VERSATILE HEAT TRANSFER LAB FOR CONDUCTING BENCH-TOP EXPERIMENTS

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Abstract
This paper describes heat transfer benches that were developed at the U.S. Naval Academy, and several basic experiments that have been implemented to date. Each bench contains the necessary equipment for a variety of experiments. Using the heat transfer bench, and working in groups of four or five, students perform hands-on heat transfer and thermo-fluids experiments. These experiments include measuring the thermal conductivity of different materials; measuring an overall heat transfer coefficient; testing the performance of heat sinks; monitoring transient heat conduction; measuring convection heat transfer coefficients and measuring the effectiveness of different sized heat exchangers. The students are required to perform uncertainty analyses, and recommend methods for reducing uncertainty. The flexibility of the heat transfer bench also allows the students to design and conduct their own experiments. Involving the students in the design of the experiment places the responsibility for the outcome on them, and challenges their basic understanding of the subject. A description of each experiment is presented along with some anecdotal student evaluations.

Background
In recent years, the U.S. Naval Academy has invested in a number of pieces of "self-contained" educational laboratory equipment. This type of educational laboratory equipment is commercially available and generally comes completely instrumented. The individual units tend to demonstrate a single concept, and different units are available for a number of subjects including thermal conductivity; free and forced convection; transient heat conduction; boiling and condensation heat transfer, heat exchangers, internal combustion engines, air conditioning systems and many other topics. This type of equipment can and has been used effectively. Shawn Kim [1] presents an interesting article on getting students involved in thermal design by improving existing commercial equipment. There are a number of papers that describe apparatuses for single experiments that can be built relatively easily and for significantly less expense than comparable commercial products [2,3].

In order for every student to be directly involved in each exercise, multiple units must be purchased. This can be cost prohibitive and requires additional storage space for the units not actively being used. With only a single unit, the exercises tend to be demonstrations rather than actual laboratories. Student groups take turns collecting data that is consolidated and distributed to the other groups in a class. The majority of the work tasked to the students comes in the form of performance calculations and the uncertainty analysis for the experiment.

Single-function laboratory equipment is required for some complex systems, but simpler equipment that can be configured for multiple uses is often more versatile and can provide students with more opportunities for experiment design. A pre-assembled and instrumented apparatus is often viewed by students as something of a black box, from which data emerges, even when the apparatus is described in the laboratory instructions. If students must assemble and instrument their own experimental apparatus, however, they are more likely to appreciate the physical meaning of their data. Heat transfer is a subject that tends to focuses on basic concepts versus complex applied systems. One of the more challenging aspects for most students is gaining a physical understanding of the mathematics that describes the physics. There are numerous basic experiments that can be designed and implemented with a relatively small amount of equipment. Therefore, this subject was ideal for developing more hands on laboratories and encouraging student to design and conduct their own experiments.

The calculations that support the various experiments were typically performed using Engineering Equation Solver (EES). The students were already familiar with EES, as the software was used extensively during their Applied Thermodynamics course. Each lab involved an uncertainty analysis; accordingly, the students were required to estimate and input the uncertainty in every measured quantity. The students had already learned about conducting an uncertainty analysis analytically during a course on experimentation. During this course, the students were encouraged to use the uncertainty propagation capability in EES.

Table 1. Inventory of Heat Transfer Bench

Laptop Computer	$1,500
National Instruments NI-4350 Data Acquisition Unit	$1,100
National Instruments Terminal Block TBX-68T	$200
National Instuments Labview	$1,300
Thermo-Neslab Merlin-33 Recirculating Chiller	$3,000
Thermo-Neslab Recirculating Hot Water Bath	$1,500
Workbench	$500
Hand Tools	$500
Fluke Digital Multimeter	$300
Variable AC Transformer	$300
Omega Handheld IR Probe	$250
Heat Exchanger	$200
Water Cooled Heat Sink	$150
Flowmeters, Valves & Tubing	$150
IR Heating Lamp	$150
Kapton Heaters (Various)	$150
Vernier Calipers	$100
Wind Speed Indicator	$100
Multi-Speed Fan	$50
Total Cost (2003)	$11,500

Heat Transfer Benches

Laboratory benches were designed and assembled for use in a heat transfer course. A complete inventory of the items purchased for each heat transfer bench is shown in Table 1. In the subsequent sections, several select experiments will be described in which this equipment has been utilized. In general the equipment was selected to keep the bench as versatile and the experiments as interesting as possible. Depending on budget constraints, not all of the equipment listed would be absolutely necessary, and the selection would depend on the type of experiments envisioned. Figure 1 shows a photograph of a complete bench.

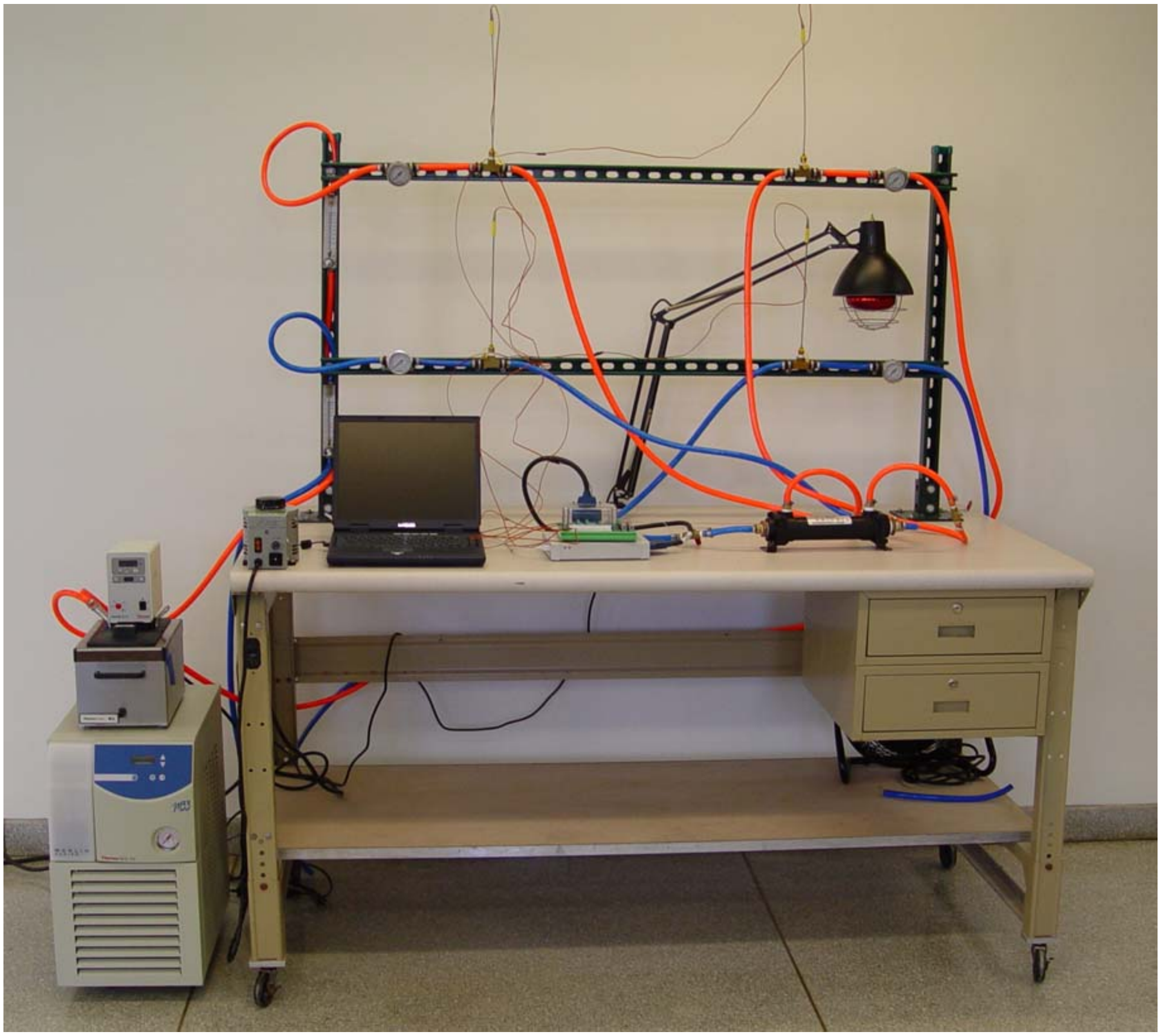

Figure 1. Photograph of USNA Heat Transfer Bench

A total of five benches were constructed representing a total investment of $57,500. The lab sections have a maximum of twenty students, which correspond to roughly four students per lab group. As long as everything is working properly, one instructor can easily handle the entire lab section, although some assistance from a teaching assistant or technician can be valuable.

One requirement common to all the experiments is the ability to record temperature. This is accomplished using a National Instruments NI-4350 precision temperature and voltmeter. These units are capable of recording data from up to 14 thermocouples with an accuracy of 0.4 °C at a rate of up to 60 readings per second. The units come with software that enables the display and recording of data, and allows some basic control of the sampling frequency. Labview was purchased with the ultimate goal of developing a more user-friendly and flexible interface; however the basic software that came with the NI-4350 has proven to be sufficient.

Thermal Conductivity Experiment

In this laboratory each group measures the thermal conductivity of four samples: 6061 aluminum, brass, plain steel, and stainless steel. The heat source is a 2" diameter kapton heater. The specific amount of heat applied is controlled using the Variac, which is set to a specified voltage reading using the digital mulitmeter. The heat sink is a water cooled copper block connected to the recirculating chiller. Two thermocouples are used to measure the temperature difference across a known distance.

Each sample has a cross-sectional area of 2" x 2", and has two 1/16" diameter, 1" deep holes that have been drilled into the sample. The general configuration for the electrical heater, copper heat spreader, sample and the copper heat sink is shown in Fig. 2. The entire assembly is clamped together, the heater is energized, and the sample temperatures are allowed to reach steady state. The stainless steel sample takes the longest time to reach steady state at about 30 minutes. While waiting for the sample to reach steady state, it helps to encourage the students to begin the calculations described below.

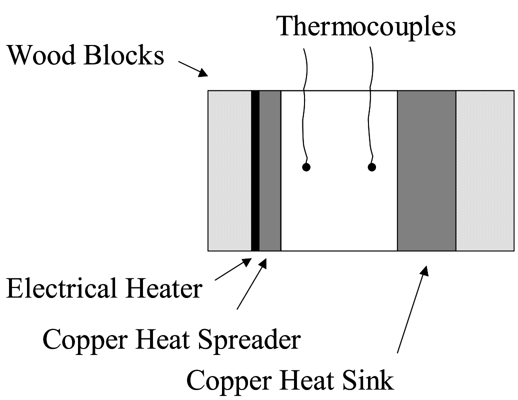

Figure 2. Thermal Conductivity Experimental Setup.

Using the measured voltage applied to the heater, heater electrical resistance, sample cross sectional area, distance between the thermocouples and the temperature difference; the students are able to calculate the thermal conductivity of each sample. The student must estimate the uncertainty in each measured quantity. They report all four conductivity values along with a confidence interval for the measurement. They must also clearly state which source of uncertainty was the most critical for each sample and compare their results to anticipated results. The experimental results were typically within ±10% of the textbook value for each material and the uncertainty of the measurements ranged between ±10-20%. The uncertainty is higher for the aluminum sample due to the small temperature difference. The aluminum sample had to be about 1” thick in order to achieve a measurable temperature difference.

Heat transfer through the samples is assumed to be one dimensional, but since no attempt has been made to insulate the assembly, heat loss from the sides can become a major source of error, particularly for low conductivity samples. The most significant source of uncertainty in the stainless steel sample comes from the estimated heat loss to the surroundings.

Overall Heat Transfer Coefficient

In this laboratory the students measure the overall heat transfer coefficient associated with an insulated box. A known amount of ice is placed in a tray inside the box and allowed to melt. Thermocouples are placed on the inside and outside walls of the box in order to quantify the heat flux through each wall. Additional thermocouples are placed in the air inside and outside of the box, and in the ice tray. The thermocouple located in the ice tray can be used to find the time required for all the ice to melt. The experiment typically runs overnight with the laptop recording data once a minute. Figure 3 shows a picture of the box instrumented with thermocouples. While this experiment runs overnight, it only takes about 30 minutes to set up. During the remaining portion of the lab period, the students use a computer classroom for resistor network calculations.

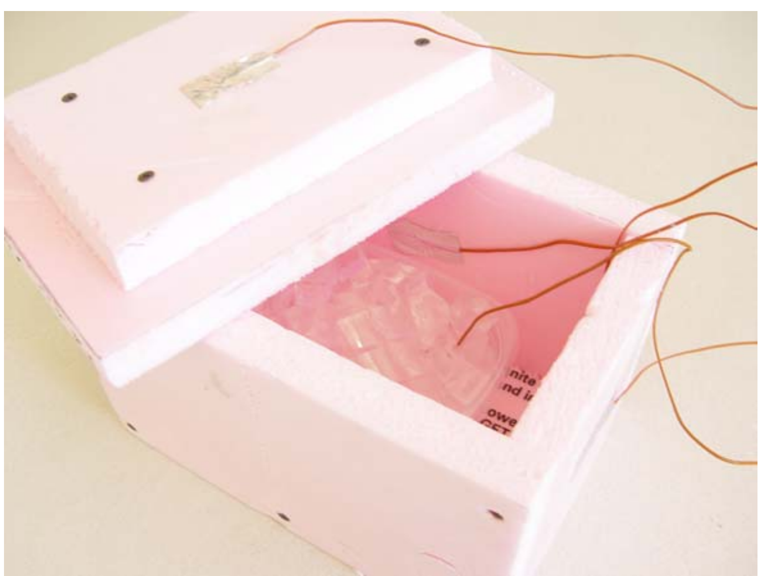

Figure 3. Overall Heat Transfer Coefficient Experiment for an Insulating Cooler.

The heat transfer rate into the box is computed from using the heat capacity of the ice and the measured time required for melting. The overall heat transfer coefficient is then computed using the heat transfer rate and the temperature difference between the ice and room air. The measured overall heat transfer coefficient is then compared to a predicted value determined using a resistor circuit. The students have to make several assumptions concerning the geometry of the problem since it is not strictly 1D. Reasonable convection heat transfer coefficients are provided along with an estimated uncertainty. The walls of the box are 1" thick polystyrene foam, which has a known thermal conductivity. Using the temperature difference across the polystyrene, the heat flux and heat transfer rate for each wall can be calculated and compared to the measured rate of heat transfer. The measured rate of heat transfer into the coolers used was about 2±0.4 W which corresponds to a UA of 0.1±0.04 K/W. The predicted rate of heat transfer was about 2.9±0.7 W this corresponds to a UA of 0.15±0.04 K/W.

Extended Surface Heat Transfer

This laboratory is an experimental and analytical investigation of heat transfer through uniform cross-sectional area fins. The students conduct an experiment in which they estimate the convection coefficient from single uniform rectangular fin using the measured temperature profile along the length of the fin, and for an array of fins using the measured base temperature. Figure 4(a) and 4(b) show the single fin and the array of fins used for this experiment. The finned surfaces were cooled by the multi-speed fan.

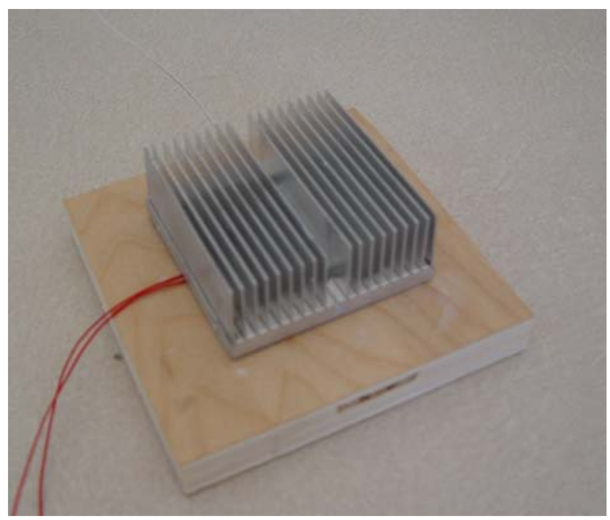

Figure 4 (a) Single Fin (b) Heat Sink

The single fin consists of a 1/16" thick aluminum plate which is bent into an "L" shape. A kapton heater supplies heat to the base of the "L", which is held between wooden blocks. The longer leg of the "L", which extends from the wood, comprises the fin. The multi-speed fan is used to blow air across the fin for cooling. The temperature profile along the fin could have been measured using thermocouples attached to the surface; however, we chose to use the handheld IR probes. The surface of the fin was painted black to improve the measurement, and the probe was then used to measure the temperature at 1" increments starting from the base of the fin. The

IR probes that were purchased are only accurate to about 1 ºC, and depend on the estimated emissivity of the sample surface. Despite these limitations, reasonable profiles were measured. The measured temperature profile is then compared to an analytical solution to determine a value for the convection heat transfer coefficient. The IR probes are certainly not required, although measuring the temperature of your fellow student's forehead seemed to be quite popular.

The array of fins that comprise the heat sink shown in Figure 4(b) is heated using a 2" diameter kapton heater, and cooled by the multi-speed fan at three different settings. The students calculate the average heat transfer coefficient for the fins as a function of the base temperature, the air temperature and the power supplied to the heater. The base temperature is measured using a thermocouple placed inside the base plate. The calculated values are reasonable for forced convection in air, and increase with the fan speed.

Transient Conduction

In this laboratory each group measured and numerically predicted the transient temperature distribution for a piece of 5" x 5" x 1" steak cooking on a kapton heater. The lower surface of the steak is subjected to a uniform heat flux using a 5" x 5" square kapton heater. The sides of the steak were insulated and the upper surface is exposed to natural convection with the room air. Thermocouples were placed at the base of the steak, at the center plane, and on the upper surface. The steak was then allowed to cook for a little over an hour. During this time the students began their finite difference calculations. Figure 5 shows the experimental results versus the finite difference solution.

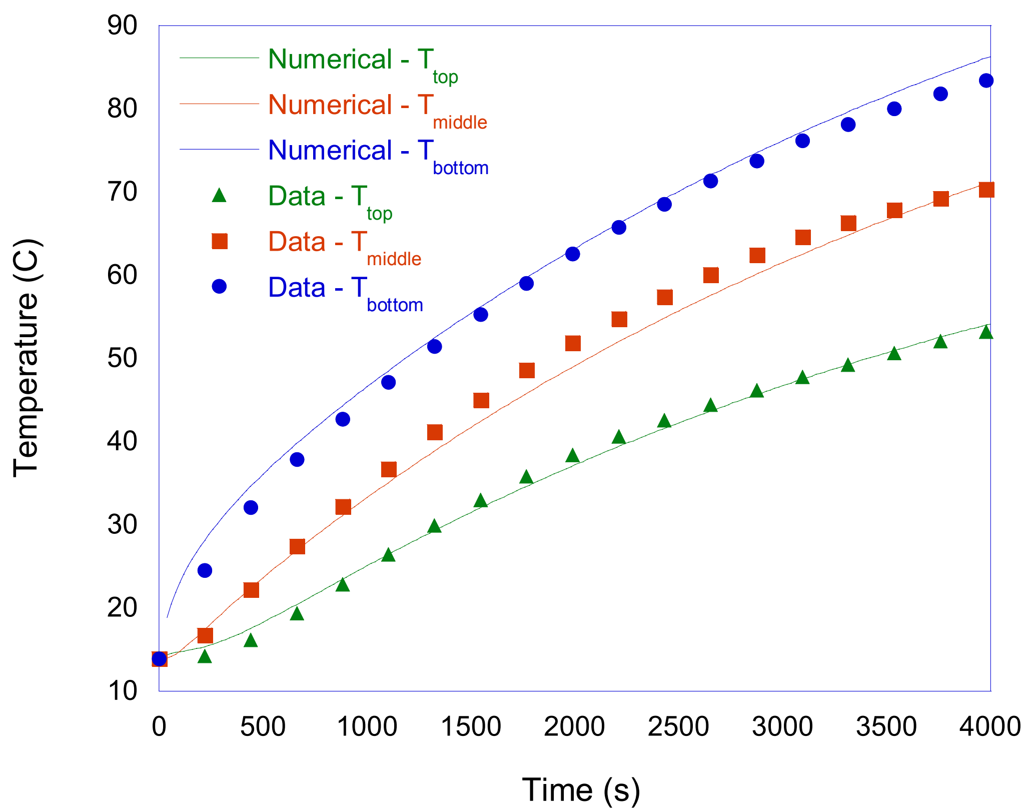

Figure 5. Results of the transient conduction lab for a 1" thick steak subject to a uniform heat flux on one side and convection on the other.

Convection

The Accreditation Board for Engineering and Technology requires that engineering programs demonstrate that their students have "an ability to design and conduct experiments, as well as to analyze and interpret data" [4]. The heat transfer benches are an ideal platform through which to accomplish this objective. Incorporating the design of experiments in heat transfer laboratories has been the topic of several other recent investigations [5,6]. Having the students design their own experiment can be more challenging for both the students and the instructor; however, the potential reward is also greater.

In the series of experiments described above, the students have gained an understanding of the available equipment along with a clearer understanding of our expectations. The objective of this laboratory was to have the student design their own experiment to measure a convection heat transfer coefficient. Appendix A shows the directions provided for the self-design convection experiment. The experiment also had to include either steady-state or transient conduction. The different groups attempted a wide variety of experiments, and achieved various degrees of success. Figure 6 shows an internal flow experiment where the students are measuring the heat transfer coefficient for water flowing through a copper tube in an ice bath.

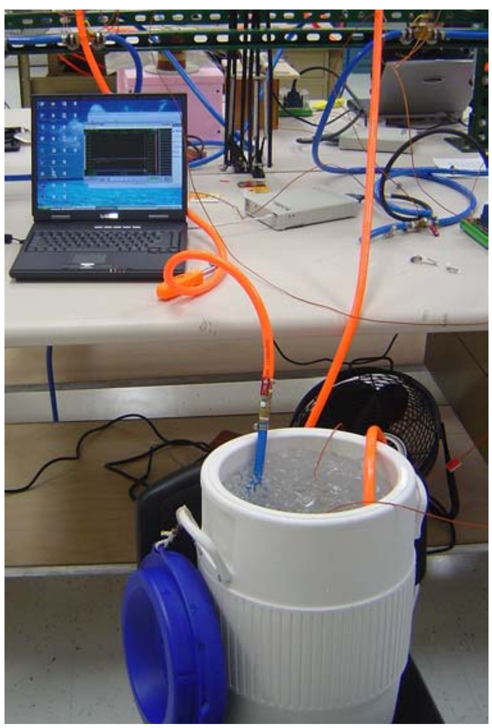

Figure 6. Internal flow through copper tubing in an ice bath.

This seemed to be a lab the students either really liked or really disliked. In general, the groups that put more effort into their design had better results and enjoyed the lab. The students were surveyed at the end of the semester for their opinion on the various laboratories. It was interesting to see that several students listed the convection laboratory as both their favorite lab and their least favorite. Several of the student comments are listed below.

Positive Comments

- "Cool to see our work progress from something to nothing."
- "Had us seriously think about the problem and the possible ways to solve it."
- "This lab allowed us to actually think about the concepts."

Negative Comments

- "Difficult to figure out. As each experiment was different, we could not ask fellow classmates."
- "Solutions never worked out and concepts didn't explain results."
- "Too difficult and confusing. Couldn't get correct solutions."

Heat Exchangers

In this laboratory, the students test the performance of a single-pass shell and tube heat exchanger. The experimental results are used to determine the effectiveness and the overall heat transfer coefficient. The heat exchangers are configured to operate as both parallel and counter-flow heat exchangers. The flow rate of the fluid in the shell is incrementally increased in order to demonstrate the influence of flow rate on the overall heat transfer coefficient. The recirculating chiller and hot water baths are used to maintain the temperature of the hot and cold sides of the heat exchangers. If the temperature difference between the fluids is set too high, the rate of heat transfer exceeds the capacity of the chiller and begins to warm the cold water reservoir temperature. This lab could be accomplished at a more reasonable price with a large supply of building hot water.

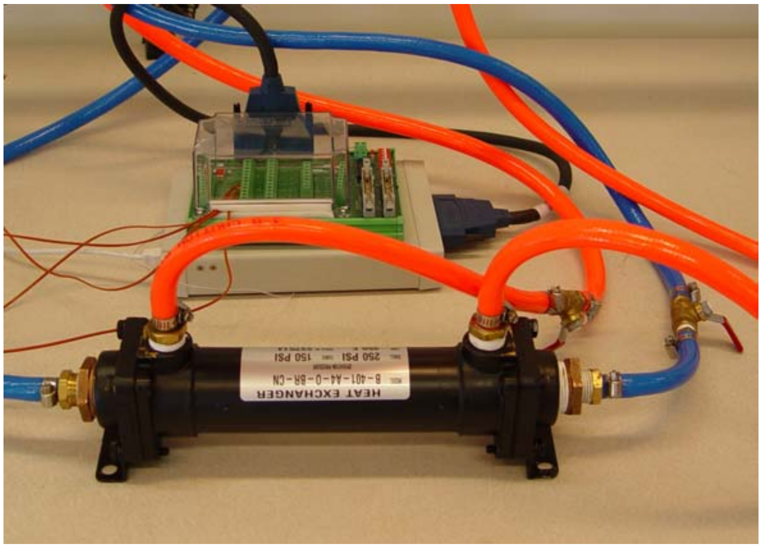

Figure 7. Heat Exchanger Lab

Figure 7 shows one of the heat exchangers used in the laboratory. There were a total of four different heat exchangers of various dimensions. The first step of the experiment is to open one end of the heat exchanger to expose the manifold at the tube entrance and count the number of tubes, measure the tube diameter and measure the overall length. Using these measurements, the student can calculate the overall heat transfer area. The students then measure the inlet and outlet temperature of each fluid for a variety of flowrates. The flowrate can be set between 0-3 lpm for the hot fluid and 0-10 lpm for the cold fluid using a needle valve that is part of an in-line flowmeter. The systems reach steady state in about 10 minutes. If the capacity of the chiller is exceeded, it can take slightly longer.

Student Feedback

At the end of the course, the students were asked to complete an evaluation of the laboratories. The first question:

"Did the laboratories help with your physical understanding of the material?"

This question received a favorable response from about 80% of the students. The remainder of the students generally commented that the concepts weren't that difficult and therefore the labs were not necessary. The final questions asked the students was

"Do you find the laboratories more interesting and/or frustrating than other Mechanical Engineering Laboratories? Please provide some specific examples."

The majority opinion was **both**. Some representative comments have been provided.

- "BOTH - they are interesting but analyzing them on EES can be frustrating."
- "I think that the labs in this course convince you that this stuff actually works. They may be frustrating, but when they work they really are a positive educational experience"
- "Interesting. The self-design experiment brought in the actual engineering problem approach, and the heat exchanger was easier to understand after we switched the flow direction."
- "Hands-on labs were more interesting, but frustrating when we got inaccurate readings. There was less of a chance of bad readings with the computer based labs."

Conclusions

The heat transfer benches being used at the U.S. Naval Academy have been described, along with several bench-top experiments. These systems are very versatile and can be used to implement any number of conduction, convection and radiation experiments. The students are required to assemble and instrument each experiment which creates a more "hands-on" environment. At times the experiments were deliberately kept simple, which meant that only limited effort was put into controlling experimental uncertainty. While this may result in additional error in the measurements, the overall purpose of these experiments is to provide a better conceptual understanding of heat transfer, and simplicity helped in this effort. After the students have been familiarized with the available equipment, they are tasked with designing their own convection experiment. While challenging, this was a rewarding experience for many of the students and the instructors.

Acknowledgements
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Appendix A

EM-415 Laboratory Assignment "Convection Experiment"

Objective: Each group will design and execute an experiment where they will measure a convection heat transfer coefficient by recording steady state or transient temperatures. The temperatures will be recorded using up to 10 thermocouples. The experiment must also include one aspect of conduction heat transfer that has been covered in class.

Requirements: The experiment must meet the following criteria.

(1) Include the calculation of one or more convection heat transfer coefficients using the correlations provided in the textbook.
- (a) External Flow (Chapter 7)
- (b) Internal Flow (Chapter 8)
- (c) Free Convection (Chapter 9)

(2) Include conduction calculations in one of the following forms:
- (a) Thermal Resistor Circuit
- (b) Extended Surface Heat Transfer (fins)
- (c) 2D Steady State Numerical Solution
- (d) Transient Conduction

Proposal: Submit a proposal that provides a detailed description of the experiment including a physical sketch. The proposal should also include preliminary calculations and a prediction of the anticipated results.

Report: Each group will prepare a Memorandum Report using the Mechanical Engineering Department format. The memorandum should include a detailed description of the experiment, the necessary calculations described above including the correlation used to predict the convection heat transfer coefficient, and a discussion of how well the predicted value compared to your experimental results. The experimental results must include an uncertainty analysis. Present several ideas on how would you redesign your experiment in order to achieve better results. Attach to the memorandum all of your calculations, plots, etc. in an organized format that can be easily understood by a reader.