

**Implementation of Remote Laboratories into the Mechanical
Engineering Curriculum at The Ohio State University**

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The Implementation of a Remote Laboratory within the Mechanical Engineering Curriculum at The Ohio State University

1. Abstract

Remote laboratories for engineering education enhances student learning by providing ample time for students to work through problems individually, giving the student a deeper understanding of the material being covered [1]. A remote laboratory was implemented at The Ohio State University within the Mechanical Engineering department. The system was comprised of software that managed scheduling and data collection, and hardware that included a heat exchanger and an on-board data acquisition card. Students ran the experiment as a homework assignment associated with a heat transfer course. Students supported the idea of remote labs and would, in general, like to see increased utilization throughout the curriculum. The students reacted positively to the “anytime/anyplace” learning aspect as well as the ability to spend time to thoroughly understand the experimental system. Remote laboratories have also proved complimentary to traditional course lecture material by providing real world applications that students can access, and study, at any time.

2. Introduction

The focus of this project was to implement remote laboratories within the Mechanical Engineering curriculum. As a result of the project, students had the capability to run a physical experiment located on campus remotely from anywhere in the world. Each student underwent hands-on, real-world experiences at their own pace which resulted in a more profound understanding of the material.

Remote laboratories complemented existing physical experiments, but did not replace them. This approach introduced innovative laboratory techniques to improve the student experience.

The objectives of the project were to enhance student learning, motivate student participation through a game-like environment, and keep maintenance and teaching cost at a minimum while arranging for individual work at a comfortable pace for each student. The usage of a remote laboratory within the curriculum assisted in obtaining the objectives developed for the project.

The results of this project will better educate instructional staff on how well students learn when working individually, at their own pace, at whatever time they choose. There are many questions educators may ask when looking at this approach: Do students spend more time learning the concepts if they have ample time to do a lab exercise? Are students motivated to do a laboratory if they know they can do it at any time of day, at their own pace? Does the usage of a remote laboratory take away from the physical aspects of the experiment and create too much of a simulation environment?

2.1 How Virtual Labs Work

There are two different types of configurations available when building a virtual lab, batch experiments and interactive experiments. In batched experiments students submit design parameters, wait in a queue, and then obtain their data. In an interactive experiment the students schedule a time to get on the apparatus (using the ilabs scheduling program) and work on the experiment live.

The project started by attempting to install interactive experiments and facilitate student usage

Figure 1 depicts the interaction between the student and the physical laboratory. A student working from home, or in a computer, lab logs into ilabs in order to open the communication between the computer and the physical lab located on campus. Once logged in the student interacts with National Instrument's software program, LabVIEW, to manipulate a physical experiment located on campus.

Ilabs is a tool developed by MIT that manages the communication between the student working from home and the physical experiment located on campus. LabVIEW is the interactive software that the students manipulate to obtain results. MIT developed the ilabs software as well as implemented a virtual laboratory using ilabs into their curriculum successfully.

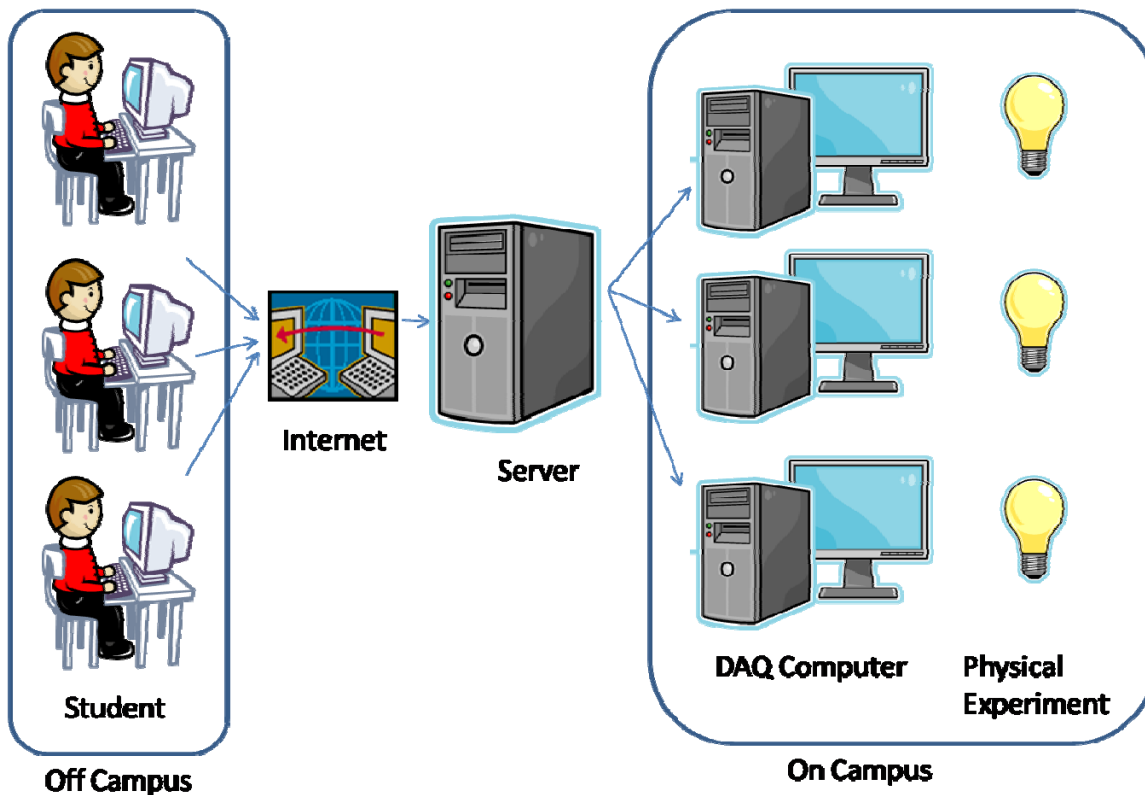


Figure 1: Connection of three virtual lab set-ups from student to physical equipment.

The goal was originally to have five working set-ups that would host the exact same physical experiment on each of the five computers. It was later found that only one computer and setup is needed to satisfy the number of students that used the experiment. Since there are 90 students in the course and they can run the experiment anytime within four weeks, there were no scheduling concerns that would require more than one system. Also, due to budgetary reasons, only one apparatus could be purchased. The physical space to house one set-up was minimal as it sat in a corner of a closet.

2.2 The Ohio State Universities Implementation of Remote Labs

Throughout the summer and fall of 2008 and winter of 2009 the heat transfer remote lab was developed. The exercise was then implemented in spring of 2009 as a homework assignment within a course on heat transfer theory (ME 510). The faculty member involved answered all student questions on the exercise and assignment while the staff in charge of the remote labs as a whole answered all student questions related to technical issues. In the future, a teaching assistant (TA) would be assigned to managing this lab just as they would any other physical lab. They would answer questions during office hours or on Carmen's online discussion board. The TA would be responsible for informing key staff when technical support is needed. The TA's time involvement would be greatly minimized with this type of program when compared to an on campus traditional laboratory and therefore the TA could accomplish more during their appointment.

2.3 Advantages of Remote Laboratories

Remote labs have proven to increase student learning and give students a deeper understanding of the material being presented [1]. Students get hands-on experience at a

comfortable pace. The ability to run labs on their own time from home or school using an internet browser motivates students to tinker and manipulate the experiment in various ways resulting in a better understanding of the system. The lab becomes a challenge to them. Having more time to work on a laboratory has been found to benefit students with disabilities as well.

Student learning is limited in a laboratory environment due to physical space and enrollment numbers. Currently in Mechanical Engineering there are four students per apparatus in order to accommodate the high number of students in a given quarter. Generally one student acts as the leader and interacts with the equipment. A second student generally takes notes. The other two students may or may not get involved significantly with the experiment. One way to help alleviate this issue is to implement virtual laboratories. Each student gains hands-on experience with lab practice and theory.

The University of Queensland created a virtual lab where the students controlled the position of a pendulum by designing and implementing control theory through a remote lab. The students adjusted control parameters so that the pendulum would balance when inverted. Figure 2 is an image of the front panel that the students used to interact with the system via the Internet. There was a webcam in the lab that showed the physical arrangement of the apparatus.



Figure 2: Front Panel of the inverted pendulum experiment located at the University of Queensland [2].

As might be expected, parameter tuning for this type of experiment could take numerous iterations. Figure 3 displays how the remote lab decreased the cycle time required for a student to try various configurations which in turn gave them more chances to diagnose issues and have fun with the exercise. As a result of this new interface, students were more able to successfully balance the pendulum (4% to 73% more). Students also had more insight into the results of their experiments when running the lab virtually than when running in the physical lab environment. Finally, course coordinators found that they could better monitor the students [2].

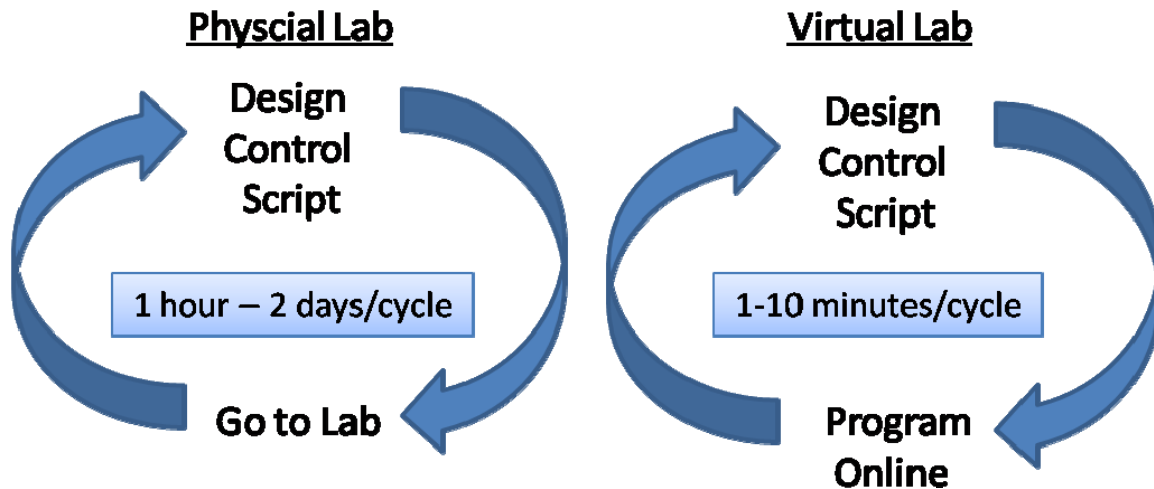


Figure 3: Cycle time in which it takes to complete a physical lab vs. a virtual lab

Troubleshooting and data analysis are two areas in which students should excel. Remote labs are a way of implementing an experiment while concentrating on those two expertise areas. In a traditional on-campus laboratory, students work through a step-by-step guide in order to obtain data which they then analyze. They have to complete an assignment that states exactly what is expected of them. With virtual labs, students work through a problem and fix their own errors as they go. They then have the ability to answer more open-ended questions as they can return to the experiment and manipulate other parameters that then give them more insight into the system and how it works. The arrangement creates an environment where the students need to have a true understanding of their data in order to know if it makes sense.

The implementation of remote labs will not only be a benefit to Mechanical Engineering undergraduate education but also may generate some interest in other departments on campus which, in turn could lead to the creation of interdisciplinary activities, distance laboratory courses and the usage of remote labs in the research environment.

Figure 4 and Table 1 summarize the student usage and the student feedback (in 2005) from a virtual lab in microelectronics that MIT implemented in 1998. Students from all over participated in the lab and the students felt they gained a better understanding of the material being presented.

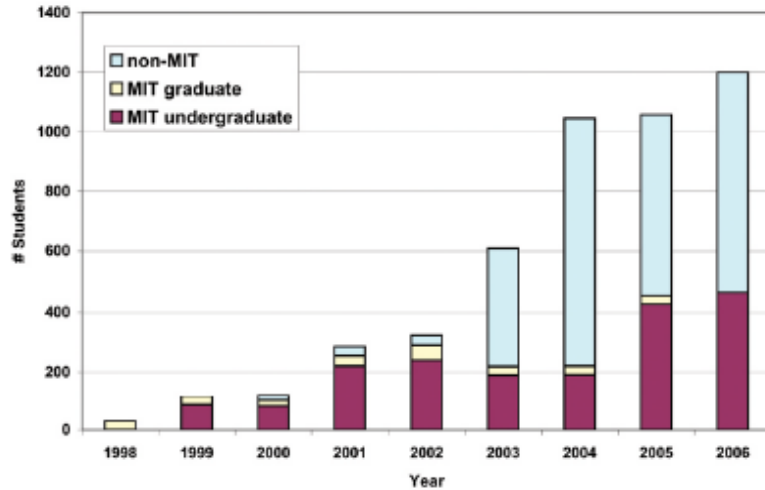


Figure 4: MIT representation of student use of microelectronics weblab in formal graduate and undergraduate courses [2].

Table 1: Sample of Survey Results in evaluation of MIT’s Microelectronics Weblab in a Junior-Level Subject in Electrical Engineering. The results were ranked on a seven-point likert scale, ranging from “1” (Poorly) to “7” (Extremely Well) [2].

How well the WebLab experience affected understanding in particular areas	Spring 2005		Fall 2005		
	Mean	SD	Mean	SD	%Change
Behavior of the devices	4.30	1.73	5.42	1.17	+26.0
Differences between theory & application	4.22	1.49	5.55	1.03	+31.5
Using intuition to understand devices	3.81	1.66	5.00	1.20	+31.2
Related lectures and assigned readings	3.62	1.52	4.82	0.88	+33.1

Remote laboratories are generally easier to manage and maintain as well. There is only one piece of equipment hosting all students rather than five to six set-ups to maintain. Also, there is little coordination or intervention needed throughout the quarter.

Below is a list of resulting benefits from the implementation of virtual laboratories:

Student

- Each individual student gets hands-on experience.
- Students experience usage of high-end technologies.
- Students can complete labs where and when they want because Virtual Labs are always open.
- The time given to complete the lab is open-ended. (Very helpful for students with disabilities).

- According to studies, virtual labs result in higher cognitive understanding among students.
- Students are gathering data from a physical experiment and therefore are analyzing data with noise and other environmental variations that may not be part of a simulated experiment.

Employee

- Teaching assistants can accommodate more students in a shorter amount of time.
- Less maintenance is required on the actual equipment because there is no actual physical touching of the equipment. It is being run through the internet.

College

- The program integrates real-world technology into the laboratory.
- There is enhanced ability to add topics to the curriculum as it is more difficult to do this in a physical lab.
- There is less physical space required for equipment and teaching.
- A variety of subjects can be taught with less cost.
- Other research groups can learn about remote labs and may decide to install these in their areas as well.
- Interdisciplinary and team activities can be facilitated through remote labs
- The remote lab provides more opportunities for desired distance education.

- Large, previously inaccessible equipment can be demonstrated to large enrollment courses.

3. Methods

A simple remote lab can be implemented with two computers and one experimental apparatus. One computer, the service broker, is used for scheduling and data storage. This computer communicates directly to another computer, the lab server that is used for the acquisition of data from the experiment apparatus. In order to take data from an analog source and turn it into a digital signal, a data acquisition card, DAQ, is needed. In this experiment the DAQ was internal to the experiment apparatus.

3.1 Service Broker Operating System and Database Installation

One computer, the service broker, manages the scheduling and stores the data collected during the experiment. To get started the following software needs to be installed on the computer.

- Microsoft Windows XP with IIS
- Microsoft SQL Server Express
- .NET 2.0 Framework

It should be noted that Microsoft SQL Express and .NET 2.0 Framework are free downloadable programs through Microsoft [3, 4]. The Ohio State University was the first school to attempt to use this combination of products in order to reduce cost.

MIT received a grant through Microsoft which allowed them to create software and documentation that leads the user through the entire process of setting up the remote lab. The first document [5] to follow describes how to install the three software programs mentioned above with the right configuration. This document also goes into detail on all drivers necessary (audio, network). The service broker hosts many different types of servers within it as well as becoming a web server. Therefore, Internet Information Server, IIS, and .NET framework are used to generate the web server. Simultaneously with setting up the websites necessary, an email server is started so that bugs and requests can be emailed through the website. It is assumed that this computer will have Internet access and a valid IP address. Once the web server has been created using Windows XP, the SQL Server Express package is installed using the provided instructions. MIT created all needed databases for the SQL server and therefore the installer only needs to generate an account, as well as make some adjustments to the security settings.

3.2 Service Broker – Process Agents Installation

The second document [6] for implementation describes how to set-up the service broker to be a scheduling server as well as using the service broker to activate the lab server when the user's time request is valid. The computer on which the service broker is located also houses three other servers:

- Service Broker – Main Server
- Experiment Storage Server – Stores data from experiments
- User-side Scheduling Server – allows for user to select a time to run the experiment.

- Lab-side Scheduling Server – Schedules the usage of the lab server based on the user-side scheduling request.

Each server has a set of database scripts that need to be loaded within Microsoft SQL. All the scripts were written and provided by MIT [7, 8]. The user creates a virtual website associated with each server. Registration information for each server is entered into the respective databases through a website. This portion of the project is time consuming and prone to errors as mentioned below within the *Troubleshooting* section.

3.3 Bootstrapping the Service Broker

The web servers generated on the service broker need to communicate with each other to exchange information. In order to do this, a process called bootstrapping is carried out. Bootstrapping is performed within an administration account located on the service broker. MIT's pre-compiled databases include the website which is utilized for the set-up and operation of ilabs. These websites can be edited to allow for personalized logos and messages but is, in general, already in an easy-to-use package. It is here that credentials for each web server are added and recognized. The web servers are also linked to each other by various association options with the website. Users and groups are also managed on the main website through the service broker.

3.4 Test the Service Broker

MIT provides a program that can be used to test the operation of the Service Broker. This program, in essence, creates a lab server on the service broker (or lab server) with a simulated experiment. Once the user has this program running they are approximately half-way through the implementation of ilabs.

3.5 Lab Server Installation and Set-up

MIT generated a third document [9] that prepares the Lab Server for usage and communication to the Service Broker. This machine is very similar to the service broker but has some extra steps in order to run with LabVIEW, a software program used as a tool to view data and acquire data. The following software needs to be installed on the lab server:

- Windows XP with IIS
- Microsoft SQL Express
- LabVIEW 8.2.1

Currently, the ilabs software provided by MIT only runs with LabVIEW 8.2.1. Developers feel they have a new beta version of software that can be used with LabVIEW 8.6 which will hopefully be tested in the near future. More details on this are mentioned in the *Future Work* section below.

The same basic procedure is used for the lab server as the service broker. A virtual website is created, pre-built databases are loaded in to SQL, and the lab server website is used to register the experiment. The service broker and the lab server are associated to each other via the information entered through the websites that is held on the computer databases. The lab server databases also start the appropriate LabVIEW file when called by the service broker. In order for LabVIEW to work with the system, some settings within LabVIEW need to be updated. The TCP/IP Port needs to be correct and the DCOM Configuration needs to be set with the appropriate paths and security. These steps are listed within the provided MIT documentation.

If the end user would like to have data collected and stored on the service broker, LabVIEW's data socket server needs to be configured and started. The data socket server allows for data transfer between LabVIEW, on the Lab Server, and the storage component of the Service Broker. It is basically a file transfer protocol. In order for data to save, the data socket server must be started and running on the Lab Server. The lab server can be tested using a simulated experiment provided by MIT.

3.6 Troubleshooting

In The Ohio State University's program, the process of installing the lab server and service broker took about three months due to issues that arose during the installation. Much of these were because the two Mechanical Engineers working on the project were unfamiliar with the technology and the documentation provided by MIT did not covered installation using Windows XP and SQL Server Express. The Ohio State University was the first set of non-computer-science personnel implementing remote labs solely off documentation and with offsite help from MIT.

The first month was spent getting the two computers ready for installation and obtaining all the necessary software and documentation. The service broker installation took approximately one month. One error that delayed progress a bit was a bug in SQL Express with XP. When loading a database into SQL, the software would change the default database into which the script was loaded and therefore would not load the information into the correct place. Also, because of the unfamiliarity with the program, it was not known that the user needed to "execute" each database after loading. Entering of data on the web server's websites was found to be very finicky. The required information, with the right text and in the exact right order,

needed to be entered in order for things to work correctly. At one point there were so many errors building up (which could have been from the databases, website data, or security settings) that the entire service broker was cleaned out and the project started over again.

The second time attempt was much easier, indicating that many of the issues were due to lack of experience. It is important to stress that the information for registering the websites and performing the bootstrapping must be completely accurate. To troubleshoot these items, there were some adjustments that had to be made to the database scripts themselves, rather than through the virtual websites.

The lab server implementation started during the second month of the project and went fairly smoothly. One error, which delayed progress for quite some time, was caused by the placement of the LabVIEW file within the file structure on the computer. The file was put in a folder called “user.lib” which is a library folder. When the LabVIEW file was in that folder LabVIEW would not release control of the file once the user was done running an experiment. Once the file was moved out of the library folder, the system operated properly.

3.7 Experiment Apparatus

A packaged experiment was purchased from Armfield Corporation and arrived approximately six months into the project. The experiment was a heat exchanger with six thermocouples, three on the hot water side and three on the cold water side. Figure 5 displays the heat exchanger apparatus. The experiment came with an onboard data acquisition card and pre-made software. The software provided could not be used with ilabs and therefore a new program was developed within LabVIEW. This development took approximately three months. Figure 6 displays the front panel of the LabVIEW file used by the students. The ability to save

data onto the student's computer was desired, however, this outcome could not be accomplished. Therefore the data socket method of data collection was used. The instructions for the lab exercise also stated that the students must hand-write their data as they run through the experiment. Overall, the equipment is very robust and easy to use. There were not many problems during the installation or the LabVIEW file creation.

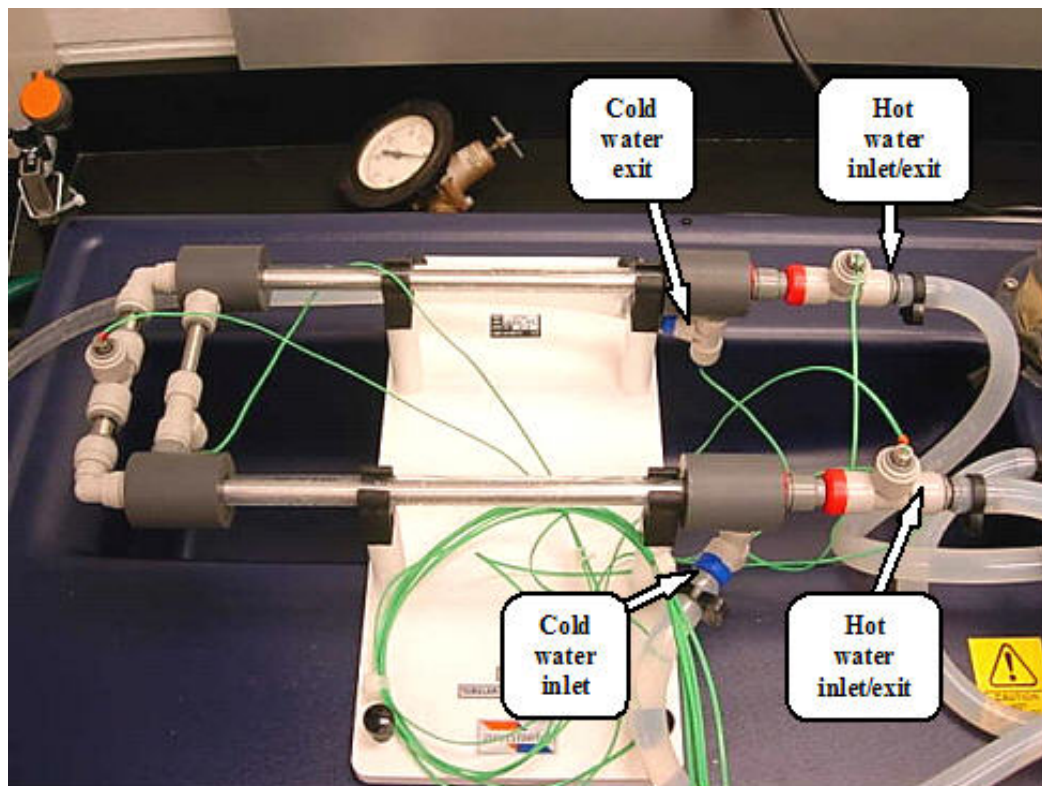


Figure 5: Heat Exchanger Apparatus

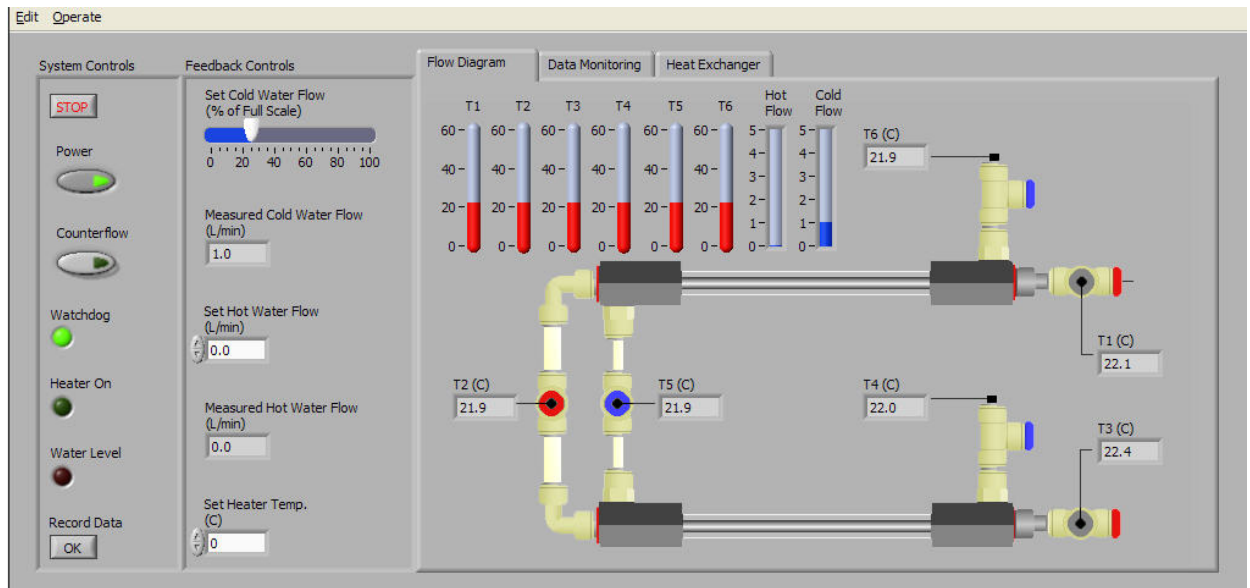


Figure 6: LabVIEW front Panel for Heat Exchanger Experiment

This completed the remote lab set-up. Students could now reserve a time to run the experiment by logging into the service broker. Once the time was validated, they launched the lab, which caused the service broker to communicate to the lab server to open the LabVIEW file. The student interacted with the LabVIEW file which turned on or off the heat exchanger and took temperature measurements. Once complete, the student retrieved their data from the service broker.

3.8 Networking

The next step was to put the entire system on to the university network so students could log in from anywhere to run the experiment. The computers were put on the DNS and given a static IP address. The web ports were opened for those specific computers. The ME computer staff, for security purposes, asked that the computers reside within the Mechanical Engineering VPN (Virtual Private Network). For this reason, students had to download and use Cisco VPN Client, which is available through The Ohio State University's free download site. As it turned

out, students had to be logged into the VPN even to see the main website. This caused some confusion for students because they thought they only needed the VPN to run the experiment, not to access the website all together.

Not only did students need to have the VPN running but they also needed to install LabVIEW Runtime Engine 8.2.1. This program allowed for the user to run the LabVIEW executable without having LabVIEW installed on their computer. It is a free download from LabVIEW and available on the online teaching website for the corresponding course. The computers within the Mechanical Engineering domain are on the correct network and have LabVIEW runtime installed. Therefore if the students ran the experiment from within the Mechanical Engineering computer lab they could access the experiment by simply typing in the address: <http://ilabs.eng.ohio-state.edu/interactivesb>.

3.9 Lab Exercise

A faculty member who specializes in heat transfer theory developed the lab exercise. Armfield, the manufacturer of the experiment set-up, supplied many suggested exercises which this faculty member modified to match the needs of the curriculum. Heat transfer theory was to be emphasized and therefore was enhanced further than indicated in the provided experiments. The final lab exercise can be found in the appendix of this report.

3.10 Bells and Whistles

A few extra items were added to enhance the learning experience for the students and to customize OSU's remote laboratory. A webcam was installed midway through the quarter so that the students could see the experiment operating while running through the exercise. The webcam was put on the DNS and was linked to the OSU ilab's website. The webcam's view is

shown in Figure 7. Also, all the websites, through the service broker and lab server, were adjusted to have The Ohio State University logo, OSU color scheme, a link to OSU's main website, news and updates, and the supervising staff person's contact information.

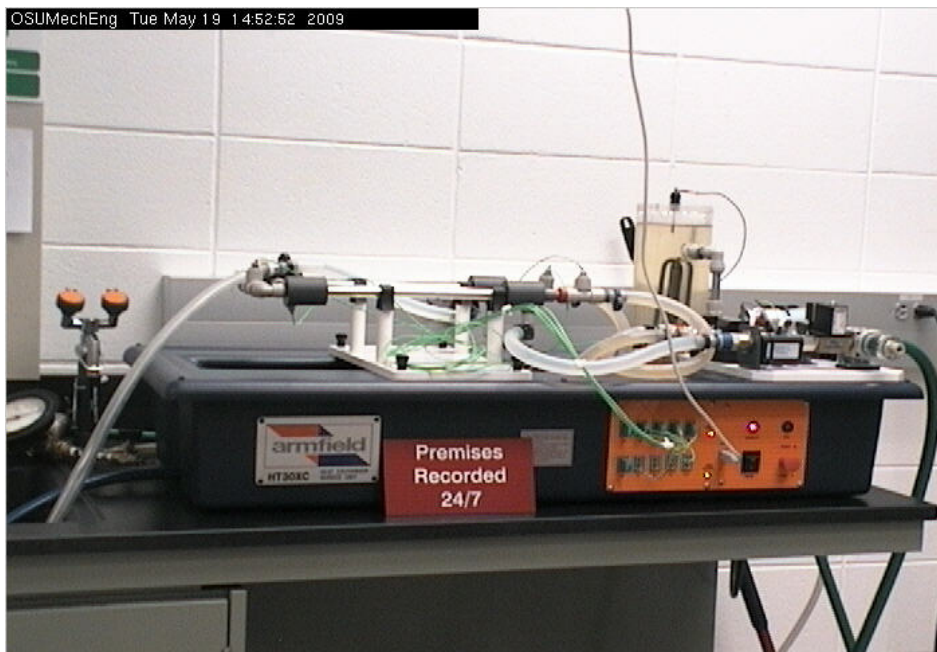


Figure 7: Webcam image of Heat Exchanger Remote Lab Experiment

4.0 Discussion

4.1 Implementation Effort Level

Implementing a remote lab for the first time is quite time consuming. Subsequent set-ups, if done by the same staff member, can be accomplished substantially faster. Implementation of additional experiments onto the existing system is also relatively straight forward. The service broker can host many experiments and therefore if another exercise/apparatus were to be developed, only the Lab Server would need to be created. It is very easy to add on to the existing remote lab system.

The implantation of this project was more time consuming than necessary due to the lack of experience and training in computer science of the staff members involved. On the other hand, The Ohio State University provided MIT with a good example of the difficulties encountered by a staff person with little computer background using their written instructions. An information technology associate who has had experience setting up the system is recommended to work with an inexperienced team of people attempting to create another system (service broker through experiment). Adding an experiment to an existing service broker can be done by someone with some computer experience but does not require a certified individual in the field.

4.2 Implementation Timeline

The original Gantt chart for the project can be found in the appendix. The project was broken down into four phases. Figure 8 displays the phases as listed in the proposal for the project. Phase 1, Preliminary Study, was delayed by complications which occurred when creating the service broker and lab server. Rather than being complete in August of 2008, this phase was complete in December of 2008. This project delay did not result in any issues, though, because Phase 2, experiment development, was completed much faster than initially projected. Phase 2 started in late November 2008. The team bought a packaged experiment rather than making one from scratch which saved time. The equipment arrived in early January which put the project back on track for Phase 3, documentation and release. From January to April the equipment was tested, a LabVIEW file was written, and the experiment exercise was created. Because of items going more smoothly than originally predicted, the experiment was piloted in spring 2009. The original intention was to pilot in autumn 2009 so the project was ahead of schedule. The pilot ran very smoothly and student feedback was gathered. This student

feedback will be reviewed in the *Results* section of this report. Overall, the project milestones were met and exceeded within the timeframe.

Phase 1 – Preliminary Study

The first step to this project is a preliminary study on implementing remote labs. Collaboration with National Instruments as well as other universities who have explored remote labs would be crucial. The largest cost of this project is labor. A graduate student would first work on the implementation of ilabs by using MIT's installations guides located online. A simple remote experiment using existing apparatus would be used for the preliminary study. National Instruments has also volunteered to donate \$2000 in data acquisition equipment for this phase.

Phase 2 – Experiment Development

Once the preliminary study is complete, staff and faculty will decide on the objectives and subject matter for the virtual laboratory. The initial idea is to create a black box in which the students need to identify the system. Once identified, the students will return to the experiment and use their results to design a structure. The decision on the experiment objectives will lead to purchasing equipment as well as creating the LabVIEW interactive interface. Enough equipment will be purchased to develop five systems. The systems will be built and tested.

Phase 3 – Documentation and Release

A part of this project being successful is having good documentation for students to follow. The documentation has to be written well enough that a student can guide themselves through the lab without assistance. A TA will be available during office hours but not while the student is interactively working with the apparatus. Once documentation is created a small number of students will run through the lab and give us feedback and general advice. The documentation and equipment will then be optimized for course usage.

Phase 4 - Final Report Generation

All lessons learned and information needed to be able to continue and replicate this project will be compiled in a final report. Suggestions for future projects will be included in the document. Needed improvements as well as positive outcomes will be summarized.

Figure 8: Project Phases as written in the project proposal.

4.3 Cost

Table 2 displays a comparison of the proposed cost and the final cost of the project. The hardware associated with the experiment was more expensive than originally predicted. This increase in cost didn't affect the overall cost of the project since the labor cost was less expensive than expected. While a faculty member was involved with creating the experimental procedure and assignment, he did not get involved with the development of the remote lab. The computer staff did help to port the system onto the university network but did not help with development of the remote lab itself. In the future, it is recommended that the computer staff be involved in implementation of remote labs in order to facilitate better meshing with their network. The majority of the labor cost during the development supported the work of two graduate students and an undergraduate student worker. While the ME department donated a rather large amount of staff member time, a small portion of the funding did go to compensate for staff time involvement. Overall, the project stayed within the projected cost outline.

Table 2: Proposed cost and actual cost of the remote labs project.

	Item Description	Proposed Cost	Actual Cost	Proposed Description	Actual Description
Preliminary Study	Labor	\$ 6000	\$6000	1 summer graduate and undergraduate student, results in 1 working set-up	1 summer graduate student, a portion of 1 WI09 graduate student
Implementation	Hardware	\$ 10,000	\$20,866	Five Stations	One Station to Serve All Students (it was found that five was not needed).
	Student Worker	\$ 2,000	\$2,000	Undergraduate to Manage Replica of Initial Set-Up	1 student worker in WI09
	Staff Labor	\$10,000	\$3,500	Management and Technician	Management and Coordination
	Faculty Advising	\$ 2,000	\$0	Integration of Experiment in to Course Materials	N/A

4.4 Issues during Pilot

In general the pilot of this experiment went very well. There were very few technical issues. One issue that surfaced was the water level in the tank reservoir of the heat exchanger going below its operating point to due to evaporation. There is a safety feature built into the LabVIEW program which will not allow the heater to work when this happens, and also gives a warning to the student. The student contacted the staff person in charge and the problem was fixed within five minutes. This water level is now monitored via the webcam. Another problem that occurred during the experiment was that the lab server computer restarted itself to install

updates. When the computer restarted, the data socket server did not automatically start with it. The students were able to run the experiment but their data was not being stored. Since they are hand-writing their data as they did their work, this did not cause many issues but two students do not have the backup data on storage. There are two ways to fix this issue. One is to turn off auto updates and remember to do this manually every so often. The second is to set the data socket to automatically start upon computer boot-up. The only other technical issue reported, which a fair number of students experienced, was that the students could not access the website. In all cases this was because the student was not in the Mechanical Engineering building, or did not have the VPN client running.

5.0 Results and Conclusion

The implementation of the remote lab into the curriculum was both successful and considered very promising for future labs. As stated above, adding more experiments to the remote laboratory is not difficult. It was very evident that this type of laboratory is low cost and low maintenance. The initial cost of the apparatus can be expensive if a trainer stand is purchased and used (as in this project) but the maintenance and operating costs are minimal. The fact that the apparatus is expensive is mitigated by the need for only one system vs. five to six in a regular ME lab experiment. The financial and time efficiency of the remote lab is also demonstrated by the need for less technical staff intervention, and fewer graduate teaching associate contact hours.

Two surveys were given to students once the laboratory was complete. The surveys asked for comments about remote labs in general, and also in regard to the lab exercise itself. The positive feedback focused on the fact that the students could work on this experiment

individually at the time of their choice and at their own pace. They also noted that the interaction with the equipment was easy to understand. The negative comments focused on the lack of being able to ask questions to a lab TA, confusion with the procedure and the assignment associated with the experiment and difficulty understanding how the system worked. In the future, a lab TA will be assigned to answer questions so that problem should be alleviated. As for the second issue, the lab manual documentation will be reviewed and updated. This point does not reflect positively or negatively on the remote lab aspects of the project. To alleviate the confusion on how the system works, it may be best to have the faculty member go into more detail during lecture and possibly even demonstrate the remote lab for the class. For the pilot quarter the intention was to evaluate how little instruction was required to have students use the system successfully and have a satisfactory result. Therefore, the faculty member did not go into details much in class. It should be noted that this complaint is common in our traditional labs on campus as well.

The implementation of a remote lab into the Mechanical Engineering curriculum was successful. It was evident to students, staff and faculty that the remote lab had many advantages that help students gain a more profound understanding of the material being taught. There were few technical issues with the operation of the equipment during the pilot quarter. Overall, the students enjoyed having a remote lab as part of their curriculum at The Ohio State University.

6.0 Future Work

MIT ilabs has recently released updated software which allows the system to run with LabVIEW 8.6. There are many advantages to this change. For summer 2009 there is a plan to create an entirely new service broker and lab server to accommodate the new software.

National Instruments donated equipment for The Ohio State University to create an inverted pendulum experiment. This experiment lends to a game-like atmosphere that would motivate students. There are plans to develop this experiment over the course of the next year and possibly implement an exercise into a controls course in spring 2010.

Other departments across the university have shown some interest in this set-up. Since it is fairly easy at this point to set-up additional experiments, there may be some collaboration with these departments. As of now, no departments have specific plans but in the future there may be possibilities in this area. Across the university, faculty members have also inquired about using this method to display large, inaccessible equipment during a lecture to a large enrollment course.

7.0 Acknowledgements

This project could not have been completed without technical support from Phil Bailey and Kirky DeLong of MIT and Andrew Watchorn of National Instruments. Bailey and DeLong provided many hours of technical assistance getting the ilabs portion of the project running. Watchorn came to our site to help us with technical complications with National Instruments and with ilabs. These people were invaluable resources and deserve acknowledgement for this project.

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9.0 Appendix

9.1 Lab Exercise

Mechanical Engineering 510 (Heat Transfer)

Special Homework Assignment

Heat Exchanger Performance Analysis Using a Remote Access Experiment

Objectives

1. Study convection heat transfer between two fluid flows separated by a solid wall by measuring inlet and exit flow temperatures and flow rates in a concentric tubular heat exchanger.
2. Analyze energy balance and calculate the heat exchanger efficiency.
3. Determine the overall heat transfer coefficient using the Logarithmic Mean Temperature Difference (LMTD).
4. Study the effect of varying flow rates and temperatures on the efficiency and on the overall heat transfer coefficient.
5. Demonstrate differences between co-flow and counter-flow operation modes: effect on temperature profiles, heat rate, heat transfer coefficient, and efficiency.
6. Calculate the overall heat transfer coefficient and the efficiency using convective heat transfer theory and the effectiveness – number of transfer units (NTU) method. Compare theoretical predictions with the experimental results.

Background / Theory

The recommended text for background theory is *Introduction to Heat Transfer*, by F.P. Incropera et al., 5th edition, New York, Wiley, 2007. All references in this manual are to this text.

To complete this assignment, you will need to be familiar with the following topics:

1. Thermal resistance and overall heat transfer coefficient (Section 3.1), specifically for cylindrical geometry (Section 3.3).
2. Convection heat transfer correlations for internal flows (laminar and turbulent) in circular tubes (Sections 8.4, 8.5) and in a concentric tube annulus (Sections 8.6).
3. Overall heat transfer coefficient for a tubular heat exchanger (Section 11.2).
4. The use of energy balance and log-mean temperature difference for heat exchanger analysis (Section 11.3).
5. The use of effectiveness-NTU method for heat exchanger analysis (Section 11.4).

Although Chapter 8 and 11 material will be covered in class during Weeks 7 and 8 of the quarter, you are strongly encouraged to schedule and run the experiment in the first half of the quarter. The data obtained during the experiment can be reduced and the report can be completed gradually, as the necessary material is being covered in class.

Experimental Setup

For this assignment, you will use the Armfield Tubular Heat Exchanger remote access experiment located in Scott Lab W269, shown in Figure 1. The experiment can be controlled remotely using a specially designed web site and remote LabView application. The heat exchanger consists of two concentric tube heat exchanger sections connected in series (see Figure 2). In each section, the cold stream flows through a cylindrical annulus between the outer tube made of transparent acrylic plastic and the inner tube made of stainless steel, while the hot stream flows through the inner stainless steel tube. This arrangement minimizes the heat loss from the heat exchanger. Water is used as the working fluid in both streams.

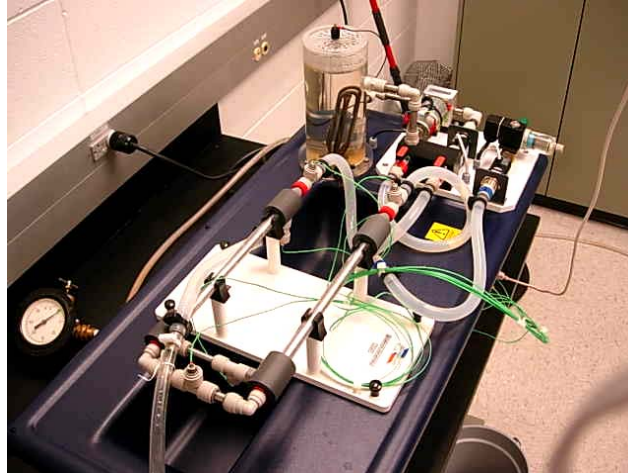


Figure 1: Overall view of the concentric tube heat exchanger

The heat exchanger is instrumented with six K-type thermocouples (temperature range 0-133°C, resolution 0.1°C) used to monitor the hot and the cold stream temperatures at the inlet and the outlet of the two sections. The outlet of the first section is the inlet of the second section (see Figure 2).

The cold flow is supplied from a standard water faucet, so its inlet temperature cannot be controlled, and is discharged to the drain, flowing through the heat exchanger in an open loop. The cold flow rate can be varied using an automated valve controlled by the user in the LabView application, and is measured by a flow meter.

The hot flow is heated in a reservoir using a 2 kW electrical heater (see Figure 3). The temperature in the hot water reservoir is set by the user in the LabView application and is maintained at the specified level using a thermocouple and a feedback temperature controller. The hot flow is circulated through the heat exchanger in a closed cycle by a reversible pump (see Figure 3), which enables the user to switch between co-flow and counter-flow operation modes. The hot flow rate is also set by the user in the LabView application and is maintained at the specified level using a flow controller.

Analog signals from the thermocouples and flow meters are converted to digital signals using an analog-to-digital signal converter and sent to a computer in W269 through a USB interface.

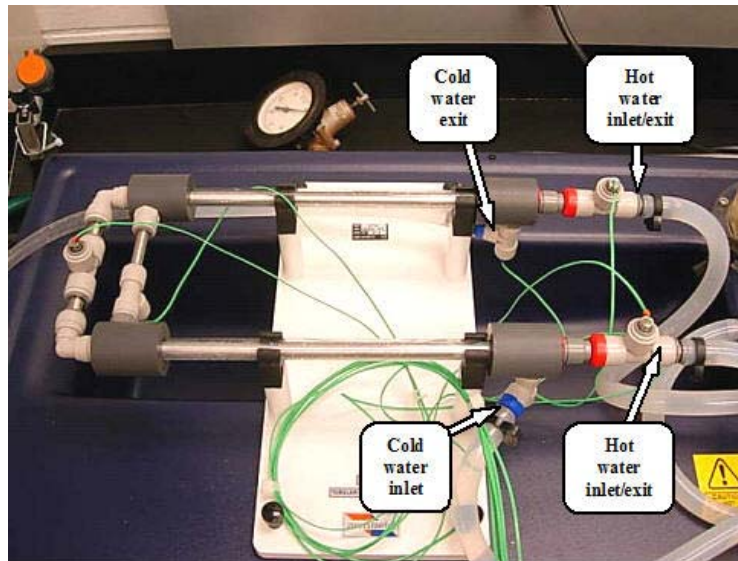


Figure 2: Heat exchanger section connection. During co-flow operation, the hot water inlet is on the bottom and the exit is on the top. During counter-flow operation, the hot flow direction is reversed.

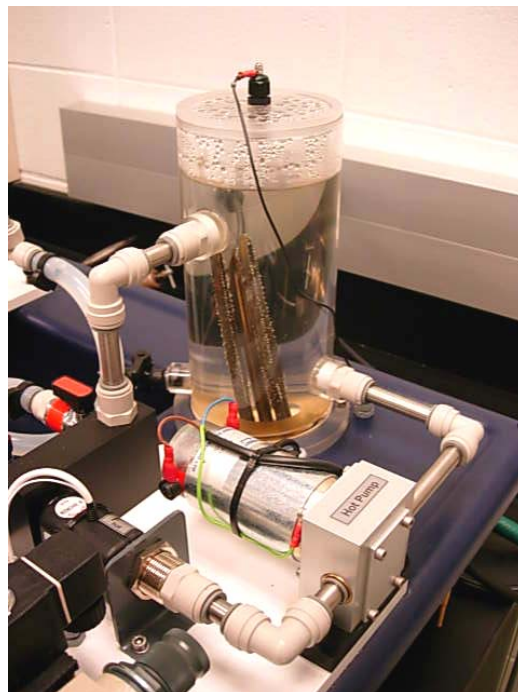


Figure 3: Hot water reservoir and reversible pump

Registration and remote access

Before you can access the remote lab server, you need to follow these steps.

1. All students need to register to obtain an account on the **iLabs** server before scheduling a time to run the experiment. *This needs to be done during the first week of classes, so lab access can be granted by the lab administrator in a timely manner.*

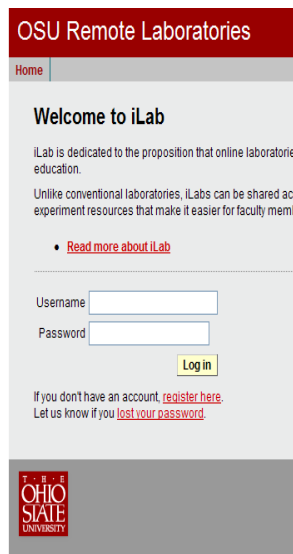


Figure 4: Ilabs Login Window

2. Go to <http://ilabs.eng.ohio-state.edu/interactivesb>
3. Click **Register here**
4. Fill in your username, first name and last name, and email address. Select **Student** as your affiliation, and request to be in the **HeatTransfer_Group**. Please note that this is not a secure certificate (https) website, so please pick a unique password (different from other passwords you may use elsewhere).
5. Access to the labs is granted by the lab administrator each Friday. You will receive an email when you are approved.

If you are planning to run the remote lab experiment on one of the computers located in Scott Lab (recommended), you can now schedule your experiment (see **Scheduling the experiment** below).

If you are planning to run the remote lab experiment on a computer not on the Mechanical Engineering domain (e.g. from your home), you will also need to download and install two software packages, VPN client software and a Labview Run-Time Engine 8.2.1. The VPN client allows remote access to your Z:\ drive on the Mechanical Engineering computing labs, and the Run-Time Engine allows running Labview applications on your computer.

1. Go to <http://www.mecheng.osu.edu/computing-labs/accessing-z-drive-personal-pc>. Follow steps 1-13 of the instructions to install VPN client software and access your Z:\ drive.
2. Download and install the standard Labview Run-Time Engine 8.2.1 (LabVIEW821RuntimeEngine.exe) from Carmen. This will allow you to execute the Labview panel remotely without having to install the entire Labview package. Download using all default selections.

The remote lab is operated using **iLabs** software developed at MIT. The software allows each student to logon to a remote lab server in W269 Scott Laboratory. *Remember that although you will run the lab remotely, this is not a videogame but an actual experiment.* After reading this manual, you are strongly encouraged to stop by at Scott Lab W269 and take a look at the experimental setup when you have a chance. The room is open from 7:30am – 5:00pm Monday through Friday.

Scheduling the experiment

Note: to schedule the experiment, you will need to turn off the pop-up blocker in your Web browser (e.g. Tools → Pop-up Blocker → Turn Off Pop-up Blocker) or allow pop-ups at the ilabs website. If you have a Google or Yahoo bar you may need to turn off pop-up blocker there as well.

1. Log on to the ilabs website: <http://ilabs.eng.ohio-state.edu/interactivesb>. Remember to turn off the pop-up blocker.
2. Go to **My Labs** tab.
3. Press **Schedule/Redeem Session**
4. Select a date when you will run the experiment.

5. A pop-up window will appear where you need to select a two-hour time slot on that day and click on **Make Reservation** (see Figure 4). Please select only one time slot, it actually takes about 1½ hours to run the experiment. Currently, the time slots start from the time you log on. In future software releases, the time slots will start on the hour.
6. Now you should see your reservation listed on the scheduling page. If you are going to run the experiment right now, highlight your reservation in the window and click on **Redeem Reservation**. If you will run the experiment later, go back to service broker and log out until your time slot begins.

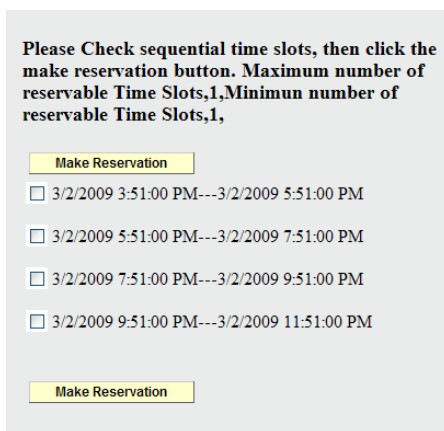


Figure 5: Left: Logon window. Right: reservation pop-up window

Starting the Experiment

1. Log on to the ilabs website, go to **My Labs** tab, and click on the **Launch Lab** button. If your time slot has not started yet, you will not see the **Launch Lab** button. You can check your reservation by going to **Redeem Reservation** but you will not be able to start the experiment until your time slot has started.
2. You should now see the Labview experiment panel in your browser. Sometimes downloading the experiment panel can take a couple of minutes due to Labview start-up time. If you do not see the experiment panel appear, and get an icon in the upper left corner of the window instead, you may not have installed Labview Runtime Engine 8.2.1 (see **Registration and Remote Access** above).
3. To activate the experiment, press the button with an arrow on right above the application window (Start button).
4. Start the program by pressing the **Power** button in the upper left corner of the window. Temperature readings should now be active.

5. Take a few minutes to examine the experiment layout and controls. You can also switch the view from the experiment layout tab to the data monitor tab and to the experimental setup photo tab. T_1 , T_2 , and T_3 are the hot (red) flow temperatures at three different locations, and T_4 , T_5 , and T_6 are the cold (blue) flow temperatures at the same three locations. The **Counterflow** button, located under the **Power** button, switches between the co-flow and the counter-flow operation modes of the next exchanger. *You should start the experiment in the co-flow mode (Counterflow button light off).* During co-flow operation, T_3 is the hot flow inlet temperature ($T_{h,i}$) and T_1 is the hot flow exit temperature ($T_{h,e}$). During counter-flow operation, the hot flow reverses direction, so in this case $T_1 = T_{h,i}$ and $T_3 = T_{h,e}$. For both co-flow and counter-flow operation, $T_4 = T_{c,i}$ and $T_6 = T_{c,o}$.
6. Prior to running the experiment, it is necessary to remove air bubbles which may accumulate in the pipes and hoses. For this, set both hot and cold flow rates to approximately 4 L/min and let them flow for about 10 seconds, then reduce both flow rates to 0. The cold flow can be changed by adjusting the slider (4 L/min is approximately 80% full scale). The hot flow can be set by entering the desired flow rate in a dialog box. The system is now ready and you can start the experiment.

Exercise 1. Taking data and estimating experimental uncertainties

1. Set both flow rates to 3 L/min. The cold flow, which comes from the faucet, may fluctuate around the set value within approximately ± 0.2 L/min.
2. Set the heater temperature to 50°C by entering the temperature in a dialog box. After that, allow the temperatures and the flow rates to stabilize. After the heater is turned on, this will take approximately 5 minutes. During the experiment, once the heater is on, the time for the flow temperatures to stabilize may become shorter (2-3 minutes).
3. When the temperatures have stabilized, capture the temperature and flow readings by pressing the **Record** button. Click on the **Monitor/Data** tab to make sure that data set appears in the spreadsheet.
4. Without changing the experiment settings, repeat Step 3 several times (8-10), 10-20 seconds apart. Since both the temperatures and the flow rates fluctuate with time, this is necessary to determine the uncertainty in temperature and flow rate measurements. For each location, calculate the average temperature and the standard deviation. Also, calculate the average hot and cold flow rates and their standard deviations (see **Data Reduction** below). To save time, this procedure will be done only once, in Exercise 1. All subsequent data will be taken once for every set of conditions.
5. Save the data either by using **Print Screen** or writing down the information by hand. Current software version does not allow copying and pasting the data into a spreadsheet. Remember that restarting the experiment by pressing Stop and Start buttons erases the data on the

Monitor/Data tab. After the experiment, you can also access your data saved by ilabs software when you press **Record** button (see **Accessing Saved Data** below). However, it is recommended to keep a backup copy in case of software malfunction.

Exercise 2. Co-flow operation, varying cold flow rate

Keep the heater temperature at 50⁰ C and the hot flow rate at 3 L/min. Vary the cold flow rate from 1.0 L/min to 4.5 L/min (pick 6 flow rate values in this range). Each time you change the flow rate, wait until the temperatures stabilize. For each set of conditions, take the temperature and flow rate data once by pressing the **Record** button. Save the data either by using **Print Screen** or writing down the information by hand.

Exercise 3. Co-flow operation, varying heater temperature

Now keep both the hot and the cold flow rates at 3 L/min. Vary the heater temperature from 50⁰ C to 20⁰ C (pick 6 temperature values in this range). In case $T_{c,i}$ is higher than 20⁰ C (this could occur during the summer), vary the heater temperature from 50⁰ C to 25⁰ C. Each time you change the heater temperature, wait until the temperatures stabilize. For each set of conditions, take the temperature and flow rate data once by pressing the **Record** button. Save the data either by using **Print Screen** or writing down the information by hand.

Switching to counter-flow operation

1. Set both flow rates to zero (it may take a minute or two for the flow rate readings to decrease). This will turn the heater off automatically.
2. With both flows at zero, press the **Power** button. Then press the **Counterflow** button to reverse the hot flow pump (the **Counterflow** button light should come on). After that, press the **Power** button again. Note: reversing the pump and switching between the co-flow and the counter-flow modes would not work unless the hot flow rate is zero.
3. Set the cold and the hot water flow rates to 3 L/min and the heater temperature to 50⁰C. Important: before proceeding further, double check that the flow is indeed reversed. *Remember that in the counter flow mode $T_1=T_{h,i}$ should be higher than $T_3=T_{h,e}$.*

Exercise 4. Counter-flow operation, varying cold flow rate

Keep the heater temperature at 50⁰ C and the hot flow rate at 3 L/min. Vary the cold flow rate from 1.0 L/min to 4.5 L/min (pick 6 flow rate values in this range). Each time you change the flow rate, wait until the temperatures stabilize. For each set of conditions, take the temperature and flow rate data once by pressing the **Record** button. Save the data either by using **Print Screen** or writing down the information by hand.

Exercise 5. Co-flow operation, varying heater temperature

Now keep both the hot and the cold flow rates at 3 L/min. Vary the heater temperature from 50⁰ C to 20⁰ C (pick 6 temperature values in this range). In case T_{cs,i} is higher than 20⁰ C (this could occur during the summer), vary the heater temperature from 50⁰ C to 25⁰ C. Each time you change the heater temperature, wait until the temperatures stabilize. For each set of conditions, take the temperature and flow rate data once by pressing the **Record** button. Save the data either by using **Print Screen** or writing down the information by hand.

Stopping the experiment

After you completed taking the data, turn the power off (press **Power** button) and press **Stop** button at the top of the application window.

Accessing saved data

After you have completed the experiment, you can access your data in a comma-delimited format using your **iLabs** account. For this

1. Log on to your **iLabs** account.
2. Go to **My Experiments**.
3. Highlight the experiment you want to access and press **Display Experimental Data** (see Fig. 5).
4. In the next window, check **Data Only** box and press **Get Records**.
5. You can now copy and paste you comma-delimited data (see Fig. 6) into Notepad or Excel.

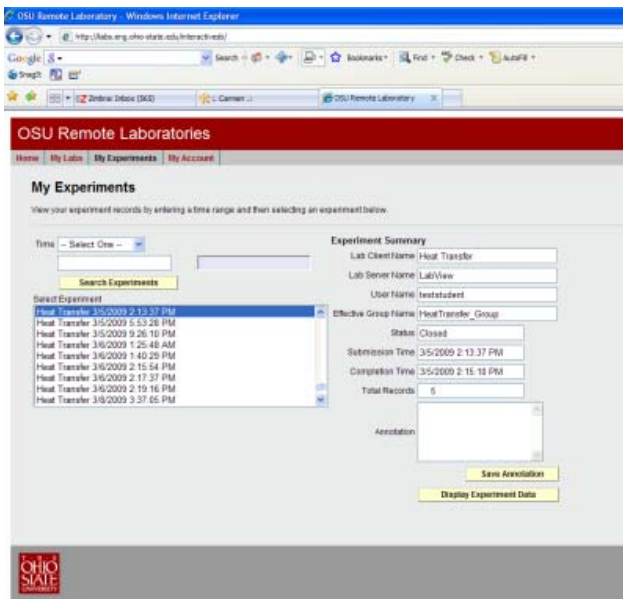


Figure 5: Selecting an experiment to view data

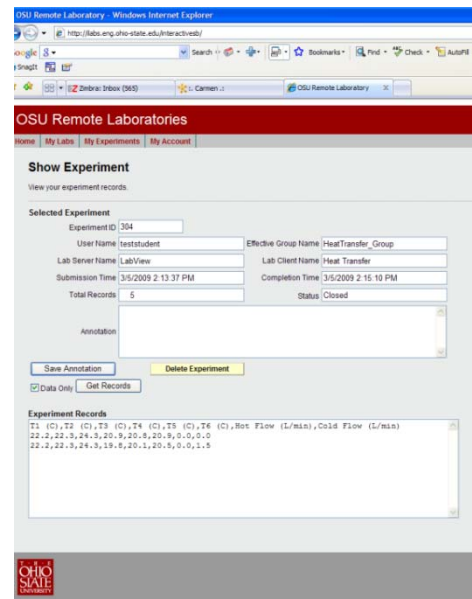


Figure 6: Data sets saved by iLabs.

Reducing and analyzing the data using Excel spreadsheet

1. (a) Using the data collected in Exercise 1, calculate the mean temperature values and the standard deviation (absolute measurement uncertainty):

$$\bar{T} = \sum_{i=1}^N T_i \quad \delta T = \frac{1}{N} \left[\sum_{i=1}^N (T - T_i)^2 \right]^{1/2}$$

Here T_i are temperature values taken at the same set of conditions and N is the number of measurements.

The temperature value measured at each location, averaged over multiple measurements, should be written as $T = \bar{T} \pm \delta T$. $\delta T / \bar{T}$ gives the relative measurement uncertainty in per cent.

- (b) Repeat this procedure for the cold and hot mass flow rates, \dot{m}_C and \dot{m}_H (in kg/s)
 - (c) Calculate the mean heat rate lost by the hot flow and the mean heat rate absorbed by the cold flow, q_C and q_H . Do this for each of the two heat exchanger sections, as well as for both sections combined (in W), and determine their uncertainties.
 - (d) Summarize the results in **Table 1**. Comment on the absolute and the relative uncertainty of your temperature, flow rate, and heat rate measurements. **Question 1:** Based on your results, can you conclude that q_C and q_H (for each section separately and for both sections combined) are the same? If not, can you explain why?
2. For every set of data collected in Exercises 2-5, determine
 - (a) Cold and hot flow mass flow rates, \dot{m}_C and \dot{m}_H (in kg/s)
 - (b) Heat rate lost by the hot flow and heat rate absorbed by the cold flow, q_C and q_H , for both sections combined (in W).
 - (c) Log-mean temperature difference for both sections combined, ΔT_{lm} (in °C).
 - (d) The overall heat transfer coefficient, U , for both sections combined. For this, you will need the flow contact area, A . Calculate the area as an arithmetic average of the inner and the outer surface areas of the stainless steel tube. The inner and the outer diameters of the steel tube are 8.3 mm and 9.5 mm, and the tube length in each of the two sections is 330 mm. The inner and the outer diameters of the acrylic tube are 12.0 mm and 18.0 mm, respectively.
 - (e) The heat exchanger efficiency (effectiveness), ε , i.e. the ratio of the actual heat rate to the *maximum* heat rate that can be transferred for given flow temperatures and flow rates. Again, do this for both sections combined.

3. For every set of conditions in Exercises 2-5, calculate
- Reynolds and Prandtl numbers, Re_D and Pr , for the cold and the hot flows. For the cold flow in the annulus, use the hydraulic diameter (see Section 8.6 of the text). Determine whether the flows are laminar or turbulent, and whether the flows are fully developed or not (thermal entry, combined entry?). Summarize the results in **Table 2**.
 - Choose an appropriate heat transfer correlation and calculate the Nusselt numbers, Nu_D , and convection heat transfer coefficients, h , for the cold and the hot flows.
 - Calculate the overall heat transfer coefficient, U . **Question 2:** How significant is the effect of conduction through the stainless steel wall on U , compared to convection?
 - Calculate the heat capacity rates for the cold and the hot flows, C_C and C_H . Calculate $C_{\min} = \min(C_C, C_H)$, $C_r = C_{\min} / C_{\max}$, and $NTU = UA / C_{\min}$.
 - Using the effectiveness-NTU methods, calculate the heat exchanger effectiveness (efficiency), ε .
 - Using the effectiveness-NTU methods, predict the efficiencies of the co-flow and the counter-flow heat exchangers consisting of *four*, rather than two, identical sections.
4. Make the following **9 plots**:
- Experimental q_C and q_H vs. \dot{m}_C for co-flow and counter-flow operation (Exercises 2 and 4).
 - Experimental q_C and q_H vs. $T_{h,i}$ for co-flow and counter-flow operation (Exercises 3 and 5).
 - Experimental ΔT_{lm} vs. \dot{m}_C for co-flow and counter-flow operation (Exercises 2 and 4).
 - Experimental ΔT_{lm} vs. $T_{h,i}$ for co-flow and counter-flow operation (Exercises 3 and 5).
 - Comparison of experimental and theoretical U vs. \dot{m}_C for co-flow and counter-flow operation (Exercises 2 and 4).
 - Comparison of experimental and theoretical U vs. $T_{h,i}$ for co-flow and counter-flow operation (Exercises 3 and 5).
 - Comparison of experimental and theoretical ε vs. \dot{m}_C for co-flow and counter-flow operation (Exercises 2 and 4).

- (h) Comparison of experimental and theoretical ε vs. $T_{h,i}$ for co-flow and counter-flow operation (Exercises 3 and 5).

For plots (e-h), comment whether the theory agrees with the experimental results.

- (i) Theoretical ε for co-flow and counter-flow operation, for 2-section and 4-section heat exchangers. **Question 3:** Is the predicted efficiency for a 4-section heat exchanger higher or lower than for a 2-section heat exchanger? Based on the results shown in plots (e-h), do you expect the theoretical prediction to be accurate or not? Explain.

Reporting the results

Your completed assignment should contain a brief summary of the equations used for Parts 1-3, Tables 1 and 2, answers to Questions 1-3, 9 plots, and a printout of the Excel spreadsheet with the data sets, columns, and units clearly labeled.

Deadline: approximately 8 weeks into the quarter (TBA).

9.2 Project Timeline - Gantt Chart

Phase	Tasks	Task Lead	Start	End	Duration (Days)	Working Days	7/1/08	7/6/08	7/15/08	7/22/08	7/29/08	8/6/08	8/12/08	8/19/08	8/25/08	9/2/08	9/9/08	9/15/08	9/22/08	9/29/08	10/7/08	10/14/08	10/21/08	10/28/08	11/4/08	11/11/08	11/18/08	11/25/08	12/2/08	12/9/08	12/16/08
1	Preliminary Study	Graduate Student	7/01/08	9/02/08	64	46																									
1.1	study ilabs materials	Assistance from Kimberly Clavin and Jerry Kingzett	7/01/08	7/07/08	7	5																									
1.2	install ilabs on server		7/08/08	7/22/08	15	11																									
1.3	set up initial testing apparatus		7/23/08	8/11/08	20	14																									
1.4	create interactive interface		7/28/08	8/06/08	10	8																									
1.5	test remote capabilities		8/07/08	8/16/08	10	7																									
1.6	generate final report		8/16/08	8/25/08	10	6																									
1.7	transfer of information		8/25/08	9/03/08	10	8																									
2	Experiment Development	Jerry Kingzett	9/03/08	12/11/08	100	72																									
2.1	develop desired experiment	Assistance from Undergraduate Student, Kimberly Clavin and Faculty	9/03/08	10/22/08	50	36																									
2.2	purchase necessary equipment		10/01/08	10/05/08	5	3																									
2.3	build five set ups		10/05/08	11/10/08	37	26																									
2.4	create interactive interface		10/22/08	11/10/08	20	14																									
2.5	test operation		11/11/08	12/11/08	31	23																									
3	Documentation and Release	Kimberly Clavin	12/12/08	6/07/09	178	126																									
3.1	create experiment documentation	Assistance from Faculty Member	12/12/08	3/30/09	107	77																									
3.2	test on small # students		3/31/09	4/16/09	17	13																									
3.3	Fix errors, improve		4/17/09	6/08/09	62	37																									
4	Generate Final Report	Kimberly Clavin	6/08/09	6/30/09	23	17																									

Phase	Tasks	Task Lead	Start	End	Duration (Days)	Working Days	12/22/08	12/29/08	1/6/09	1/13/09	1/20/09	1/27/09	2/3/09	2/10/09	2/17/09	2/24/09	3/2/09	3/10/09	3/17/09	3/24/09	3/31/09	4/7/09	4/14/09	4/21/09	4/28/09	5/5/09	5/12/09	5/19/09	5/26/09	6/2/09	6/9/09	6/16/09	6/23/09
1	Preliminary Study	Graduate Student	7/01/08	9/02/08	64	46																											
1.1	study ilabs materials	Assistance from Kimberly Clavin and Jerry Kingzett	7/01/08	7/07/08	7	5																											
1.2	install ilabs on server		7/08/08	7/22/08	15	11																											
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3	Documentation and Release	Kimberly Clavin	12/12/08	6/07/09	178	126																											
3.1	create experiment documentation	Assistance from Faculty Member	12/12/08	3/30/09	107	77																											
3.2	test on small # students		3/31/09	4/16/09	17	13																											
3.3	Fix errors, improve		4/17/09	6/08/09	62	37																											
4	Generate Final Report	Kimberly Clavin	6/08/09	6/30/09	23	17																											

