Oakland University catalogue course description:

“Study of systems involving fluid and thermal phenomena. Includes conventional and unconventional energy conversion, fluid and thermal transport. Analysis for the purpose of design and optimization of systems are emphasized using basic integral, differential and lumped-parameter modeling techniques. The course bridges conventional engineering design disciplines with design-oriented laboratory projects.”

The singular goal of the Fluid and Thermal System Design course is to expose students to, and challenge them to think about, the entire taxonomy of the design process. The lectures, including student-centered and active learning techniques, promote knowledge, comprehension and application. Regular homework and frequent small quizzes further promote these three important aspects of the design process. The hands-on laboratory design experiences then take students through the analysis, synthesis and evaluation. In this light, students get a global perspective of the design process.

Students are tested on all six elements in the taxonomy of the design process. The frequent homework and small quizzes test the students’ knowledge, comprehension of the subject material as well as the ability to apply these aspects to solve engineering problems. The design projects then test the students’ ability to analyze design problems, synthesize solutions and evaluate and therefore optimize the design.

IV. Design of a Thermal Recuperator

Following several lectures dedicated to heat exchanger applications, the final design project is assigned to the student teams. Figure 1 is the specification sheet describing the design goals and available material, including material and other costs.

Fall 2000

**FLUID AND THERMAL SYSTEM DESIGN
ME 482/582**

**G.L. Wedekind
C.J. Kobus**

OPTIMAL DESIGN OF A THERMAL ENERGY RECUPERATOR

Assume you are a design engineer working for a company that specializes in the design and manufacture of customized heat exchangers. A chemical company, OU Chemicals, Inc., asks your company to bid on the design and construction of a thermal recuperator system for one of their chemical processes. You are given the responsibility for the design.

The company has four identical processing plants. The chemical process needs 60,000 gal/hr of fresh water at a temperature of 120°F. During the process the water becomes contaminated and cools to 110°F. The contaminated water is biodegradable, but it cannot be filtered, so it is pumped into a holding pond and then later thrown away. Therefore, fresh water at a temperature of 65°F must be heated in a gas hot water heater to the required 120°F. These are the design specifications.

At present natural gas prices, and including water heater efficiency, the water heater operating costs are \$0.014 per kilowatt-hour of water heating capacity. In order to cut down on the energy costs of heating the fresh water, a concentric-tube heat exchanger is being considered as a **recuperator** to recover some of the thermal energy from the waste water to pre-heat the fresh make-up water prior to its entering the water heater.

The recuperator is to be designed as a multi-modular unit (5,000 concentric-tube recuperators operating in parallel with equal flow in each). The advantage to this multi-tube modular type of design is that the analysis and optimization can be done on a single recuperator module, and then virtually any size unit can be constructed by choosing the appropriate number of modules. This approach also simplifies prototype construction and testing, because both can be carried out on a **single** recuperator module.

Formulate a theoretical model that will yield the **optimum design of the recuperator** module in terms of economics, taking into consideration both capital equipment costs and natural gas operating costs. The optimum design will be that design which will meet operating specifications and will cost the least amount of money (heat exchanger material and natural gas costs) over a total anticipated operating time of 1000 hours (8 hrs/day, 5 days/wk, 25 wks). Material costs are as follows:

COPPER TUBING			TEES	BUSHINGS	
OD [IN]	WALL [IN]	\$/FT	\$/TEE	SIZE	\$/BUSHING
1/4	0.030	0.70	-	3/8 X 1/4	0.05
3/8	0.030	0.80	0.25	1/2 X 3/8	0.08
1/2	0.035	0.90	0.35	1/2 X 1/4	0.11

Using the tools and materials provided, build a prototype module of your recommended recuperator design. Its performance will be tested¹ early December in the presence of a representative from the chemical company requesting the bid. The best design will be the one that meets the design specifications while saving the most money. Augmentation of the convective heat transfer is encouraged. Prepare a technical report describing your proposed design, and write a one page cover letter to accompany the report and to be a sales pitch for your proposed design.

¹ Details pertaining to the testing procedure will be given later.

Figure 1. Assignment Specification Sheet.

At the time the above design project assignment is handed out, several class lectures have already been concluded regarding heat exchangers. The lectures draw on knowledge and comprehension already taught in previous courses in thermodynamics, fluid mechanics and thermal energy transport. In these lectures, and subsequent homework assignments and small quizzes, the students are challenged on not only the related knowledge, comprehension and application, but also on analysis. In this way, it is assured that they have the necessary tools to synthesize the design and evaluate the results. Figure 2 illustrates the summary of the developed analysis regarding concentric-tube heat exchangers.

FLUID AND THERMAL ENERGY SYSTEMS ME 482/582 G.L. Wedekind C.J. Kobus		
Concentric - Tube Heat Exchangers; Summary		
	Parallel-Flow	Counter-Flow
1. Flow Geometry		
2. Heat Transfer Rate; $\dot{Q}$		
a) Physical Mechanisms	$\dot{Q} = U_o P_o L (\Delta T)_m$	
(i) Overall H.T. Coefficient; U_o	$U_o = \left\{ \left(\frac{d_o}{d_i} \right) \frac{1}{h_H} + \frac{d_o \ln(d_o / d_i)}{2k} + \frac{1}{h_c} \right\}^{-1}$	
b) Consequences of H.T. Rate	$\dot{Q} = C_H (T_{H,i} - T_{H,o}) = C_c (T_{c,o} - T_{c,i})$	
c) Flow Capacitance; Definition	$C_H \equiv \dot{m}_H c_{p,H}$, $C_c \equiv \dot{m}_c c_{p,c}$	
3. Fluid Temperature Difference		
a) Local; $(T_H - T_c)$	$T_H - T_c = (T_{H,i} - T_{c,i}) e^{-\gamma z}$	$T_H - T_c = \frac{(T_{H,i} - T_{c,i})[1 - (C_H / C_c)] e^{-\gamma z}}{[1 - (C_H / C_c) e^{-\gamma L}]}$
b) Mean; $(\Delta T)_m$		
(i) Theoretical Model	$(\Delta T)_m \equiv \frac{1}{L} \int_{z=0}^L (T_H - T_c) dz = \frac{(T_{H,i} - T_{c,i})}{\gamma L} [1 - e^{-\gamma L}]$	$(\Delta T)_m = \frac{(T_{H,i} - T_{c,i})[1 - (C_H / C_c)][1 - e^{-\gamma L}]}{\gamma L [1 - (C_H / C_c) e^{-\gamma L}]}$
(ii) LMTD; Inlet and outlet temps	$(\Delta T)_m = \frac{(T_{H,i} - T_{c,i}) - (T_{H,o} - T_{c,o})}{\ln \left\{ \frac{(T_{H,i} - T_{c,i})}{(T_{H,o} - T_{c,o})} \right\}}$	$(\Delta T)_m = \frac{(T_{H,i} - T_{c,o}) - (T_{H,o} - T_{c,i})}{\ln \left\{ \frac{(T_{H,i} - T_{c,o})}{(T_{H,o} - T_{c,i})} \right\}}$
4. Heat Exchanger Effectiveness; ϵ		
a) $(C_H / C_c) \leq 1$		
(i) Definition, Inlet and outlet temps	$\epsilon_H \equiv \frac{\dot{Q}}{\dot{Q}_{\max}} = \frac{(T_{H,i} - T_{H,o})}{(T_{H,i} - T_{c,i})}$	
(ii) Theoretical Model	$\epsilon_H = \frac{1 - \exp[-(NTU)_H][1 + (C_H / C_c)]}{[1 + (C_H / C_c)]}$	$\epsilon_H = \frac{1 - \exp[-(NTU)_H][1 - (C_H / C_c)]}{[1 - (C_H / C_c) \exp[-(NTU)_H][1 - (C_H / C_c)]]}$
b) $(C_c / C_H) \leq 1$	$\epsilon_c \equiv \epsilon_H (C_H / C_c)$	
5. Terminology: $(NTU)_H \equiv (U_o P_o L / C_H)$	$\gamma \equiv \left(\frac{U_o P_o}{C_H} \right) [1 + (C_H / C_c)]$	$\gamma \equiv \left(\frac{U_o P_o}{C_H} \right) [1 - (C_H / C_c)]$

Figure 2. Summary of Knowledge Base Related to Design Project.

The student groups are given broad discretion in the design of their recuperator. Based on the assignment specification sheet shown in Figure 1, they have the discretion to choose the best tubing combination from those available. It is not intuitively obvious which combination will yield the best results. The student teams therefore have to formulate a theoretical model that will predict recuperator performance in terms of the three possible tube combinations.

One of the unique aspects of this design project is that the optimal design is that design which will yield the best *cost savings*. This is a departure from earlier design projects that focus on optimizing system output, efficiency, etc. By adding this unique dimension to the design process, it becomes more real world and adds an interdisciplinary element.

V. Results of Design Experience

Very early in the design process, almost without fail, every design team focuses on the recuperator design rather than the overall system. This invariably leads to dead-ends because several system parameters, such as the flowrate ratio between the fresh and waste water, and the coupling of the thermal performance of the recuperator with the water heater, are not immediately obvious. The teams then learn that before meaningful synthesis can occur, the problem must first be formulated to include the entire system, of which the recuperator is only a part. The schematic in Figure 3 is the correct one for the design specifications. It should be noted that all the Figures in this section were taken from actual student reports.

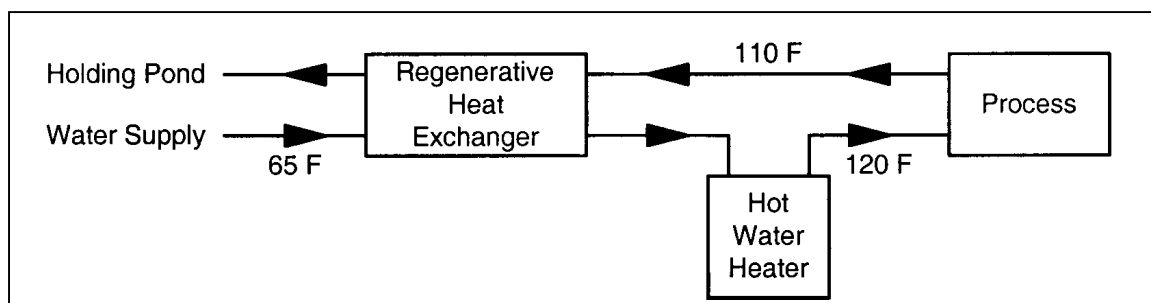


Figure 3. Schematic of the Overall System Involved in the Design Problem.

Once the overall system is understood and defined, a model can be formulated, analysis occurs, and the recuperator can be designed. One of the obvious conclusions that are reached once the overall system in Figure 3 is drawn, is that the fresh and waste water flowrates in the inner tube and annulus of the concentric-tube heat exchanger are the same. Thus, the flow capacitance ratio, C_H/C_C , which appears in many of the governing equations shown in Figure 2, is determined. Figure 4 is a schematic of such a recuperator.

The optimum length of the recuperator must be determined by coming up with a single theoretical (model) equation for the cost savings. The cost of heating 100 percent of the incoming fresh water in the water heater alone (no recuperator) is the baseline. With the recuperator in the system (Figure 3), the capital cost of the recuperator material plus the energy cost of operating the water heater to raise the temperature to the required process temperature must be considered. The difference between the former and the latter is the cost savings.

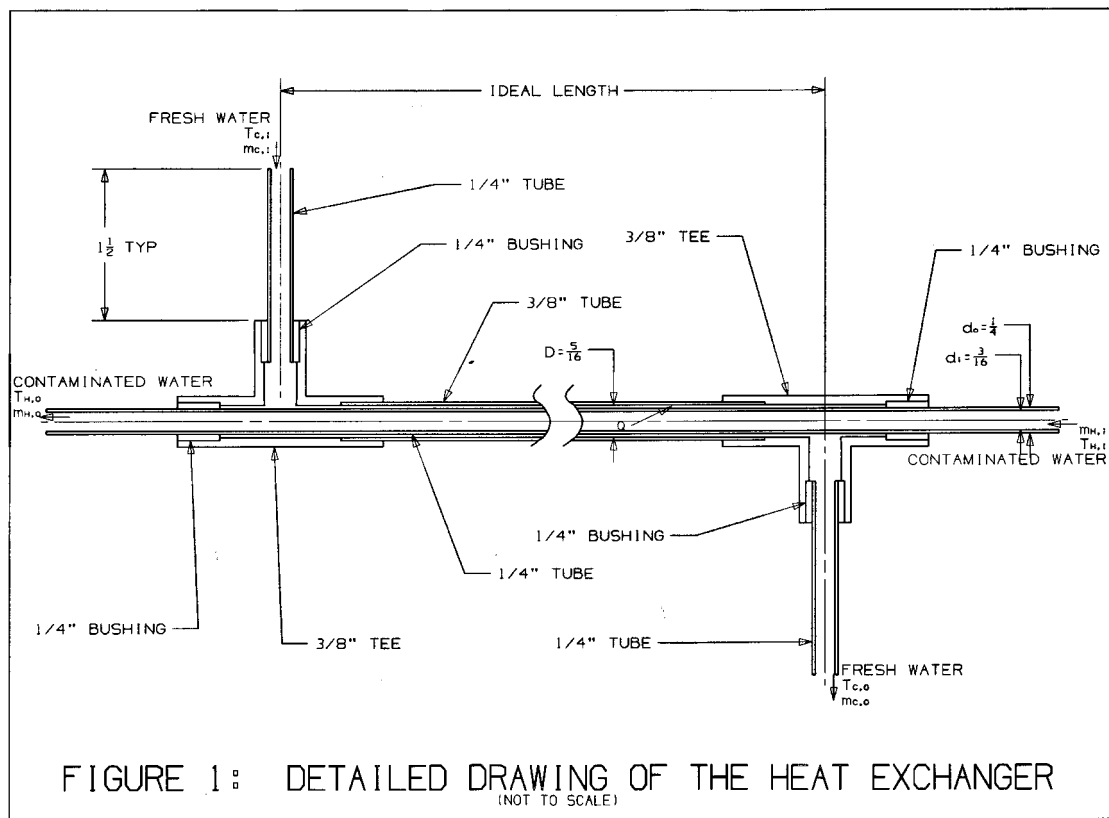


Figure 4. Schematic of a Concentric-Tube Thermal Recuperator.

The cost savings curves for the three possible tube combinations can be altered significantly by augmenting the heat transfer in either, or both, the inner tube or the annulus of the recuperator. Augmentation is encouraged but not demanded. Over the years, many clever augmentation schemes have been developed by students to enhance the heat transfer and thus increase the cost savings. Because of the already lofty goals associated with the design project, there was no monetary charge for the augmentation, nor are pumping costs considered at this time.

Some of the clever augmentation techniques include running a thin wire down the center of the inner tube, which has the effect of making the flow inside the *inner tube* annular because of the no-slip at the thin wire, therefore sharpening the velocity profile and therefore increasing the heat transfer. Other schemes include wrapping a thin wire around the inner tube that is the precise thickness of the annular space between the inner and outer tubes. This has the effect of making the annular flow helical around the inner tube, where the flow now travels through an almost rectangular channel. The velocity of the flow can therefore be increased by decreasing the pitch of the wire wrap. In this way, laminar flow can be made turbulent, which in turn enhances heat transfer. Other schemes include packing the inner tube and annulus with a porous material such that the heat transfer behaves as if it were in a packed bed.

One of the more unique heat enhancement methods was to make the recuperator a triple-channel concentric-tube heat exchanger. This led to research that was subsequently published².

Figure 5 illustrates the typical curve shape of the cost savings versus recuperator length for the three possible tube combinations. Note that for very short heat exchanger lengths, the savings is negative, meaning that it actually costs more to implement the recuperator use than to just heat all of the fresh water in the water heater. For very long lengths, the savings can also become negative because of the eventual point of diminishing performance returns with increasing recuperator length. The uppermost curve represents the best tube combination (1/4" inside 3/8") where the optimal length is approximately 35 inches.

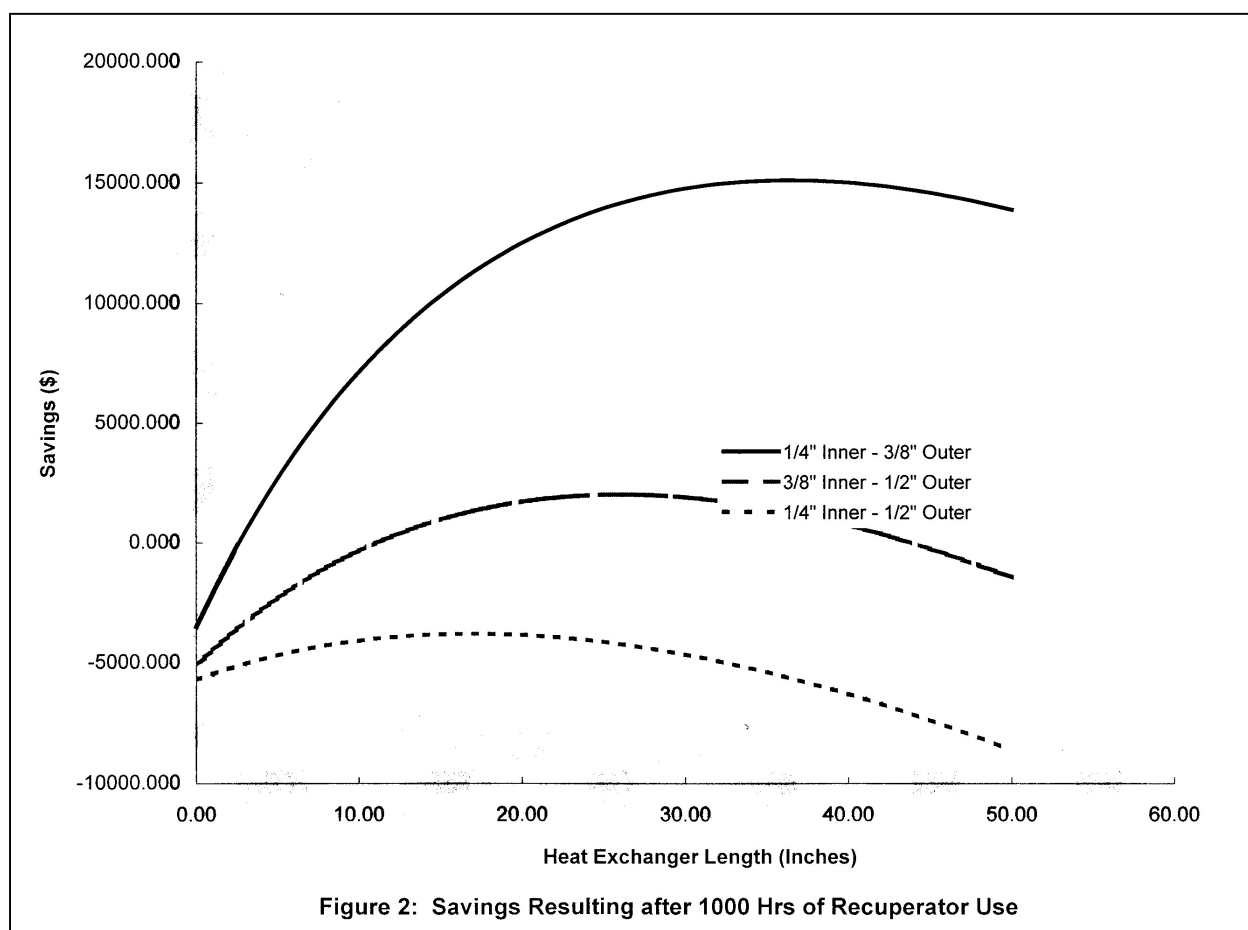


Figure 5. Cost Savings for Different Tube Combinations.

During the final two weeks of the design project, the students are given instructions on how to sweat solder copper tubing. Safety measures, equipment, materials and methods are explained in detail, including a demonstration. The individual design teams then fabricate their own concentric-tube recuperator module.



Figure 6. Sweat Soldering of the Thermal Recuperator.

Figures 6 and 7 illustrate various stages in the fabrication of a thermal recuperator by a student design team. For many students, this was the first time that they have been given the opportunity to build a working prototype of their design. It was also the first time that most of them had done any sweat soldering.



Figure 7. The Finished Product.

Testing of the recuperator prototypes was done on the last day of class. As a rule, the recuperator could not be experimentally tested prior to the last day, thereby eliminating trial-and-error experimental designs. Figure 8 illustrates a typical test set-up for measuring the performance of a recuperator module. Once the system reaches steady-state flowrate and temperature, inlet and outlet temperature measurements are taken for both the fresh water and the waste water. This provides a means for computing the recuperator effectiveness, and how well it met the predicted design performance.



Figure 8. Testing of the heat exchanger.

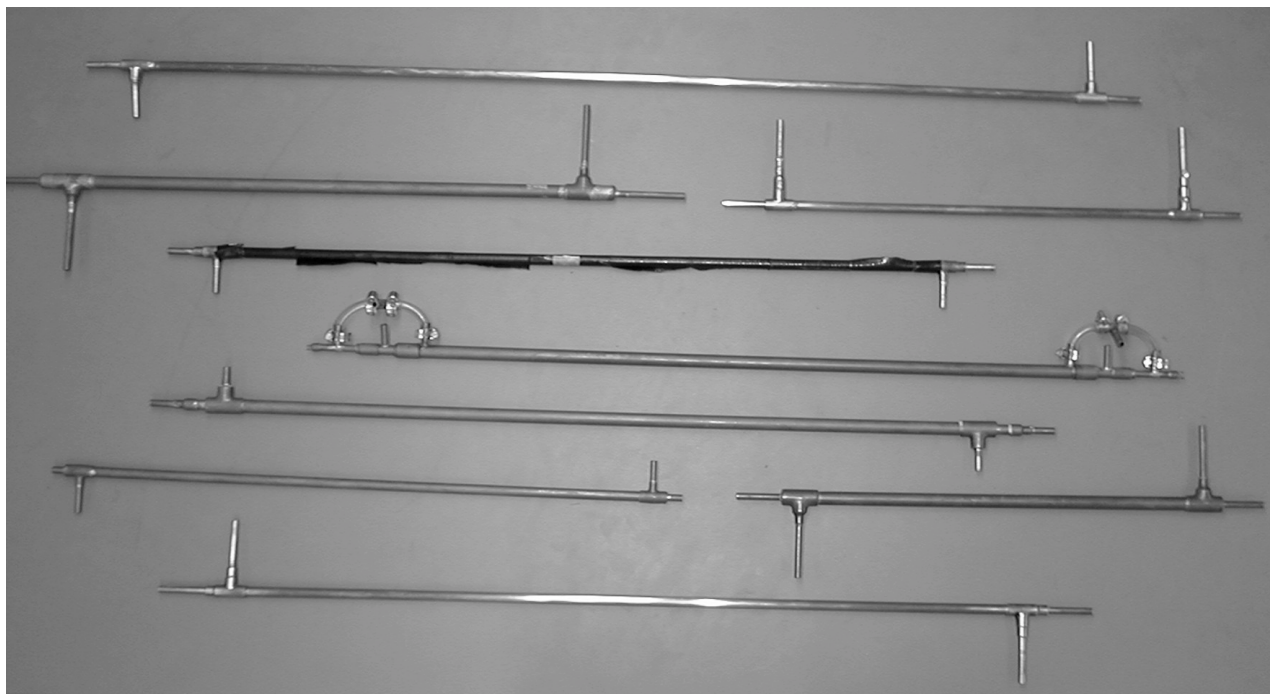


Figure 9. Various recuperator design prototypes.

Referring to Figure 9, it is obvious that creativity and imagination has been stimulated by this design project, judging purely from the wide variety of recuperator designs.

VI. Student Feedback and Comments

Over the many years that this final design project has been assigned, the student response has been overwhelmingly positive. During the course of the design project, we have had countless enthusiastic and excited design teams asking us questions almost daily on recuperator design, and particularly the augmentation. Nearly every semester we see new ideas being generated by the teams.

This high level of enthusiasm invariably feeds back on the instructors, enhancing our own excitement for the project and for education in general. In turn, we continually work harder to refine our methods for education. Aside from the verbal enthusiasm, it is very apparent when the project write-ups are handed in that the design teams expended considerable energy toward the design project. In fact, the average grade for this particular project is generally higher than those associated with hands-on laboratory experiences in lower-level courses.

In addition, the final student course evaluations are unilaterally positive on their design experience in this course, and in particular this project. Although challenging, former students years later will visit us and the recuperator design project is an early topic of discussion.

VII. Summary and Conclusions

This paper provided a detailed description of the final design project in the *Fluid and Thermal System Design* course offered to seniors at Oakland University. This course is intended to give students a global perspective of the design process, integrating the entire taxonomy from knowledge, comprehension and application to analysis, synthesis and finally evaluation. The recuperator design project involves all of the aforementioned steps in the design process. The project is performed over the final five weeks of the semester in teams of three to four students, with one student being the team leader.

Student groups are design-engineering teams working for fictitious competing companies that specialize in customized heat exchanger design, testing, and installation. The teams are to formulate a theoretical model that will provide insight into the optimal design of the recuperator module, taking into consideration both the capital equipment costs and the energy operating costs. In addition to the responsibility for design, teams are provided with the raw material and tools to build and test the performance of a prototype module of their recuperator design.

Judging from the wide variety of recuperator designs, it is obvious that creativity had been stimulated by this design project. In addition, the many positive student comments on course evaluations, as well as unsolicited comments by the students, leads to the conclusion that this design project is not only valuable to the students' educations as engineers, but is a confidence builder as well.

Acknowledgements

The authors would like to acknowledge the many students who have participated in this particular design project over the years. Their enthusiasm, creative thinking and constant questions and challenges to us in synthesizing a better design, continually fuels our enthusiasm to discover and develop new ideas and methods to enhance our effectiveness as engineering educators.

Bibliography

1. Bloom, B. S. and Krathwohl, D. R., *Taxonomy of Educational Objectives. Handbook 1. Cognitive Domain.* New York: Addison Wesley (1984).
2. Ko, C.L., and Wedekind, G.L., Analysis for the Optimal Performance of Three-Channel Split-Flow Heat Exchangers, *International Journal of Heat and Mass Transfer*, Vol. 39, No. 4, pp. 691-705 (1996).

GILBERT L. WEDEKIND

Gilbert Wedekind is the John F. Dodge Professor of Mechanical Engineering at Oakland University in Rochester, Michigan. He received his B.S., M.S. and Ph.D. (1965) at the University of Illinois at Champaign-Urbana. He was hired by Oakland University in 1966 to develop the Fluid and Thermal Science curriculum at the then start-up School of Engineering. He is responsible for the vast majority of course development as well as the development of most of the hands-on laboratory experiences integrated into every fluid and thermal science course offered at Oakland University. In addition to a highly respected research program that has garnered half a dozen NSF Grants as well as other corporate sponsorship, Dr. Wedekind has received numerous teaching awards, including the 1992-93 Outstanding Teacher Award by ASEE, North Central Section.

CHRISTOPHER J. KOBUS

Chris Kobus is an Assistant Professor of Mechanical Engineering at Oakland University in Rochester, Michigan. He received his B.S., M.S. and Ph.D. (1998) from Oakland University. Dr. Kobus was hired by Oakland University in 1998 and is maintaining a funded research program. Known as a challenging and enthusiastic teacher, he frequently garners some of the highest student evaluations in the School of Engineering and Computer Science.