An Experimental Process Course

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1 Introduction

In many industrial environments today an engineer is expected to perform tests or simple experiments. This will become ever truer in the future as more and more design is done offshore and outsourced to countries such as India and China. Consequently, it will become even more important for future engineering graduates to be familiar with testing and experimental procedures.

A typical engineering curriculum has a number of laboratory courses distributed throughout its four years to illustrate the principles associated with various courses such as solid mechanics, fluid mechanics, or thermodynamics. Almost all of the courses consist of directed experiments, which have been chosen and designed to ensure that a specific principle is clearly demonstrated. To achieve this objective the students are required to perform the test or experiment at a particular set of conditions using a specific collection of equipment following a given experimental protocol. Consequently, the students discover that the theoretical principle being examined can be observed in practice.

Such experiments also allow the students to determine the magnitude and influence of experimental errors, and therefore the need to keep these values within check if the principle being examined is to be accurately observed. In addition, this type of laboratory exercise also allows the students to obtain practice in technical communication, and the presentation of experimental results.

However, this type of laboratory experience provides students with very little opportunity to appreciate the principles and practices associated with designing, building, performing, and communicating an experiment from scratch. In particular, the ideals associate with the statistical design of an experiment and the selection of appropriate instrumentation are more often than not never addressed in an undergraduate engineering curriculum. In addition, issues of the development and implementation of a good experimental protocol, and the most appropriate presentation of data, are rarely taught.

To address all of these issues, while still at the same time exposing students to experiments that illustrate particular thermal and fluid mechanic concepts, the senior Thermal and Fluids Laboratory in the Mechanical Engineering Department at Manhattan College was redesigned. Originally, the Thermal and Fluids Laboratory was a one credit “standard” laboratory course, consisting of twelve directed experiments (six thermal and six fluid), but it has been redesigned to be a three credit (four hour long) course that consisted of eight directed experiments (four thermal and four fluid), a series of lectures addressing experimentation issues, and an experimental process project.

2 Background

Several efforts have been made over the years to improve the experimental experience that students obtain at the undergraduate level. With respect to teaching students about mathematical design of experiment concepts and statistical analysis Gleixner, *et al*.[2] and Munson-McGee[4] both introduced these elements into a laboratory course in chemical engineering. Equally, Lyons, *et al*.[3] has introduced the teaching of instrumentation and experimental practices into a mechanical engineering laboratory, while Cyr, *et al*.[1] has exposed students to open ended experimental process projects to promote creativity and innovation. However, there is no documented case of where all of the material and practices necessary to address a truly open ended experimental experience have been included in one class.

3 Course Structure

The structure of the redesigned Thermal and Fluid Laboratory is such that salient thermodynamic and fluid mechanic concepts are demonstrated experimentally, while providing the students with the knowledge necessary to understand and apply the background needed to undertake their own experiments from scratch. The directed experiments, which address the issue of examining thermal/fluid phenomena, also allow the students to gain additional experience at collecting, processing and presenting data, while the lectures and experimental process project emphasized the creation and execution of an experiment, in general.

This course is also divided, time wise, between a lecture component and an experimental component in that two of the four hours per week are used to cover lecture material (either as a single unit or as two one hour periods), while the other two hours run contiguously to provide enough time for the directed experiments to be performed or for the students to work on their experimental process projects. The experiment time slot is also occasionally used to demonstrate how to use pertinent software.

The grading of the course is almost divided evenly among the three components in that 40% is associated with the directed experiments (5% per experiment), 30% is for testing of the lecture material, 25% is assigned to the project (10% for the quality of the work, 10% for the written report, and 5% for the oral presentation), and 5% is for computer software assignments. The test and computer assignment components are associated with individual students, but, the experimental work is performed by groups of three/four students and this work is graded on a group basis.

3.1 Directed Experiments

The experiments associated with the directed experiments address issues of conduction, forced convection, transient heat transfer, and heat exchangers, in the area of thermodynamics, and venture meters, jet momentum, airfoils, and pipe friction in the area of fluid mechanics. In these experiments data acquisition, data fitting, and error analysis is emphasized along with creating a well-written short presentation of the experiment and its results. To engender good report writing the students are provided with a standard report and are required to use the format of that report for all reports submitted by them.

3.2 Lecture Material

The lecture material covered is broken down into five categories: the mathematical design of experiments, instrumentation, experimental practices, data analysis, and data presentation. The material is also covered in the order that it is needed to complete the semester long experimental process project, except for the data presentation material, which is covered at the beginning of the semester to ensure that the students can create appropriate graphs, charts, and pictures in the reports associated with the directed experiments. All of the lecture material is presented using PowerPoint slides, which the students have access to in Adobe Acrobat format but with some of the material excised to ensure student involvement in class.

3.2.1 Design of Experiments

The mathematic design of experiments material is designed to show why it is necessary to identify a correct collection of factors and factor levels to test, and to provide the student with the tools needed to create appropriate and efficient designs. The initial material addresses the issue of factor selection and the identification of any nuisance variables and noise sources. In particular, students are shown how “fishbone“diagrams can be used to focus on the parameters that may have an influence on a specific phenomenon, and how a non-dimensional analysis can further identify the salient variables that can then be used as the factors in an experimental study.

The concepts of a full factor set of experiments and experimental replications are then examined when factors and factor levels are combined to develop a set of experimental treatments. In addition, the issue of reducing the number of experiments by using a partial factorial set of experiments is also covered, along with the ideas of confounding and resolution. Other topics covered include completely randomized blocks, blocking including Latin and Graeco-Latin squares, nested experiments, split plots, and mixture experiments.

It is also necessary, at this point, to introduce the statistical analysis associated with determining sample sizes. However, the basic concepts behind sample size determination are familiar to the students, since these ideas are covered in the statistical quality control portion of the junior Manufacturing Process course, which the students take prior to the Thermal/Fluids Laboratory course.

3.2.2 Instrumentation

The instrumentation material is designed to provide students with enough background information to allow them to select and operate basic devices. A major portion of this part of the lecture material examines the operation of position measuring systems, since most instruments ultimately rely on displacement measurement elements. Other devices covered are associated with measuring velocity, acceleration, force, pressure, strain, fluid flow rates, and temperature.

Of all the physical principles employed by instrumentation used to measure mechanical phenomenon, only the four most common are presented: variable resistance (potentiometers and strain gauges), variable capacitance, variable inductance, and piezoelectric effects. In the area of fluid flow measurement, a number of devices are studied; these include constriction devices, drag meters, and reverse pumps/turbines. Finally, resistance temperature devices (RTD), thermistors, and thermocouples are examined with respect to measuring temperatures.

Finally, as part of the instrumentation component, basic instrumentation interfacing and signal procession are discussed. This includes issues such as ground loops, shielding, and filtering.

3.2.3 Experimental Practices

The experimental practices covered not only examine the procedures and tasks associated with performing experiments, but also, the design, construction, and operation of experimental equipment (other than instrumentation), such as elements needed to produce specific phenomenon, with a wind tunnel being the most obvious example. Also, in this respect, non-dimensional analysis concepts are revisited with regard to scaling experimental models.

The procedures associated with undertaking a well run experimental study, which are discussed in class, cover subjects such as the concept of single and double blind studies, treatment replication, and experimental protocol development. In addition, particular attention is given to setting up the equipment, instrument calibration, creating data collection formats, documenting the procedures involved, and recording salient equipment settings and primary data values.

Finally, the ideas behind data acquisition are presented. This includes how to use basic recoding devices such as digital voltage meters, and oscilloscopes as both setup devices and primary data acquisition systems. However, most attention is paid to computerized data acquisition systems, with an emphasis being placed on quantization of data signals, sampling rates, and aliasing. The preliminary data examination techniques of error analysis and outlier identification are also included in this material.

3.2.4 Data Analysis

The data analysis material covers the basic concepts associate with hypothesis testing primarily with regard to examining means; either the comparison of a mean to a specific value, a comparison between means, or the variation of means, using an analysis of variance (ANOVA), and associated *post hoc* tests. Variation comparison, however, is also discussed with respect to the chi-square test.

Regression analysis is also presented to show how relationships can be established between single or multiple factors and associated results. Specifically, single and multiple variable linear regression analysis and single variable non-linear regression analysis are discussed. The issue of the degree to which a specific regression is appropriate is addressed via the concepts of correlation coefficients and residual analysis.

The time needed to cover these statistical elements is not as significant as might be expected, because a large portion of the material is covered earlier in the junior Machine Design, and Manufacturing Processes courses. As a result of these classes, the students are very familiar with using hypothesis testing, binomial distributions, and normal distributions when they start the Thermal/Fluids Laboratory class.

3.2.5 Data Presentation

The topics addressed in the data presentation section of the lecture portion of the course are those of selecting an appropriate chart type, chart formatting, graph annotation, and data linearization. This material is presented with the aim of improving the student's ability to communicate data clearly and efficiently.

Chart types presented are pie charts, histograms, box and whisker plots, scatter graphs with and without error information, and multi-dimensional surface representations. With regard to chart formatting particular attention is placed on such matters as clear axis labeling, the appropriate number of decimal places used on axes scales, careful selection of lines and makers for gray scale images, the need to have a clear origin on a chart, etc. Finally, data linearization is discussed with respect to generating easy to read charts and identifying possible relationships prior to applying a non-linear regression analysis.

3.3 Experimental Process Project

The project portion of the course exists to provide the students with the opportunity to participate in an experimental exercise from beginning to end, and thereby discover how to apply the material learned from the lectures appropriately. Consequently, the projects assigned are reasonable simple, requiring minimal technical support, but with an emphasis being placed on the experimental process, which is expected to be employed correctly and rigorously. However, the projects are at a level of complexity that required the students to work in groups of three or four.

All of the experimental process projects require the students to identify three or four factors that have an influence on a stated phenomenon, and to identify a relationship that relates these factors to the magnitude of the phenomenon. Examples of phenomena studied are the strength of scones, the drag associated with drafting behind a truck, the heat dispersal within a room, and the noise reduction associated with a silencer.

The lecture material is then timed to provide the students with the procedures and practices needed for the particular stage of the experimental process at which they are expected to be. The order of the lecture material is therefore factor and level selection, experiment design, instrumentation selection, equipment design and construction, experimental practices, data accumulation, data processing, and technical communications.

At the equipment design and construction phase the students are expected to use standard materials such as metal, wood and plastic, however, a three dimensional printer is also available, which allows small models to be constructed and tested rapidly. This is specifically useful when models have to be built for wind tunnel testing.

Finally, at the time when the students are about to start performing their experiments a lecture on experimental ethics is presented where issues such as faking data, ignoring data, conflict of interest, human subject protocols, and confidentiality are examined via posed problems and case studies. The materials for discussion are provided to the students via the web prior to the class, with the expectations that the students will make themselves acquainted with the material before class. In class a “round table” is established and opinions are sought from the students with the instructor acting as moderator and devil’s advocate as needed.

4 Software Applications and Course Materials

The course is also designed to expose students to software applications commonly used in the experimental process; these being a data acquisition and processing package and a statistical data analysis package. In the case of the data acquisition software, LabVIEW is used and the students are given a very basic introduction to this software, such that they are able to create elements that can be integrated with a preexisting LabVIEW data acquisition module. In the case of the statistical software package, SPSS is used and the students are taught how to generate descriptive statistical information from a data set, and to analyze the data via chi-square and ANOVA tests. The students are also shown how to perform linear and non-linear regression analyses.

To help the students to become familiar with these software packages various materials are also made available to them on the web via Blackboard. These materials include instructions and guidance for those unfamiliar with LabVIEW and SPSS, and sample LabVIEW and SPSS files to illustrate how these programs can be used to acquire and analyze data, respectively.

In addition, Blackboard is used to provide the students with materials to complement the lecture and experimental process elements of the course. These include the lecture presentations, lecture notes, a sample directed experiment and an associated model laboratory report with annotation to help in the creation of equivalent reports, worked examples that covered various aspects of the lecture material, and sample tests. All of these materials are made available in Adobe Acrobat format.

5 Project Example

A good example of how the experimental process project works was the drafting experiment. In that project the students were asked to identify the factors that affected the reduction in drag associate with following closely behind a large vehicle, and to establish a relationship between the drag and the factors identified.

In this case the students identified three factors that they believed had an affect on the drag associated with drafting; these were distance behind the leading vehicle, vehicle speed, and trailing vehicle geometry. Since it was recognized that full-scale experiments could not be performed safely, it was decided to use a model of the system for testing in a wind tunnel. Consequently, the students then had to establish an appropriate scaling ratio based on good wind tunnel practices and a non dimensional analysis. Using this scaling ratio four trailing distances were then selected, along with three vehicle speeds (i.e. wind speeds), and two trailing vehicle types, resulting in a total of 24 experimental treatments, all of which were performed twice, which therefore required 48 experiments to be performed.

The students then designed the lead truck and following vehicles using the I-deas CAE software package. The lead vehicle was based on a Ryder truck and the two trailing vehicles were based on a Mini Cooper and a Toyota Rav4. Rapid prototyping files were then created from the CAE models and exported to a 3D printer. The resulting models were then placed in the wind tunnel with the trailing vehicle being attached to a sting, in the tunnel's working section that was connected to a drag meter, and the lead vehicle was placed at various positions upstream of the tunnels working section to simulate the different vehicle separations. The tunnel was then run at the different required speeds and the data was collected.

The subsequent statistical analysis involved performing an ANOVA and associate *post hoc* analysis using a Duncan Grouping approach. This clearly showed that all of the factors selected had an influence on the associated drag. A regression analysis was then performed that established a quadratic relationship between the wind speed and the drag, and the vehicle separation and the drag.

6 Discussion

This course has now run for three semesters and receives favorable responses from students as measured by course evaluation surveys performed as part of the department's continuing improvement scheme. Also, it is noted that during the semester the students are very enthusiastic with respect to the project, with the higher GPA student being involved with the more mathematical aspects of the project such as the design of experiment elements and the statistical data analysis, while the less academically inclined student are very involved in the design and construction of the experimental equipment and the running of the actual tests.

However, it is also noted that despite the extensive coverage of the design of experiments material, many groups either failed to apply the basic principles or misapplied those principles. Nevertheless these ideas eventually do become more concrete to the students as they begin to develop their experimental protocols and discovered that some factors are not being examined appropriately or that there is a paucity of salient results. Consequently, some groups have to rethink their project and formally apply the design of experiment practices.

The value of this course, however, will not become evident until the present group of students, who have experience this course, have been in the work environment for several years, and the employer and graduate surveys associate with this cadre of students have been returned to School of Engineering at Manhattan College. In the meantime, because of the favorable responses evidenced from the course evaluation questionnaires this course will continue in its present format with some minor changes.

Future changes to the course will be the addition of video presentations of how to use the various software packages. These will be developed using Real Player and Camtasia and once again will be made available to the students via Blackboard. In addition, lectures will be recorded using a screen capture of the PowerPoint presentations along with a voice over using Camtasia, thereby allowing the students to review the lecture if certain point were not appreciated sufficiently during the actual lecture. These lectures will be made available to the students two to three weeks after the actual lectures to ensure that the students will still have to attend class, if they wish to be up-to-date with the latest lecture materials. Finally, with the introduction of a required mechatronic course in the sophomore year, some of the instrumentation and data acquisition material will be remove from the course to allow more time for the discussion of experimental practices, error analysis, and experimental system design.

7 Conclusions

The experimental process elements within the redesigned Thermal/Fluids Laboratory have provided the students with an experience that was never available to them before. The preliminary feedback from the students who have now taken the course show that they appreciate the material presented and the opportunity to participate in a practical engineering experience. In addition, because of the additional emphasis on technical communication skills the students now produce better quality reports, in general. Consequently, the redesign of the course has been viewed as a significant improvement to the Mechanical Engineering curriculum at Manhattan College.

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