

Internet of Things: Remote Integrated Laboratory Activities in Green Energy Manufacturing and Energy Management Learning Modules: Heat Exchangers Efficiency, the Design Perspective

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Abstract

While the world moves fast towards implementing strategies, policies and ultimately technologies that help alleviate the climate change through sustainable energy systems, the educational programs and their components should follow suit, adapting to the new challenges. During the past decade and beyond, the traditional lecture-based courses in “thermal-fluid” area were subjected to various improvements and changes by educators in their effort to introduce industry-like experiential activities in order to enhance and complement the lectured material and attempt to improve students’ understanding. However, due to increased cost of the equipment paired with limited physical space, these endeavors seem to fade. As a result of the funded educational research through a DOED grant, we developed remote-operated experiential activities aimed to enhance the theoretical approach of the traditional Thermal-fluid area courses. These activities are manufacturing industry-inspired and oriented towards green and sustainable manufacturing, including integration of renewable energy sources into the manufacturing industry. The remote-operated platforms may be used to deliver knowledge to students in different locations, including disadvantaged communities of students that may otherwise not have access to this type of education. The modules are described in detail, including student assessment, student feedback as pertinent to student learning outcomes.

Introduction and Project Rationale

The global context regarding energy and sustainability evolved rapidly and what we considered to be emerging technologies less than a decade ago have now matured and are already being implemented at large scales in industry. Moreover, the constant preoccupation regarding green energy manufacturing as a method of reducing the carbon footprint generated not only the path towards new technologies but also to new educational programs and trends. Following these trends and industry demands, the engineering curricula evolved to include more and more courses in the area of energy conversion, green energy and sustainability. However, several “traditional” courses remained more or less the same, mostly in the area of thermo-fluids. While there have been several reported attempts to improve these courses by including project-based learning activities, it was concluded that such projects involving industry-like scenarios were lengthy and costly, and eventually were stopped or replaced with traditional lectures. Nonetheless, these studies and attempts had a significant contribution in underlying the importance of practical approaches in conveying knowledge to students in heat transfer and thermodynamics courses, which traditionally are dry-lecture based. Moreover, the contribution of thermal-fluids energy systems performance in global sustainable development is substantial

but was not emphasized until recently. Therefore it may not be reflected in the already developed learning modules for these traditional courses [1].

In this paper we aim to present our efforts in re-developing our thermal-fluid related courses in Drexel University's Engineering Technology curricula by including several modules involving industry-like scenarios as laboratory activities performed remotely (through Internet), using four heat exchanger configurations and thermography (using a thermal imaging camera) in teaching fundamental principles and notions of heat transfer as well as teaching more complex aspects of heat exchanger design and performance. The scenarios were inspired from manufacturing industry related energy management applications, focusing on giving the students a more global and interdisciplinary understanding of the applications of the imparted knowledge. This lab-lecture integrated approach, with "in-lecture" Internet based remotely performed activities, complemented by hands-on laboratory activities, significantly improved the understanding, knowledge retention and also enhanced student motivation. Students were required to compare results obtained through various methods including thermography to discuss and assess system efficiency and design parameters.

As traditional learning methods are time consuming and sometimes impractical, learning through the Internet will significantly increase the access to modern learning tools for all students including minorities and disadvantaged student communities, due to its affordability and ease of use, without curtailing the quality of knowledge conveyed. In recent years due to the Internet advances, the use of virtual and remote distance experiments in engineering education has been well accepted in many different education areas and at many universities. **This paper presents an Internet-based remote platform for remote experiments conceived for the study of the thermal energy conversion systems, as well as monitoring using virtual instrumentation.** This platform will provide students with enhanced tools of study. The platform was developed as a part of a DOED funded educational research.

Curricular Context

Engineering Technology programs across the country places greater emphasis on practical applications, learning by doing, and engineering theory related to energy and energy conversion, manufacturability, maintainability, reliability, and quality assurance. Engineering Technology graduates often specialize in prototyping, instrumentation, statistical process control, and manufacturing operations. The Engineering Technology program at Drexel University is a quarter based program having four concentrations: Mechanical Engineering Technology, Electrical Engineering Technology, Industrial Engineering Technology and Biomedical Engineering Technology.

The Engineering Technology Program at Drexel University in particular represents an attractive option for technically-inclined students whose interests and motivations center on practical applications, manufacturing, hands-on problem solving, and intuitive and visual thinking; and for

whom the abstract theory and analysis emphasized in traditional engineering courses of study proves to be a disincentive. Due to its straightforward conceptual basis, amenability to visual demonstrations, remotely operated laboratory activities integrated with well-developed lectures offers excellent means for attracting students to engineering and engineering technology[2].

Thermodynamics and Heat Transfer course is a three hour-credit junior to senior undergraduate core curriculum course designed for all ET students.

This course was developed as being writing intensive but also one of the main precursors of Capstone project, having embedded in its curricula a final student-led team project that has its main outcome a working prototype of a thermo-fluid system. While the pre-requisites for this course do not include traditional senior courses for mechanical engineering technology such as fluid mechanics (only Fluid Power laboratory course), or more in-depth study of Thermodynamics, the unique character of this course consist in being an integrated lecture-experiential learning of heat and mass transfer phenomena. Laboratory activities account for two thirds of the course, while the classroom-lecture part, only for one third. The material is being conveyed primarily using hands-on approaches.

During this course students will explore experimentally basic thermodynamic relations; they will conduct experiments related to flow of compressible fluids and to energy conversion of a fuel into a working substance and the related heat transfer mechanisms. The main course objectives (lectures and labs combined) are focused on using heat transfer principles to understand the behavior of thermal-fluid systems, on illustrating the development of the governing equations associated with thermal systems, on investigating the influences of various system parameters and conditions on the resulting steady or transient response of the system, on providing students with the basic tools used in thermal system design, and exposing students to heat transfer applications in industry. After the completion of this course, students should be able to apply their knowledge in analyzing thermal-fluid systems and to combine and apply analytical techniques and design principles to thermal systems. They also should be able to prepare high quality engineering reports including presentation of goals, background, results, analysis, and conclusions, as well as a working prototype of a thermal-fluid system. The topics covered in this course range from a review of basic thermodynamic concepts and principles (First and Second Law of thermodynamics, Energy Balance, Entropy), to heat and mass transfer concepts (basic modes of heat transfer, heat conduction, convection (natural and forced), and radiation), with applications for heat exchangers [1-3].

In order for students to enhance their understanding of engineering concepts, hands-on experience proves essential. Especially when the topic of interest involves energy conversion related to heat transfer, fluid dynamics or both, it becomes very difficult for students to obtain a hands-on experience due to the nature of the experimental apparatus. Virtual and remotely-

operated instrument systems have been introduced to simplify the design, implementation and use of programmable measurement systems by adopting a visual interface.

Heat Exchanger Experiment: Shell and Tube HX

In manufacturing environments, heating and cooling systems, including chillers, heat pumps and reconversion units are very important systems. The energy management of these systems is very complex, many of them being operated using fossil fuels. Most of the modern industry will soon move towards utilization of Combined Heat and Cooling Units, mostly based on renewable energy for a better energy management, sustainable and oriented towards reducing the carbon footprint. In this respect we present the Shell and tube heat exchanger experiment, which enables students to understand the basic design parameters of such equipment.

The shell and tube heat exchanger is commonly used in the food and chemical process industries. This type of exchanger consists of a number of tubes in parallel enclosed in a cylindrical shell. Heat is transferred between one fluid flowing through the tubes and another fluid flowing through the cylindrical shell around the tubes. In this miniature exchanger, baffles inside the shell increase the velocity of the fluid and hence rates of heat transfer. The exchanger has one shell and seven tubes with two transverse baffles in the shell.

Objectives: The main objective of this experiment is for students to learn how to improve energy efficiency on an energy conversion system, and to investigate the effect of changes in driving force on the Temperature Efficiencies and Overall Heat Transfer Coefficient. Students should demonstrate indirect heating or cooling by transfer of heat from one fluid stream to another when separated by a solid wall (fluid to fluid heat transfer) [4], [5]

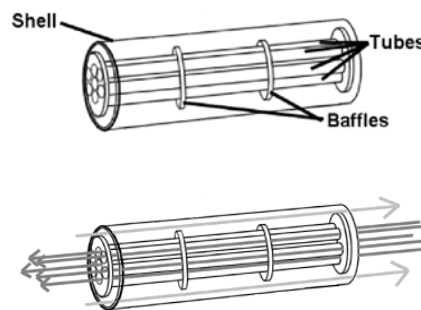


Figure 1: Shell and Tube heat Exchanger Configuration

The shell and tube heat exchanger is commonly used in the food and chemical process industries. This type of exchanger consists of a number of tubes in parallel enclosed in a cylindrical shell. Heat is transferred between one fluid flowing through the tubes and another fluid flowing through the cylindrical

shell around the tubes. In this miniature exchanger, baffles inside the shell increase the velocity of the fluid and hence increase the rates of heat transfer. The exchanger has one shell and seven tubes with two transverse baffles in the shell. To accomplish these objectives and student learning outcomes, we used an ARMFIELD HT 30XC Heat Transfer unit combined with HT 33 – Shell and Tube experiment. Also, for the remote operations we used the ARMFIELD software [4] and TEAMVIEWER platform. While the proprietary ARMFIELD software enables student to operate the experiment via a computer that is wired to the HT-30XC unit, the TEAMVIEWER enables the student to remotely operate the experiment for a distance location as described in the next sections (remotely operated from University of Texas at El Paso campus, while the hardware was in a lab in Drexel University’s main campus in Philadelphia, about 2000 miles apart). The HT 30XC unit as well as the heat exchanger is fully operated remotely without the help of another person. However, due to our lab restrictions (water connection is manual) and safety issues, the experimental activity is monitored by a teaching assistant, ready to intervene in case of an incident.

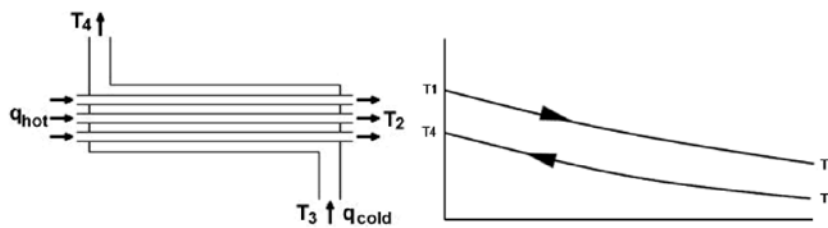


Figure 2: Counter-current operation of the heat exchanger

Theory

When the heat exchanger is connected for countercurrent operation the hot and cold fluid streams flow in opposite directions across the heat transfer surface (the two fluid streams enter the heat exchanger at opposite ends). The hot fluid passes through the seven tubes in parallel, the cold fluid passes across the tubes three times, directed by the baffles inside the shell.

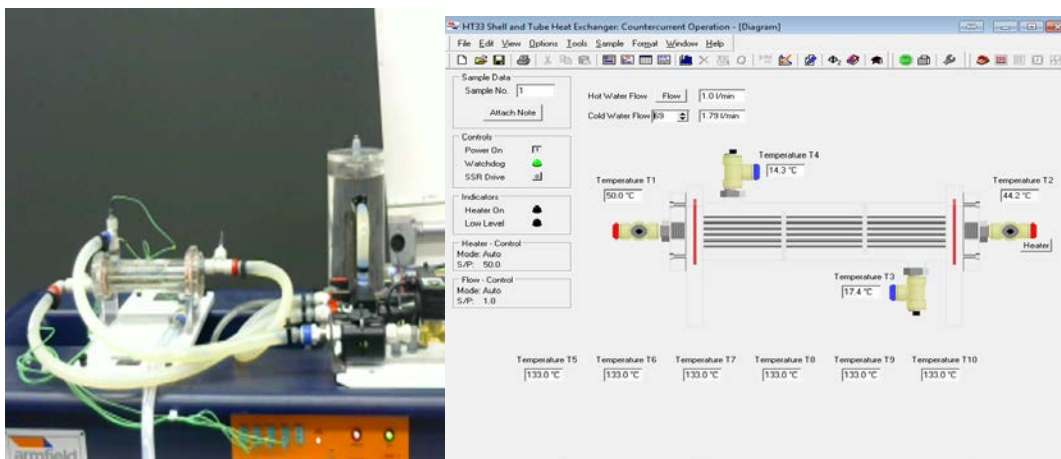


Figure 3: Shell and Tube Experimental Set-up and Remote Control interface of the Experiment [4]

Method

By measuring the changes in temperature of two separate streams of water flowing through the inner tube bundle and outer shell of a shell and tube heat exchanger. Any temperature difference across the metal tube wall will result in the transfer of heat between the two fluid streams. The hot water flowing through the inner tube bundle will be cooled and the cold water flowing through the outer shell will be heated.

Note: For this activity the heat exchanger is configured with the two streams flowing in opposite directions (countercurrent flow). The cold fluid flowing through the shell is forced to flow over and under baffles in the shell which force the fluid to flow across the tube bundle to improve the heat exchange. The students will operate the heat exchanger in remote automatic mode, using the computer interface and the learning software[4],[6].

Results and Calculations

The software records all sensor outputs and also calculates several derived figures, and presents the recorded data in tabular form. The following columns are relevant to this exercise, and are suggested as suitable column headings if recording values manually: For each set of readings, the relevant derived results are calculated and presented with the following headings[6], [7], [8], [4],[5]:

Reduction in hot fluid temperature $\Delta T_{\text{hot}} = T_1 - T_2$

Increase in cold fluid temperature $\Delta T_{\text{cold}} = T_4 - T_3$

A useful measure of the heat exchanger performance is the temperature efficiency of each fluid stream. To evaluate the temperature efficiency we need to calculate the following:

$$\text{Reduction in hot fluid temperature } \Delta T_{\text{hot}} = T_1 - T_2 \quad (^\circ\text{C}) \quad (1)$$

$$\text{Increase in cold fluid temperature } \Delta T_{\text{cold}} = T_4 - T_3 \quad (^\circ\text{C}) \quad (2)$$

$$\text{Heat power emitted from hot fluid } Q_e = qm_h (Cp)_h (T_1 - T_2) \quad (\text{W}) \quad (3)$$

$$\text{Log Mean Temperature Difference LMTD: } \Delta t_{\text{lm}} = \frac{(T_2 - T_3) - (T_1 - T_4)}{\ln((T_2 - T_3)/(T_1 - T_4))} \quad (^\circ\text{C}) \quad (4)$$

$$\text{Overall Heat Transfer Coefficient: } U = \frac{Q_e}{A \cdot \Delta t_{\text{lm}}} \quad (\text{W/m}^2\text{-K}) \quad (5)$$

$$\text{Temperature efficiency for hot fluid } \eta_h = \frac{T_1 - T_2}{T_1 - T_3} \cdot 100 \quad (\%) \quad (6)$$

$$\text{Temperature efficiency for cold fluid } \eta_c = \frac{T_4 - T_3}{T_1 - T_3} \cdot 100 \quad (\%) \quad (7)$$

$$\text{Mean Temperature Efficiency } \eta_m = \frac{\eta_h + \eta_c}{2} \quad (\%) \quad (8)$$

Area of heat Transfer:

The heat transmission area in the exchanger must be calculated using the arithmetic mean diameter of the inner tubes.

$$\text{Arithmetic mean diameter } d_m = \frac{d_o + d_i}{2} \quad (\text{m})$$

Heat transmission length $L = nl$ (m), where n = number of tubes = 7

l = heat transmission length of each tube = 0.144 (m), therefore $L = 1.008$ m

$$\text{Heat transmission area} = A = \pi d_m L \quad (\text{m}^2)$$

Figure 4 depicts the remote image of the experiment as seen using a Thermograph Camera. Results were recorded for each temperature as it was recorded using the ARMFIELD hardware and software and students were asked to compare the two sets of results. Students were asked to estimate the influence of the hot and cold temperature difference to temperature efficiencies and to overall heat transfer coefficient. Also they were asked to investigate how well we can estimate Temperature Efficiencies using Thermal camera temperature measurements.

A graph may be plotted of the results. The software graph facility may be used for this. Students are asked to estimate the cumulative influence of the experimental errors on their calculated values for hot and cold flow temperature difference and to compare the changes in temperature at the different flow rates. If time permits, students may try different combinations of hot and cold fluid flow rate.

As seen in the figure 4, measurements may be compared between the thermocouple and thermal camera and a series of measurements are presented in the tables below:

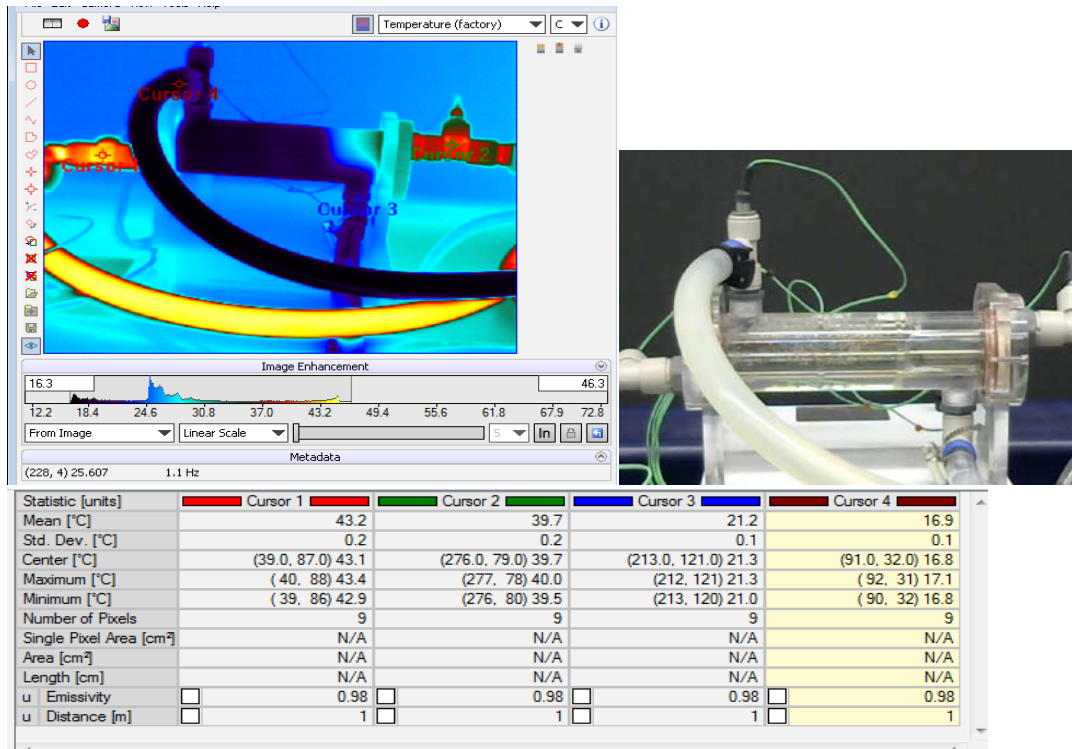


Figure 4: Thermal Evaluation of the Experiment using Thermograph Camera

Table 1 Measured values using Shell and Tube Heat Exchanger [4]

	Symbol	Units	Measured or estimated value for:	
			50°C	70°C
Hot fluid inlet temperature	T_1	°C	50.2	68.7
Hot fluid outlet temperature	T_2	°C	46.5	62.3
Cold fluid inlet temperature	T_3	°C	18.7	18.8
Cold fluid outlet temperature	T_4	°C	24.4	28.4
Hot fluid volume flowrate	$q_{V_{hot}}$	m ³ /s	2.0	2.0
Specific heat of hot fluid	$C_{p,hot}$	kJ/kg-K	4,180	4,187
Density of hot fluid	ρ_{hot}	kg/m ³	988.76	980.3

Table 2 Calculated values used to design and size a heat exchanger [4]

	Symbol	Units	Formulas	Measured or calculated value for:	
				50°C	70°C
Mass flowrate (Hot fluid)	q_{m_h}	kg/s	$(\rho_{hot})(q_{V_{hot}})$	0.033	0.032
Heat power emitted from hot fluid	Q_e	W	(3)	519.0	874.6
LMTD	ΔT_{lm}	°C	(4)	26.75	41.93
Overall heat Transfer coefficient	U	W/m ² -°K	(5)	1020.66	1097.5
Temperature efficiency for hot fluid	η_h	%	(6)	11.9	12.95
Temperature efficiency for cold fluid	η_c	%	(7)	18.1	19.19
Mean temperature efficiency	η_m	%	(8)	15.0	16.07

Table 3 Comparison with Thermal Camera measurements and calculated or estimated values

Thermal Camera Measurements	Symbol	Units	Measured or estimated value for 50°C	Formulas
Hot fluid inlet temperature	T ₁	°C	43.2	
Hot fluid outlet temperature	T ₂	°C	39.7	
Cold fluid inlet temperature	T ₃	°C	16.9	
Cold fluid outlet temperature	T ₄	°C	21.2	
Temperature efficiency for hot fluid	η _h	%	13.3	$\eta_h = \frac{T_1 - T_2}{T_1 - T_3} \cdot 100$
Temperature efficiency for cold fluid	η _c	%	16.3	$\eta_c = \frac{T_4 - T_3}{T_1 - T_3} \cdot 100$
Mean temperature efficiency	η _m	%	14.8	$\eta_m = \frac{\eta_h + \eta_c}{2}$

LMTD 22.4 and Overall Heat Transfer Coefficient U=1135.95

Using the same configuration, students measured the same parameters in real time, while the recording the measured values (thermocouple) and compared the Thermal camera estimated results vs the results obtained using the ARMFIELD software (thermocouples).

Remote-lab Conclusion

Students have demonstrated how, using a simple shell and tube heat exchanger, a stream of cold fluid can be heated by indirect contact with another fluid stream at a higher temperature (the fluid streams being separated by a wall which conducts heat). This transfer of heat results in a cooling of the hot fluid. Also, they evaluated several parameters pertinent to the design of a heat exchanger using both recorded parameters through the precise measurement of the HX unit and using the Thermograph camera and compared the results. They were able to estimate the errors involved in both measurements types for each parameter and how that would affect the design performances, such as overestimation of the overall heat transfer coefficient by measurements taken using thermal camera). In this way students were exposed to industrial type scenarios of control and monitoring as well as design perspective for energy management at various industry levels.

The entire experimental activity was remotely controlled by the students using the two mentioned software (ARMFIELD and TEAMVIEWER). In this way, resources may be shared among departments and colleges that are located in different regions, as one teaching assistant may assist several units at the same time because his involvement resumes to monitoring and troubleshooting as both the HX units and the thermal camera are to be operated entirely via remote location computer. This is a way for colleges and universities to use more efficiently their lab resources, allowing students from disadvantaged minorities to benefit of state-of-the-art

experiential education, on one hand and for the universities to acquire more units and expand their class seats, becoming more economically sound, while sharing resources.


Assessment and Evaluation

Evaluation of the course over the past decade since this course has been offered showed an increased positive perception of the students. The overall rating of the course moved from an average of 3.8 to 5.0 out of 5.0 during the last term (Winter 2015-2016). During the first meeting of each course, students are administered a preliminary assessment test to gauge students’ background and preparation for the course. For example, their knowledge of appropriate physics and chemistry are evaluated. Based on the results of the test, students are divided by groups according to the think-share-report-learn (TSRL) process, which involve student peer coaching to help each other during the laboratory procedures.

The formative evaluation provided evidence of the strengths and weaknesses of the activities implemented and the course as a whole; informing the authors’ understanding of what works and what does not in order to assess project progress and success. Our past analysis proved the quality and usefulness of materials produced in laboratory delivery. Several summary evaluations assessed during past years the quality and impact of an implemented hands-on activities. The overall analysis of these activities provided us with insight on how to improve the learning process.

After every course an overall course improvement assessment is performed using the ABET criteria [9] most pertinent to the course Student Learning Outcomes and also based on our performance criteria developed using the ABET criteria.

Student Learning Outcomes (SLOs) Aligned with ABET Student Outcomes (a-k)

ABET Student Outcomes 		b	c	d	e	f	g	j
SLO 1:	Apply their knowledge of mathematics and science and engineering to thermal-fluid engineering systems.	X				X		
SLO 2:	Develop engineering skills related to thermodynamics and fluid mechanics courses and in measurement laboratory class	X	X			X		
SLO 3:	Recognize and apply analytical techniques and design principles as applied to thermal - fluid systems, including identifying system requirements and appropriate standards.	X	X	X		X	X	
SLO 4:	Prepare a high quality engineering reports including presentation of goals, background, results, analysis, and conclusions				X	X	X	X

Upon successful completion of this course, students will attain the following ABET outcomes as listed below[9]:

- b. an ability to select and apply a knowledge of mathematics, science, engineering, and technology to engineering technology problems that require the application of principles and applied procedures or methodologies;
- c. an ability to conduct standard tests and measurements; to conduct, analyze, and interpret experiments; and to apply experimental results to improve processes;
- d. an ability to design systems, components, or processes for broadly-defined engineering technology problems appropriate to program educational objectives;
- e. an ability to function effectively as a member or leader on a technical team;
- f. an ability to identify, analyze, and solve broadly-defined engineering technology problems;
- g. an ability to apply written, oral, and graphical communication in both technical and non-technical environments; and an ability to identify and use appropriate technical literature;
- i. a knowledge of the impact of engineering technology solutions in a societal and global context;

Our ET program Performance Criteria developed for each assessed ABET criterion [9] will evaluate students' performance using laboratory activities, projects and exams. Each activity was crafted and developed in order to answer these performance criteria to a certain extent which was pre-determined. Each laboratory activity weighs 10% of the student's final grade; to a total of 5 laboratory activities per course (50% of the final grade) therefore is a very important assessment item in their overall performance. During the presented experiment as well as the entire experimental activity during the course, students are evaluated using the following Performance Criteria:

Table 4 ABET based ET Performance Criteria for experimental activity in Thermodynamics and Heat Transfer Analysis

b1. Demonstrates an ability to apply a knowledge of mathematics to engineering technology problems.	b2. Demonstrates an ability to apply a knowledge of computer programming to engineering technology problems.	b3. Demonstrates an ability to apply a knowledge of science to engineering technology problems.	b4. Demonstrates an ability to apply a knowledge of engineering and technology to engineering technology problems.
c1. Can explain theory, procedure and standard testing methods used in the experiments.	c2. Performs experiments properly.	c3. Analyzes and interprets results of experiments including, where applicable, comparison of results to theory, and error analysis.	c4. Correctly applies experimental results.
e1. Participates in development and support of team objectives.	e2. Shares the work fairly.	e3. Respects other teammate's points of view.	

During the past five years, since the HX experiments were introduced, students performed in average above 90% out of 100% with the lowest grade being 76% and the highest being 100%. However, there is a demonstrated student excellence for experiential and project learning activities for this course for the past five years; therefore the lowest grades are occurring very seldom.

Conclusions and Future Work

These experiments allow students not only to gain experience with modern temperature, pressure and flow measurement techniques, but also to better understand the phenomena associated with various heat transfer and fluid dynamic systems. In addition, students are provided with another opportunity to familiarize themselves with the various energy conversion systems. Due to the digital nature of the sensors used in these experiments, quantization error is also discussed. Students will also test concepts such as calibration during laboratory[8], [7].

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