2006-328: DEVELOPMENT OF EXPERIMENTAL APPARATUSES TO BE USED IN TWO SEQUENTIAL THERMAL SCIENCE COURSES

John Reisel, University of Wisconsin-Milwaukee

John R. Reisel is an Associate Professor of Mechanical Engineering at the University of Wiscsonsin-Milwaukee (UWM). He serves as Director of the Combustion Diagnostics Lab, Associate Director of the Center for Alternative Fuels, and the Co-Director of the Energy Conversion Efficiency Lab. His research efforts concentrate on combustion and energy utilization. At UWM, Dr. Reisel has served on both the College of Engineering and Applied Science's and the university's undergraduate curriculum committees. Dr. Reisel was a 1998 recipient of the SAE Ralph R. Teetor Educational Award, the 2000 UWM-CEAS Outstanding Teaching Award, and the 2005 UWM Distinguished Undergraduate Teaching Award. Dr. Reisel is a member of ASEE, ASME, OSA, SAE, and the Combustion Institute. Dr. Reisel received his B.M.E. degree from Villanova University in 1989, his M.S. degree in Mechanical Engineering from Purdue University in 1991, and his Ph.D. in Mechanical Engineering from Purdue University in 1994.

Kevin Renken, University of Wisconsin-Milwaukee

Kevin J. Renken is an Associate Professor of Mechanical Engineering at the University of Wisconsin-Milwaukee (UWM). He is the Director of the UWM Porous Media Heat Transfer Lab, the UWM Radon Reduction Technology Lab, and the UWM Electro-Osmotic Technology Lab, as well as the co-Director of the UWM Energy Conversion Efficiency Lab. His research interests include computational and experimental methods in heat and mass transfer, radon entry dynamics, transport and innovative mitigation techniques, convection transport in porous media, multiphase flow and heat transfer, energy conversion, energy conservation, heat transfer augmentation, data acquisition and instrumentation, engineering education, aerosol science, indoor air quality and pollution control. Professor Renken is the recipient of the 1996 UWM College of Engineering and Applied Science Faculty Outstanding Research Award, the 1994 SAE Ralph R. Teetor Educational Award as well as the 1993 ASEE Dow Outstanding Young Faculty Award. His 1995 ASEE Annual Conference paper was selected as a best paper of session. Professor Renken is a member of ASEE, ASME, AARST, AIAA, ASHRAE, CRCPD, SAE, Sigma Xi, and Tau Beta Pi. He was also selected for inclusion in the 2001-2002 Millennium Edition of Lexington WHO'S WHO. Dr. Renken received his B.S. (1983), M.S., (1985) and Ph.D. (1987) in Mechanical Engineering from the University of Illinois at Chicago.

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Abstract

Integration of concepts throughout a curriculum can aid in student understanding and retention of difficult concepts. One area that is ripe for such integration is the Thermal Sciences, where Thermodynamics, Heat Transfer, and Fluid Mechanics courses all share some common ground. In this paper, the development of experimental apparatuses, which can be used for experiments in both Thermodynamics and Heat Transfer courses, is discussed. By having undergraduate students perform laboratory experiments focused on appropriate topics for each course using the same setups, the students can relate the course materials more effectively.

Four different experimental apparatuses that have been developed for use in both a basic thermodynamics course and a heat transfer course are described. In addition, the laboratory exercises developed for each course using the apparatuses are discussed. The experiments were developed using simple, practical devices. The experiments developed center around (a) a dorm-sized refrigerator, (b) a small industrial heat exchanger, (c) a cooking wok, and (d) a high-intensity commercial light fixture. These are all devices that students have either encountered in everyday life, or can easily connect with. The experiments build upon this basic familiarity by applying engineering experiments to the equipment to demonstrate fundamental principles of Thermodynamics in the Basic Thermodynamics course. With this background, the students will then see the same experimental hardware in their Heat Transfer course, but will perform experiments that use the apparatus to elucidate the concepts of conduction, convection, and thermal radiation. In this way, vertical integration of pre-existing experiences, principles of thermodynamics and heat transfer concepts through the curriculum is achieved.

The experiments described in this paper were developed and built by undergraduate students in the Mechanical Engineering Department at the University of Wisconsin-Milwaukee (UWM). This opportunity allowed our students to gain a greatly increased knowledge of thermodynamics, heat transfer, and experimentation. The use of students in designing and building the experiments also aided the faculty involved, as the students were able to design experiments that better addressed the needs of students in understanding course content.

Introduction and Background

Mechanical Engineering students at UWM, like most other schools, are required to take several courses in the thermal sciences. These required courses are Basic Engineering Thermodynamics (ME 301), Introduction to Fluid Mechanics (ME 320), and Basic Heat Transfer (ME 321.) Traditionally, the Thermodynamics and Heat Transfer courses have been almost exclusively lecture-based, while the Fluid Mechanics course has had some experimental content. Several years ago, the experimental component of the Fluid Mechanics course was transferred into a new course, Fluid Mechanics Laboratory (ME 323), so that additional time could be spent on the experimental aspects of Fluid Mechanics. The Thermodynamics and Heat Transfer courses remained without any significant experimental component. While a primarily lecture-based instruction is sufficient for the education of some students, it has been found that many students prefer learning through a hands-on or visual approach.[1-3]

The authors wanted to bring an experimental component into the Thermodynamics and Heat Transfer courses in order to shore up this potential weakness. It was noted that many students struggled with understanding the basic concepts of the courses when they are only presented in an abstract fashion through lectures without any hands-on activity to provide concrete examples of the principles being taught. By providing the students with experiments involving real-world devices, the students would be given an opportunity to connect the abstract concepts presented in lecture to devices that they either encounter everyday or equipment that is common in industry. It was desired that the students would perform the experiments in small groups, preferably groups of three. This activity should benefit all students, but in particular would help the learning of those students who learn better visually while conducting experiments.

The authors also noted that many students don't connect the material from Thermodynamics and Heat Transfer very well. While the students learn about the concept of Heat Transfer in Thermodynamics, many do not seem to quickly connect the material learned in Thermodynamics to the Heat Transfer course. The authors have found that many of our students think of these courses as distinct subjects, rather than interconnected topics involving energy. To help bridge this gap, the authors decided that the experiments to be used in each course should be based off the same hardware. The students would perform one experiment focused on Thermodynamics-related material on one device in Thermodynamics, and then would use the same device in a future semester in the Heat Transfer course to perform a more detailed Heat Transfer experiment. In this way, vertical integration of the curriculum has been achieved, and the students would be able to relate the different courses to the same equipment to see how the two subjects are intertwined.

To further enhance the learning experiences for students, senior-level undergraduate students who had already completed the two courses were employed to design, build, test, and modify the experiments. The authors developed the general concept of the experiment, identified the equipment that the experiments would be built upon, and guided the students through their work. The students, though, had primary responsibility for determining how best to design and perform the experiment, utilizing their familiarity with the concepts and their understanding of the course material. The students were in a better position to know what should be best emphasized in the experiments to help them, and other students, learn the material more completely. Therefore, they were relied upon to build the best experiments for the future students taking the courses.

With this background in mind, the remainder of this paper will focus on describing the experiments centered on common hardware for the two courses, and then discuss the benefits and detriments of the approach taken.

Refrigerator Experiment

One experimental apparatus involves a standard 0.048-m^3 (1.7-ft^3) refrigerator.[4] This size refrigerator can be typically found in dormitory rooms, small offices, or any other location where a small amount of space is available for a refrigerator. These refrigerators are typically of a very simple design.

The Thermodynamics experiment that uses this set-up involves having the students determine the actual coefficient of performance of the refrigerator. The Heat Transfer experiment using this equipment involves the students using the equipment to study an example of free convection and an example of forced convection. The enclosed space gives an ideal location for performing such a controlled experiment, and from the experiments, the students are able to reinforce their understanding of the benefits of forced convection over free convection in a cooling environment.

The Thermodynamics experiment could be performed with little modification of the basic refrigerator. The experiment is performed by placing a heated object inside the refrigerator so that a load is provided for the operation of the refrigerator. The temperature on the inside of the refrigerator is measured with thermocouples over time, and a power sensor measures the power consumption of the refrigerator. By measuring the temperature inside the refrigerator, the heat removed from the refrigerator can be calculated from the First Law of Thermodynamics. After set periods of time, the work done by the compressor is determined from the Watt Transducer measurements, and the coefficient of performance of the refrigerator can be calculated. This experiment helps reinforce the concept of the coefficient of performance for the students.

While the Thermodynamics experiment could be performed on an unmodified refrigerator, the Heat Transfer experiment did require modification, and therefore both experiments operate on the modified refrigerator. The primary modification of the refrigerator was the insertion of a window in the door of the refrigerator and a light in the interior of the refrigerator to allow the students to visually see the air currents (as mapped by smoke trails) present during free and forced convection modes. The convection experiment also involved the placement of a cartridge heater into the refrigerator to provide the necessary steady load to the experiment. The forced convection part requires a fan to provide the moving air. These objects, plus associated measurement devices such as an anemometer, require a stand for support inside the refrigerator. Additional holes were needed in the refrigerator to provide an entry point for the wires needed to power the experiment inside the refrigerator. Pictures of the outside and inside of the Refrigerator Experiment are shown in Figures 1 and 2, respectively.

During the convection experiment, the refrigerator is operating to provide a cool surface to offset the heated rod and generate some free convection movement as well as a means to remove the input heat from the system. The experiment begins after steady state is achieved. The free convection experiment is performed first, with temperature measurements taken over a 5-minute interval. The smoke is then added to the system, and the students are able to visualize the flow patterns. The fan is then started, and the system is operated again until steady state is achieved. Air speed and temperature measurements are acquired over a 5-minute interval, and the students then proceed to their calculations. In the calculations, the students are attempting to calculate the Nusselt number, heat transfer coefficients, and heat transfer rates for their experiment. They also will compare the heat transfer rates to their heat input rate. This heat transfer experiment allows the students the opportunity to gain a better understanding of the concepts of free and forced convection heat transfer.

Figure 1: Photo of the exterior of the Refrigerator Experiment apparatus.

Figure 2: Photo of the interior of the Refrigerator Experiment apparatus.

Heat Exchanger Experiment

A second experimental apparatus was designed around a small, bench-top-sized, shell-and-tube heat exchanger.[5,6] The heat exchanger consists of 31 tubes operating in a single pass configuration. Heat exchangers come in many shapes and sizes, and while this heat exchanger may be small, it provides students with a good example of heat exchanger operation while still fitting in a laboratory setting.

In addition to the heat exchanger, the experimental apparatus includes flow meters on both the hot and cold streams of the heat exchanger, recirculating heaters and chillers, associated piping, instrumentation, and data acquisition equipment. Figure 3 shows the main experimental apparatus for the heat exchanger. While hot and cold tap water from the building could be used as the inlet working fluids for the experiment, controlled recirculating heaters and chillers provide a steadier working condition, important for the steady-state experiments being performed.

Figure 3: Photo of Heat Exchanger Experimental apparatus

The thermodynamics experiment utilizes the apparatus in a study of the First Law of Thermodynamics, as applied to steady-state, steady-flow, multiple inlet and outlet systems. In a Thermodynamics lecture on this topic, the heat exchanger is a classic example application. The use of the application in the laboratory further brings the subject matter to life for the students. When performing the experiment, students initially need to have the system reach steady state, which takes typically 10-15 minutes. During this time, students can watch traces of temperatures be generated, to give them an idea of the difference between steady state and transient operation.

Once the system reaches steady state, the students gather data on flow rates and temperature for several minutes. The students can then average the data, and are then asked to perform calculations to verify the First Law of Thermodynamics for the system. The students are asked to determine what types of losses exist in the system, such as heat transfer to the environment, and to analyze the effectiveness of the heat exchanger.

The Heat Transfer experiment delves deeper into the workings of a heat exchanger. The students are asked to take experimental data involving the temperatures and flow rates in order to develop an effectiveness vs. NTU plot for the heat exchanger. They perform the data acquisition at five different flow rates, which provides five different data points for their plots.

The students are then asked to perform a second experiment in Heat Transfer involving this equipment. In this experiment, the students are asked to take their plots generated in the first experiment, and make a calculated prediction as to the required flow rate in one of the streams that will produce a certain effectiveness in the heat exchanger. The students are then asked to set up the experimental apparatus to verify their predictions. They are also asked to take data at nearby conditions to determine the actual flow rates needed for the desired effectiveness. If the students have been performing their experiments carefully, the predicted and actual flow conditions should be close.

In the Heat Transfer course, the combination of these two experiments provide students with experience both in characterizing a heat exchanger, as well as using measured data to predict operating conditions. Assuming that the students are successful with this experiment, they should gain confidence in using experimental data to set actual operating conditions.

Cooking Wok Experiment

A third experimental apparatus used is again one that is probably directly familiar to the students. The experiments are based around a basic cooking wok.[7] While the students may not have used a wok, they certainly are familiar with cooking instruments, and so they can easily relate this to things that they have done in life. This familiarity leads to a more interesting laboratory experiment than perhaps otherwise possible for the topics covered with the apparatus. Because the experiments that use the wok are early in the semester, the students also can develop a positive attitude to the course through these experiments. The experimental set-up for the wok experiments can be seen in Figure 4.

The Thermodynamics experiment using the wok is centered on the First Law of Thermodynamics for a closed system. The wok is equipped with a power meter, three thermistors for measuring the temperature of the surface of the wok, and a small fan. The students run the wok until a steady temperature for the wok is achieved, monitoring the temperatures and the power input. The students determine how much heat is lost to the environment through the First Law of Thermodynamics. The power is then shut-off, and the students monitor the rate at which the wok cools down, by monitoring the temperature of the wok over time. This is done both with and without the fan operating. The first part of the experiment is then repeated with a beaker of water placed on the wok. The power is turned on until the water begins to boil. Comparison of the results from this experiment to those without the water allows the students to see the impact of the addition of a thermal mass on the operation of the system, through the energy balance. The students can also calculate the heat transfer to the water in the second experiment, and see how much of the increased electrical work input is accounted for by that heat transfer.

Figure 4: Photo of Cooking Wok Experiment apparatus.

The Heat Transfer experiment involving the wok is the first laboratory exercise performed during the semester. It concentrates on helping the students understand temperature measurement technology, rather than something specific in conduction, convection and radiation. In this experiment, students use several different temperature measuring devices, including thermometers, ordinary thermocouples, infrared thermocouples, and thermistors to measure the temperature on the wok surface at several locations. The students are to compare the results, the ease of operation of the different techniques, and the accuracy of the devices. In this way, the students will gain an appreciation for the uncertainty that goes into the temperature measurements that are at the heart of the heat transfer applications they will be studying throughout the semester. The Heat Transfer experiments also expect a higher level of data acquisition ability by the students than the Thermodynamics experiments (the Laboratory Instructors will do more set up of the data acquisition devices in Thermodynamics than in Heat Transfer), and this experiment also gives the students an opportunity to work on their experiment set-up skills.

Commercial Lighting Fixture Experiment

A fourth experimental apparatus is designed around a commercial lighting fixture.[8] This high-intensity fixture uses a quartz halogen bulb located in an anodized aluminum housing. While students may not have seen this particular fixture in use, they have seen similar fixtures and are familiar with lighting devices in general. Some views of the experimental apparatus are provided in Figures 5 and 6.

In Thermodynamics, this apparatus is used to relate efficiencies to entropy generation in a process. The lighting fixture is located in a test stand, which is equipped with a power sensor, infrared thermocouples, and a dimmer switch that is used to control the electrical power input to the fixture. Using this apparatus, the students perform the experiment at two input power levels:

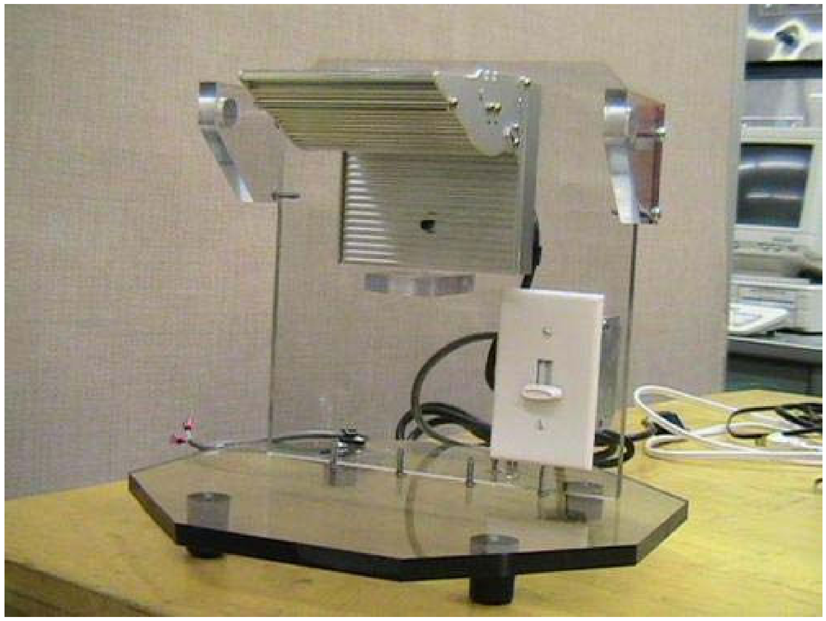

Figure 5: Photo of front view of the Commercial Lighting Fixture Experiment apparatus.

Figure 6: Photo of side view of the Commercial Lighting Fixture Experiment apparatus.

100 W and 200 W. The students acquire temperature data and power input data until the system reaches near steady-state operation. Using the First Law of Thermodynamics, the students are asked to estimate the heat loss during the transient start-up phase of the experiment. Due to the need for detailed heat transfer calculations to determine the steady-state heat loss, students are then provided with the heat transfer data for steady-state operation, as determined in the heat

transfer experiment (which is performed in a future semester.) The students are asked to calculate, using their data and an entropy balance, the total amount of entropy produced during the warm-up phase, and the entropy production rate during steady-state operation. The students also calculate the steady-state efficiency. After these tests are done at two power levels, the students are asked to relate the entropy production rate to the efficiency of the lighting fixture.

The Heat Transfer experiment considers multi-mode heat transfer; with the students needing to perform both free convection and radiation heat transfer calculations on the fixture. As with the Thermodynamics experiment, the students perform the experiment at 100-W and 200-W electrical input power levels. The students let the system run until steady state is achieved, and then move the infrared thermocouples around to various positions to obtain numerous temperature measurements on the surface of the fixture. The students then perform detailed free convection and radiation calculations in order to determine the amount of heat transfer from the fixture. (This is the data that is subsequently supplied to future students in the Thermodynamics course laboratory.) The students then determine the efficiency of the fixture at the two power levels.

The students who take both the Thermodynamics and Heat Transfer courses are most able to experience the overlap between the two courses with the experiments using the light fixture. In the Thermodynamics course, the students need to rely on data previously obtained in the Heat Transfer laboratory to help them relate efficiency to entropy generation and gain a deeper understanding of the Second Law of Thermodynamics. When the students take the Basic Heat Transfer course (ME 321), they can go through the process of actually determining the amount of heat transfer in the fixture. While the other experiments, described in this paper, allow the students to see how the concepts of the two courses can be applied to the same familiar equipment, the lighting fixture experiments take this one step further by actually using data from one course in the other course.

Benefits of the Experiments

The experiments described here, and other experiments used in traditional lecture-based courses such as Thermodynamics and Heat Transfer, have the benefit of allowing the students the opportunity to experience the principles they are learning in a concrete way. Instead of just receiving an abstract description of the processes, the students are able to test the equations on real equipment, learn the limitations of the analysis and data acquired, and hence, improve their overall understanding of the material. In addition, by using the same experiments in different courses, the students can see how the principles from the two courses can be applied and are used in the same everyday equipment.

An added benefit of the developed experiments is that students, who have taken the two thermal sciences courses, were responsible for designing, building, and testing the experimental apparatuses and the experiments themselves. The faculty involved with the project provided the overall concept to the students, and provided the basic hardware for the students. The faculty also closely monitored the students' progress, and helped make sure that the students were able to complete the task and develop a good experiment. As a result of the project, the students involved in the development process were able to gain a much deeper understanding of heat transfer, thermodynamics, experimental methods, as well as development of educational materials. This unique opportunity to actually design and build experiments to be used by future students resulted in the students having to thoroughly learn and understand the material. Such an application of engineering should help them in their future careers.

By having the students develop the experiments, the end-product of their work are experiments that are well-focused on assisting future students to understand the concepts that they typically need more help in understanding. While the faculty can provide a global sense of what is needed to be explained more deeply, the students bring a background of having gone through these courses at UWM, and having a better sense of the specific issues that confuse students. They were then able to design the experiments to help the students through those difficult topics.

Conclusions

The authors have described a series of mechanical engineering experiments that have been developed at the University of Wisconsin-Milwaukee for use in basic thermodynamics and heat transfer courses. The experiments, while having a different focus for each of the courses, use the same experimental hardware. This unique method enables the engineering students to see how the material learned in the two courses can be related to the same familiar equipment, as they progress through their studies. Not only should this aid the students in their understanding of the material in each course, they should gain a deeper appreciation between the connections between the two courses. In addition, undergraduate students who have completed the courses were employed for designing, building, and testing the experiments. This allowed the faculty to tap into the knowledge that the students have regarding how contemporary students need to effectively visualize and understand the course materials. It also gave these students a great opportunity to solidify their understanding of thermodynamics and heat transfer, and gave them additional practice in experimental methods. This model has been found to be successful in enabling the authors to provide an enhanced educational experience for our students.

Acknowledgments

The authors would like to thank the American Society for Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) for funding a portion of this work through their Undergraduate Senior Project Grant program. They also thank Badger Meter, Inc., Modine Manufacturing Co., Visa Lighting Corp., and West Bend Co. for providing equipment and supplies for the experiments. Finally, the students who worked on the projects deserve much of the credit for this project's success: Ms. Colleen Bell, Ms. Christina Wisler, Mr. Austin Schmitt, Mr. Zach Ouradnik, Mr. Todd Murray, Mr. Chad Housner, and Mr. Erik Bauer.

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