Operations Laboratory module on heat exchangers

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In the fall of 2011, Dr. Pfluger took a position as an Assistant Teaching Professor at Northeastern University in the College of Engineering as a part of the First Year Engineering Faculty with a focus on chemical engineering. In the summer of 2013, she developed and ran a faculty led Dialogue of Civilizations program to Brazil where she taught two courses that focused on Sustainable Energy Technologies and Brazilian Culture. This program has successful ran for 7 consecutive years gaining popularity among a variety of engineering students. She was instrumental in the development of the curriculum redesign of the Cornerstones of Engineering for the first-year program in 2014. In the fall of 2017, she moved into teaching full time in the Chemical Engineering department where she has implemented improvements in the Transport 2 Lab and Capstone 2 courses. Dr. Pfluger has also spent her time volunteering as Faculty Advisor for the American Institute of Chemical Engineers (AIChE) and ChemE Car student groups on campus. In 2018, the AIChE student group won Outstanding Student chapter for its numerous activities within the Chemical Engineering community both on campus, regionally, and nationally.

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Implementing Industrial Engineering statistical tools to enhance students' understanding of heat transfer for a Chemical Engineering Unit Operations Laboratory module on heat exchangers

Introduction and Background

As engineers, it is important to have statistics as part of the tools we use to solve problems of interest to society. Statistics support the creative process by collecting, analyzing and using data to make decisions, solve problems, and design processes and products. Specifically, for Chemical Engineering graduates, statistics are applied in a wide array of fields to determine process variables to make processes more energy and economically efficient. An example is in the Pharmaceutical industry where statistical tools are used to determine the need to speed up the drug-development process, and the Food and Drug Administration's (FDA's) expectations for the incorporation of the principles of quality by design (QbD) and process analytical technology (PAT) in process and analytical development [1]. In addition, employers of chemical engineering graduates require applicants to understand statistical tools prevalent in industry. Currently, statistics is not a required course in Chemical Engineering (ChemE) curriculum at Northeastern University. There is a need to teach and apply valuable statistical tools into the ChemE curriculum. However, the industrial engineering (IE) curriculum includes teaching a wide array of tools such as data analytics, statistics, operations research, and logistics among others with the main goal of devising efficient systems that integrate people, machines, materials, and information to make a product or service. One of the advantages of these tools is that they can be applied to a wide range of areas and industries like finance, healthcare, and manufacturing.

Statistics is an important area in IE since "the need for statistical thinking arises often in the solution of engineering problems" [2]. Statistics is the science of data, and as engineers we are always needing to make sense of data by summarizing and analyzing it. The field of statistics encompasses not only the analysis of data but also the collection, presentation and use of said data to help engineers make decisions, solve challenging problems, and design products and services [3]. So even though it is an area that's emphasized in industrial engineering, it is important to all engineering majors to have a basic knowledge on how to apply statistics for problem solving.

Therefore, there is a need for students to learn and implement statistical tools into Chemical Engineering courses which are currently being taught in the Industrial Engineering (IE) curriculum. This led to the interdisciplinary course module to implement IE statistical tools into a ChemE Unit Operations (UO) laboratory course at Northeastern University. Specifically, students applied hands-on and experiential learning to implement and analyze data using the statistical method Design of Experiments (DOE) to a ChemE UO laboratory module on Heat Exchangers.

Methods

A lot of a chemical engineer's work involves experimentation. DOE is a great tool that can help with the basics of planning efficient and effective experiments and then gives a methodology for analyzing the data obtained by such experiments. In DOE the experimenter changes controllable variables of the system or process and then analyzes output data to make inferences about which variables are significant and responsible for the changes observed, as shown in Figure 1 [2]. For that reason, DOE is a powerful tool when studying complex systems, such as heat exchangers.

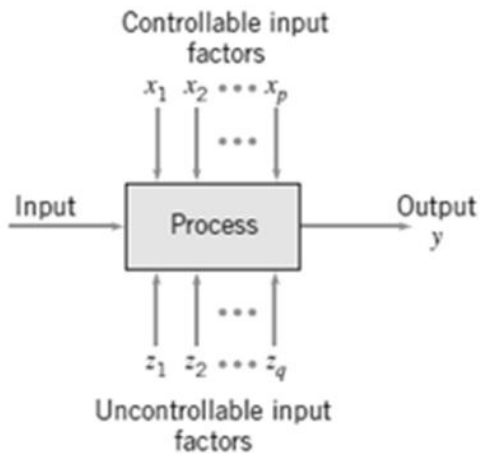

Figure 1*: Generic process to determine how factors can affect the output of a process.*

Using the shell and tube heat exchanger as an example process, as shown in Figure 2 [4], the input of the process would be the initial temperatures of the shell side and tube side streams into the system. Examples of controllable factors would be inlet cold and hot temperatures, cold and hot inlet flow rate, direction of flow (co-current or counter-current), and hot or cold in the shell or the tube side.

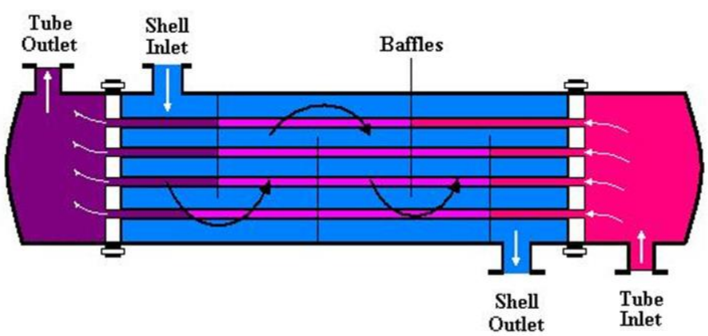

Figure 2*: Basic shell and tube heat exchanger with counter-current flow configuration.*

For this heat exchanger laboratory module, a factorial experiment was used, in which several factors of interest are varied together. In each trial or replicate of the experiment, all possible combinations of the factors are investigated. Students designed a 2^3 experiment (for a total of 8 runs). They chose 3 factors that would affect heat transfer in the system. After choosing their 3 factors they had to choose two levels for each factor. Both factors and levels chosen are dependent on heat exchanger system limitations. They chose those by looking at the system parameters from calibration tests run on the system performed the first week. Figure 3 shows the 2^3 factorial design used by students.

Run	Factor 1	Factor 2	Factor 3
1	0	0	0
2	0	0	1
3	0	1	0
4	0	1	1
5	1	0	0
6	1	0	1
7	1	1	0
8	1	1	1

Figure 3*: Example of a 2^3 factorial design*

Additionally, students had to replicate each run 3 times in order to have statistically significant results. For analysis, an IE professor created a tutorial video outlining step by step how to analyze a designed experiment using statistical software. Minitab was chosen since the College of Engineering (COE) computers have the software available for students and because Minitab is easy to use. The tutorial was made available to students through Blackboard and it detailed how to enter the data, how to analyze it by creating an ANOVA table and graphs, and then how to interpret such tables and graphs and translate it into meaningful insights about their experiment.

Pre-Experiment Survey Results

One section (N=19) of ChemE Unit Operations course were surveyed before the heat exchanger module to find out their previous knowledge of statistical tools. It was found that 71% of the class had never run a DOE before and 100% of the students surveyed had not performed a DOE statistical analysis in an engineering course. It was found that 29% (~5 students) had performed a DOE on co-op in industry. Proving once more that there is a need to teach these statistical tools in the ChemE curriculum. It was also found that only 40% said they believed the statistical tools would provide a more detailed analysis for heat exchanger conditions compared to simple heat transfer calculations in excel. This indicates that prior to learning and implementing these IE statistical concepts, ChemE students do not understand the benefits of IE statistical tools.

The students determined 3 variables to vary in their respective heat exchanger experiments to achieve their target temperature output as part of a real-world themed problem statement. They ran a full factorial 2^3 experiment with 3 replicates and then analyzed the experiment using Minitab, where they quantified main and interaction effects between variables and interpreted those results in the context of heat transfer theory.

Experiment Results

The heat exchanger module taught in the Chemical Engineering Unit Operations (UO) lab at Northeastern University has four heat exchanger systems in which groups of 4-5 students spend 3 weeks familiarizing and experimenting on one of the systems. This is taught as an open-ended laboratory course, in which students are required to develop their own experimental plan to study heat transfer. The first week the student team gets familiar with the heat exchanger system, runs start up procedures, performs calibrations on flow meters, and runs shut down procedures. The students are required to draw a Process Flow Diagram (PFD) of the system and determine variable limits that can be changed to affect heat transfer, which is system dependent. In previous taught sections of this course, students determined their parameters and variables, only evaluating how one factor affected heat transfer, such as flow rate of the inlet cold stream.

Implementation of DOE in this course, allowed students to more methodically develop an experimental design and evaluate interactions in parameters and variables not considered previously.

Students picked three variables and at two parameters to perform their DOE on the heat exchanger assigned to the team. In this UO laboratory, there are four heat exchanger (HEx) systems: G-Fin, Concentric Shell and Tube, Double Shell and Tube, and an Airflow Fin. Each system has different variables that were changed with varying parameters, which are detailed in Table 1.

***Table 1**: Types of Heat Exchangers with factor types and level details for the DOE.*

Heat Exchanger	**G-Fin**	**Concentric Shell and Tube**	**Airflow Fin**	**Double Shell and Tube**
Factor 1	Cold Inlet Flowrate (gal/min)	Hot Inlet Flowrate (lb/min)	Cold Inlet Flowrate (% Gate Height)	Direction of Flow
Level 1	3	14	70	Co-current
Level 2	15	34	30	Counter-current
Factor 2	Hot Inlet Flowrate (lb/min)	Direction of Flow	Hot Inlet Flowrate (Valve % Open)	Hot Water Configuration
Level 1	21.2	Co-current	60°	Shell
Level 2	54.7	Counter-current	30°	Tube
Factor 3	Direction of Flow	How Water Configuration	Area (# of Valves open)	Hot Inlet Flowrate (gal/min)
Level 1	Co-current	Shell	1	3.2
Level 2	Counter-current	Tube	2	4.8

The students then performed these experiments over 2 laboratory sessions and collected real time temperature data to calculate overall heat transfer and heat transfer effectiveness over the system. The DOE was used to evaluate the system effectives for the factors and levels measured using Minitab. Example of a student group report from the Double Shell and Tube heat exchanger are shown in Figure 5. Figure 5 details how students were able to apply the DOE to obtain data that was then analyzed using Minitab. This application of the statistical tools resulted in a richer and more in-depth analysis of the data, the students would have not been able to perform without this analysis.

It can be concluded that flow rate, flow type and flow direction are all statically significant; their respective p-values with error are 2.3x10^-9, 9.8x10^-5, 1.0x10^-5. Thus all main way interactions affect the temperature. In terms of error analysis, the "Adj SS" column from Table (2), was reviewed. The adjusted sum of squares, quantifies the amount of variation of temperature for each variable. The higher the SS i.e. the higher the variance, then the larger the error. Looking at the statistically significant variables, flow rate has the largest SS, with 32.5. This means that flow rate is the most volatile variable. To further investigate the effects each variable has, the factorial plots of the main way effects as shown in Figure 3, were analyzed.

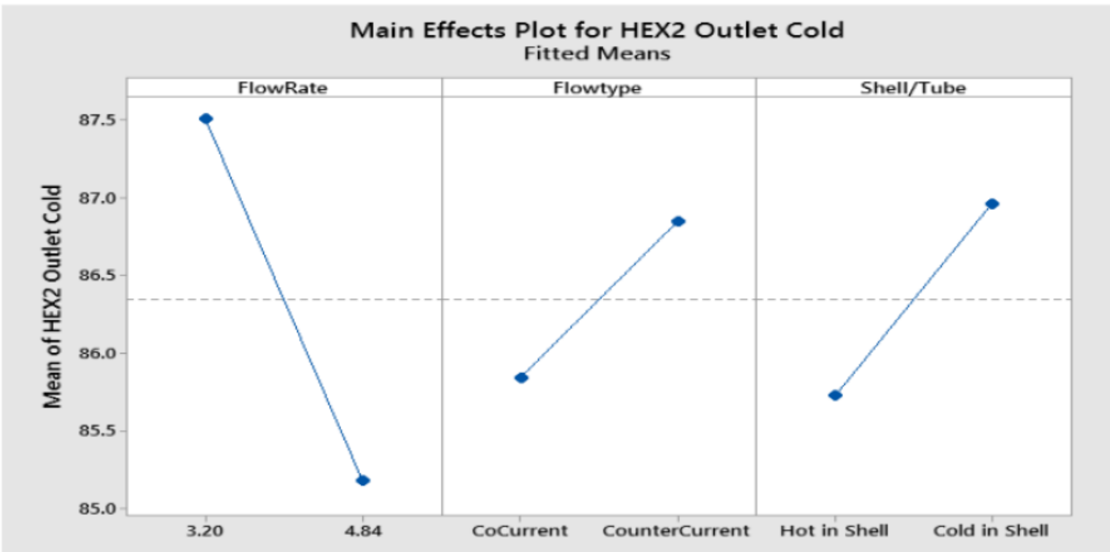

Figure 3: Main Effects Plots of the Outlet Cold Fluid for Each Variable

The main effects plots take the mean response temperature of each low and high level for each variable. Thus, this plot is able to show a positive or negative correlation. For flow rate, it can be assumed that there is a negative correlation since as flow rate increases then temperature decreases. Flow rate is directly correlated to the velocity gradient. The velocity gradient within the tubes is greater than in the shell due to the difference in area. It can be assumed that there is more turbulent flow within the pipes. While in theory, more turbulence usually leads to a higher heat transfer coefficient, it is not beneficial because it does not allow for adequate time for either cold or hot fluid to transfer heat. Overall laminar flow, with a smaller velocity gradient is preferred for this specific heat exchanger.

Figure 5*: Excerpt of student report on analysis of performing a DOE on a double shell and tube heat exchanger using Minitab*

A survey was performed after the students performed the DOE applied heat exchanger experiments and submitted a formal written report of their results. The students were asked questions using a Likert scale that went from 1 being very confident to 5 not confident at all. Table 2 details the responses from the students comparing the before (pre) and after (post) implementation of the statistical tools on the UO heat exchanger laboratory experiments.

***Table 2**: Responses to survey before and after performing DOE and statistical analysis on heat exchanger experiments*

Question	Pre	Post	P-Value
How confident are you using statistical tools (like DOE)	2.941	2.4	0.154
How confident are you using statistical software (like Minitab)	2.765	2.2	0.076
After performing a statistical analysis, how well do you believe statistical tools (performing DOE and analysis using Minitab) can provide detailed analysis of running conditions of a process?	2.059	1.8	0.48

To compare results, a two-sample t-test was conducted using Minitab to check if the differences observed in mean responses for the three questions shown in Table 2 were statistically significant. For these tests we assumed equal variances. The assumption of equal variances was revised by performing a two-sample variance test that showed that all three questions sets had equal variances with a 95% confidence (P-values: 0.364, 0.869, and 0.699 respectively). Even though the differences in mean responses shown in Table 2 did not prove to be statistically significant, which was most likely due to the small sample size of 17 and 10 responses for the pre and post surveys respectively, improvements in student's confidence about using DOE and Minitab increased in all questions.

Students also had positive comments about applying statistical tools to the heat exchanger experiments.

"It helped us gain an understanding of the results so that we could describe the results better."

"It helped make it easier to figure out which variables were important and how they interacted with each other to determine the output of the system."

"I think it allowed us to draw more relevant conclusions from the data, in a simpler format. It also made the comparison easier to follow."

"I thought it was helpful to get some experience with DOE software because it is very common in industry."

After performing the DOE and statistical analysis, the ChemE students found that the use of the IE statistical tools helped them determine variable interactions that they would not have discovered without the knowledge of these applications. The students commented that the DOE helped them understand impacts of heat transfer on certain variable conditions they did not expect. This interdisciplinary course module of applying IE statistical tools to a ChemE UO course demonstrated enhanced student understanding of heat exchanger experimental variables effect on heat transfer and how that data compares to theory. The understanding and knowledge of these IE statistical tools prepares ChemE students for their future careers in industry and research.

Next Steps

An important part of DOE is to check for model adequacy which is done by analyzing the model's residuals. This was not done during this pilot test with this one lab class but could be easily added to the Minitab tutorial for future labs. Another important part of DOE is to randomize the experiment runs to minimize any variability due to uncontrollable factors. That was not possible during this lab due to equipment set up and time constraints.

In the future more factors could be added to the experiment. Many students had situations where chosen factors proved not to be significant, so having them choose other factors and run the experiment again could be an option since they had enough time left for additional runs after they were done with the experiment. Adding more replicates (more than three) could also be done to add more validity to results.

We recognize that we had a small sample size of students to have any statistically significant results in our pre and post surveys. Performing this again with more sections could give us a bigger sample size to have more statistical validity in our conclusions.

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