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Simulated Laboratory-Based Learning In A Thermal Fluid Laboratory Course

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Abstract

The overwhelming and well documented success that stems directly from the integration of hands-on activities into the course core structure educates and develops competent and independent engineers. Most educators look for experiential learning elements to engage students through interactive concept practice, thus leading their students to reach new levels of comprehension. The SARS-CoV-2 coronavirus (Covid-19) created a unique challenge for instructors to adjust the remainder of their courses in order to adapt to a new educational medium. Traditionally hands-on courses, such as laboratory-based courses, also required adaptation. One such course employed a set of simulated thermal experiments as a replacement for the hands-on experiments for the remainder of the semester. The different experimental approach involved a remote demonstration of live simulations of a set of heat exchanger models through an interactive and user-friendly interface. The live simulation allowed for measurement of pressure and temperature differences across the heat exchanger as well as for adjustment of flow rates. This simulated based laboratory experiment was developed and conducted by a senior design group using software such as LabVIEW™ and MATLAB® & Simulink® for implementation and testing in future offering of the thermal laboratory course.

Introduction

The hands-on experience has been found through literature to be one of the most effective modes to teach and grow capable and self-sufficient engineering professionals[1]. Therefore, most engineering educators seek experiential learning techniques and implementations pioneering and captivating to help students understand and exercise the engineering concepts they learned[2]. Although laboratory-based learning allows students to deduce and apply concepts, this more commonly used approach is typically limited by the physical laboratory resources, unlike many current approaches[2,3,4]. This search for a more innovative learning technique in a thermal fluid laboratory course to give students a broader perspective leads to identifying and developing a simulation-based remote laboratory learning experience utilizing relevant computational software tools that provide students an equivalent or complementary learning opportunity as a face-to-face laboratory activity. The concept of a remote laboratory suggests the utilization of the Internet and a system of hardware and software control technologies that the user can remotely access and conduct real-time experiments[5].

The goal was to develop and implement a laboratory-scale thermal fluid system, which will be accessible both physically and online with a user interface. This interface would allow for simulated or physical data acquisition and remote access to thermal fluid laboratory equipment such as a heat exchanger. This allows engineering students to carry out laboratory activities on simulated or physical equipment located on campus through online access. The system will be available to use for interactive laboratory activities. The access to such a system in conjunction with the existing computational tools available will give great exposure and valuable practical experience to the mechanical engineering students to further depth and breadth in their engineering education, similar to the project at another institution[5].

Data acquisition systems play a vital role in the industrial sector and real-time decision making. As companies evolve towards an information focused methodology in production and operations to maintain a competitive edge while facilitating users' access to the information at any time, regardless of the location, data acquisition systems have evolved from mere processing systems to arriving at full automation capacities. Education in automation requires both theoretical and practical knowledge. In most cases, students gain theoretical knowledge in the classroom, but laboratory experience is needed to obtain practical skills. Compared to traditional hands-on experiments, the implementation of new technologies can help students comprehend and practice the concepts since it can develop conventional teaching tools and methods, similar to the laboratory environment at different institutions[6, 7]. Therefore, the university took the initiative to introduce future students to a user interface that will test the theories and concepts in the thermal fluid laboratory. This will help to effectively address the two relevant course outcomes:

1. Apply heat transfer concepts for analysis of basic heat exchangers configurations, and
2. Design, perform, and report results of a mechanical engineering experiment,

to subsequently correspond to student outcomes on the ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.

With the support from the university and the Department of Mechanical Engineering, the team initiated a pilot study. This study included the development of initial design, analysis, and simulation of the system, which resulted in very favorable outcomes. The following phase of the study involved multiple senior design groups in completing the successful design and construction of subsystem prototypes over the past two years. Last Spring semester, a new group of students led by the thermal fluid laboratory faculty worked on the user interface to monitor and collect data from these prototypes to later result in an integrated heat exchanger system for future laboratory activities. The group also began to generate pilot instructional material and exercises based on selected prototype equipment. The resulting work was evaluated over the Summer and Fall terms and then planned to be implemented by this Spring term. However, the SARS-CoV-2 pandemic thrust this ongoing project into overdrive to move up completion and evaluation by last Spring semester. This group worked to design and develop a modular graphical user interface that would allow the user to remotely operate a simulated heat exchanger and acquire data where the physical system is inaccessible.

Current Hardware

The current experimental equipment consists of the Armfield DLMX system shown in Figure 1. The system consists of a small battery-operated base unit and seven different cartridges "covering fluid mechanics, thermodynamics and heat transfer" [8]. The battery-operated base unit can be plugged into a standard wall outlet. The base consists of a clear acrylic fluid reservoir. Under the base, is a variable speed-controlled pump, a flow meter, the battery, a level sensor, and all of the base circuitry. The base unit also houses a small unit display. The DLM cartridge design creates a simple push-to-fit interface with self-sealing hose connections. The cartridges contain their own microcontroller that relays information to the base unit. Each cartridge is designed as a simple experimental representation of the applicable content. This system boasts a simplistic setup procedure[8].

Figure 1. The Armfield DLMX system[8].

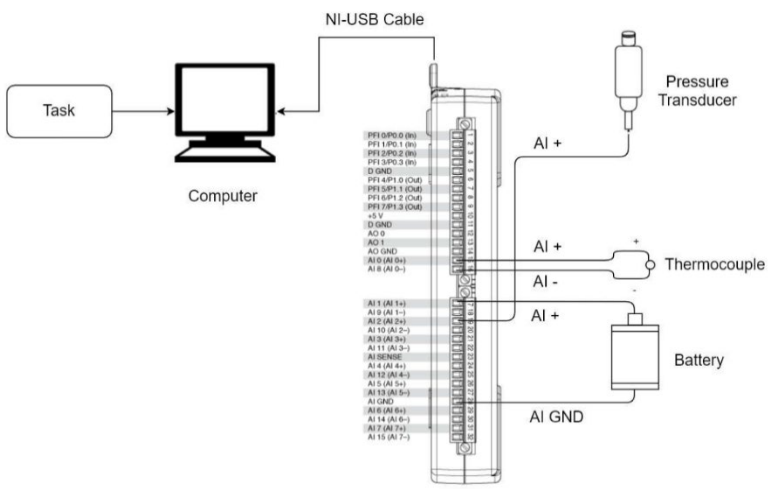

Figure 2. Connection Diagram for data acquisition[9].

Available Software

The software used was a significant factor in the development of the modular interface. The software systems introduce an ideal platform for both developing and implementing embedded applications due to its versatility. The final design contained a control algorithm using LabVIEW™ and MATLAB®/Simulink® as the platforms, which are included in the academic license for students, for design, simulation, and implementation.

Process of Simulation Based Heat Exchanger

Although the current experimental equipment for DLMX heat exchanger experiments and activity materials offers a unique small design that enables the reading of multiple units, including DLM-5 double pipe heat exchanger, DLM-1 crossflow heat exchanger, DLM-4 shell and tube heat exchanger, the integrated digital display interface lacks pressure measurements, thermal control and simple, easy-to-use data visualization. Using National Instruments™ Laboratory Virtual Instrument Engineering Workbench (LabVIEW™), the team interfaced with a simulated (or in the future physical) heat exchanger and stored the data onto the machine. The data collected had the option to be then fed into a secondary interface developed using MATLAB® and Simulink®, allowing the user to further analyze the results and visualize system performance. Figures 3 and 4 show the set of interfaces developed and demonstrated for the thermal fluid laboratory course to conduct simulated heat exchanger laboratory activities.

Figure 3. The current version of Shell and Tube heat exchanger interface for laboratory activity in LabVIEW™

In Figure 3, the top left corner of the interface consists of a drop-down option for working fluid. The top middle portion of the interface contains LEDs that determine the operating condition of parameters. In this case, the operating parameters are temperature and Pressure. The Green LED illuminates and displays the user that the parameter is operating in range. The Yellow LED lights up and informs the user that the parameter is operating in low range along with an error message. Finally, the Red LED illuminates and urges the user to initiate shutdown as the parameter has exceeded the safe operating range. The user can also access calculated parameters near the bottom of the interface. Two graphs were embedded in the interface to display the graphical representation of the temperature and pressure measurements through simulation. The left graph provides a graphical representation of the tube for inside temperature (white line), outside temperature (red line), the temperature inside the shell (green line), and temperature located outside the shell (blue line). The graph on the right side in Figure 3 shows the pressure measurement inside the tube (white line), the pressure measurement outside the tube (red line), the pressure measurement inside the shell (green line), and the pressure measurement outside the shell (blue line). The user will experience the data fluctuation over time. The graph always saves the last run by default. The portion between the two graphs features two rectangular blocks, one for the tube and one for the shell. Each block includes an analog indicator along with numeric values of the temperature inside, the temperature outside, the pressure inside, and the pressure outside.

Figure 4 shows the front panel of the same heat exchanger with virtually the same features as in Figure 3 except it is developed in Simulink®. Figure 5 illustrates the expected steps and procedures that will occur when successfully running the experimental. This flowchart is used to demonstrate the functionality of the interfaces shown in Figure 3 and Figure 4. When a user runs the program, a simulated data acquisition system or a physical data acquisition device like NI-DAQ device (further in the future) will read the signal from a sensor, which will then convert the data from analog to digital. This digital data will be stored then displayed both numerically and graphically over time.

Seamless operation is critical to mitigating any issues when utilizing the interface. Thus, it was tested and evaluated to verify the compatibility between the user interface and the heat exchanger system before implementation. The initial testing helped to identify the heat transfer within a Shell & Tube heat exchanger concerning its specific flow patterns for hot and cold fluids. It addressed the impact of various design parameters on the performance of the heat exchanger.

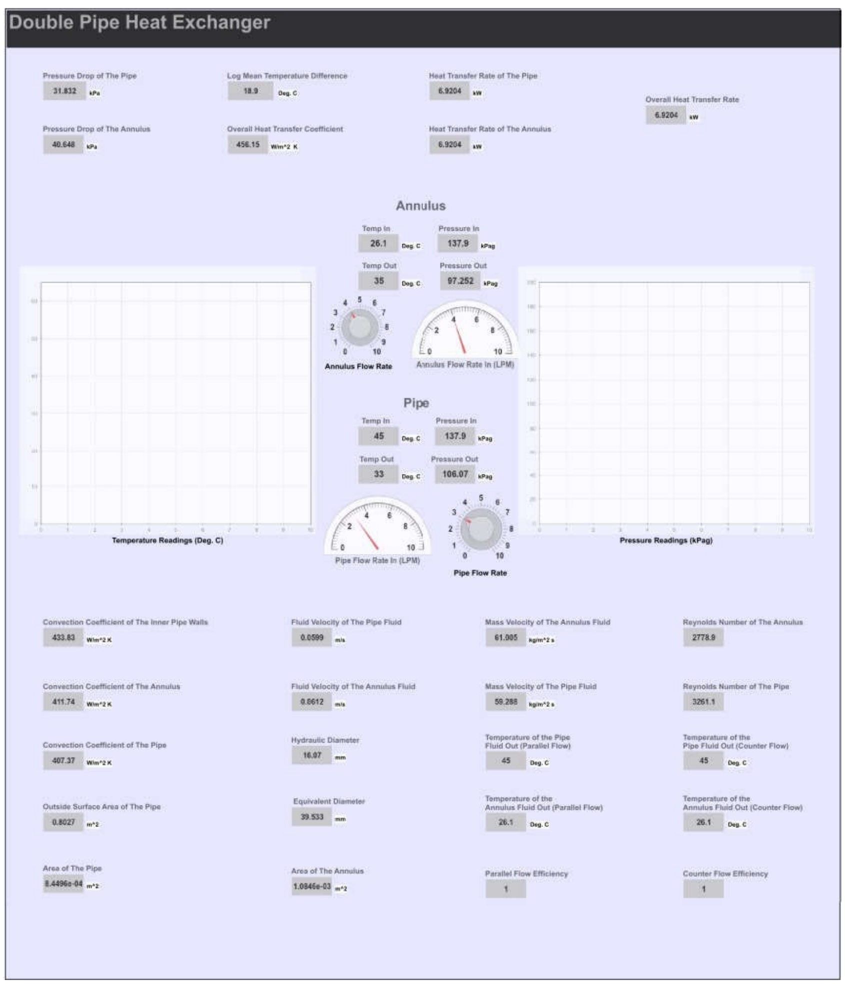

Figure 4. The current version of Shell and Tube heat exchanger interface for laboratory activity in Simulink®

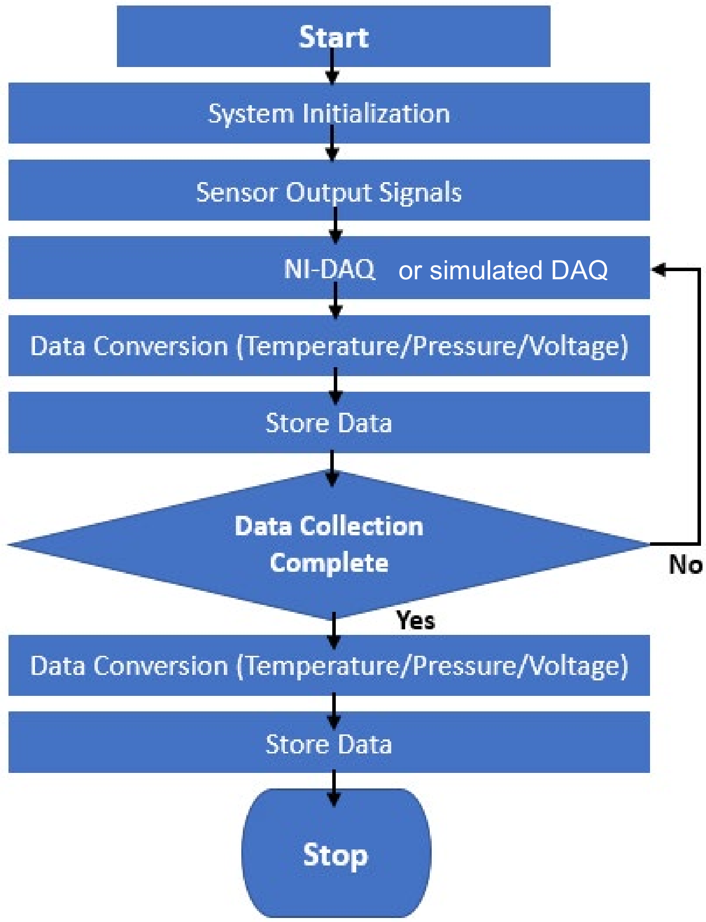

Figure 5. Flowchart for a single parameter during simulation

Laboratory Exercise

The students conducted at least one separate laboratory exercise through the simulated interface including a Shell & Tube Heat Exchanger. The simulation-based experiment was conducted to verify the operation and data accessibility of a simulated heat exchanger system. Due to the pandemic, the experimentation took place through a video conference meeting software. Like the current physical DLMX units, this heat exchanger experiment was divided into two parts. The first part consisted of the simulated data input measurements using a theoretical model with the tube flow settings of a flow rate of 2 L/min and shell flow setting at a flow rate of 5 L/min. The second portion of the experiment comprised a change in the tube flow meter flow rate while keeping the shell flow meter setting the same at 5 L/min. The change in the flow rate meter was from 2 L/min to that of 5 L/min to match the shell flow meter. The dimensions and inlet temperatures (shell at 20°C and tube at 50°C) are obtained based on existing physical heat exchangers and corresponding laboratory activities to use in the numerical analysis for concepts covered in the thermal fluid laboratory course. Such analysis includes the calculation of estimated outlet temperatures, heat duties, log mean temperature difference (LMTD), overall heat transfer coefficient, and heat exchanger effectiveness.

Comparison with physical laboratory activity

The physical heat exchanger allowed for real-time measurements of outlet temperatures using thermocouples to then allow to the use of LMTD method for heat transfer analysis. Unlike the physical heat exchanger, the outlet temperatures had to be estimated using Number of Transfer Units (NTU) method. The physical heat exchanger allowed for hands-on troubleshooting when the unit was not working, thus this simulated interface can provide valuable experience to students on developing problem-solving in unexpected, unwanted conditions.

On the other hand, the inlet flow temperatures of the simulated heat exchanger can be set at constant temperature values while the inlet temperatures of the DLMX unit heat exchanger could not maintain constant temperature values due to the mixing of the fluid in a tank on tube and shell sides, respectively. This meant the fluid temperature in the tank, which is same as the inlet temperature, changed over time as the outlet temperature flow returned instead of exiting to a sink. Moreover, the manual knob did not allow for accurate flow setting unlike the simulated heat exchanger. The physical heat exchanger did not have pressure measurements to allow for pressure drop analysis, but the simulated heat exchanger collects and presents such data. The simulated heat exchanger also allows to test and analyze the performance for various geometric designs and operating conditions including the current units in a short period of time by making changes to certain parameters, which is very limited for the available set of physical heat exchangers.

Assessment of Simulated Laboratory

The course learning outcomes are designed to meet the accreditation criteria currently required from ABET, specifically in thermal fluid science experimentation and data analysis. This system will specifically assess for simulated laboratory environment based on three course learning outcomes:

1. Apply fluid mechanics concepts for the analysis of fundamental fluid mechanics experiments.
2. Apply heat transfer concepts for the analysis of basic heat exchangers configurations.
3. Design, perform, and report results of a mechanical engineering experiment.

These course learning outcomes correspond to ABET Student Outcome 6, which is to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions[10]. Proof of effective learning is integral to the successful implementation of any new educational tool. The student assessment involves direct and indirect assessment. Direct assessment will be taken from student performance in the laboratory activities. To measure student performance, a rubric has been developed to evaluate the course learning outcomes for the course at five achievement levels that ranges from a score of 5 that corresponds to students exhibited complete understanding of the technical content of the outcome or the specified skills and a confidence in applying the techniques or skills to a score of 1 that corresponds to students exhibited no understanding of the technical content of the outcomes or the specified skills and were unable to apply them. Indirect assessment will be obtained from a student survey as shown in Figure 5. The responses of the survey questions are considering student feedback based on a Likert scale model where a value of 1 is associated with strongly disagree and a value of 5 is associated with strongly agree. The instructor will gather student input in the thermal fluid laboratory course at the end of the semester. Students will learn about its essential functions before the experiment and then complete the simulated experiment. There will be a follow up through email by a faculty outside of the course to get student feedback using a survey. These assessments will help document the value-added learning of this simulated laboratory experimental setup and provide meaningful feedback for future laboratory-based learning improvements.

Categories		Strongly Disagree	Disagree	Not Sure	Agree	Strongly Agree
Attitude Towards Interface	Visualization of the data through the User Interface was simple.	1	2	3	4	5
	The User Interface was well organized.	1	2	3	4	5
	The Lab's Remote Access was effective.	1	2	3	4	5
Attitude Towards Design	The emergency shutdown protocol is a great feature for the User Interface.	1	2	3	4	5
	The familiarity of MATLAB as the platform directly helped in the learning process.	1	2	3	4	5
	The Industrial Platform makes things more efficient.	1	2	3	4	5
Conceptual Understanding	The User Interface design makes things clear enough for anyone to understand.	1	2	3	4	5
	Performing a task on the interface is straightforward.	1	2	3	4	5
	The characters & messages on the screen were extremely simple to understand.	1	2	3	4	5

Figure 5. Questions Used in Surveys Administered by group and instructor.

Summary and Conclusions

The data and information in this report can be used to develop strategies to provide an interface that will allow the student user to visualize data display and data collection in a simulation-based laboratory environment. It will also enable the user to monitor and analyze the collected data readily. Additionally, it will allow data storage in the user(s) choice of the file during continuous operation. Utilization of LabVIEW™ and MATLAB & Simulink® provides an easy acquisition of data and monitoring at various stages of the heat exchanger. The simulated instrumentation allows the user to adjust the virtual interface at any point in time. Thus, this set of interfaces can serve as a secure, usable, and adaptable framework for using laboratory mechanical engineering experiments based on the implementation and evaluation of the Shell & Tube HX interface.

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