Redesigning Thermodynamics Labs with a Design-Implementation Experience

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ABSTRACT

We redeveloped one of the second-year thermodynamics labs into a Stirling engine design lab. This paper discusses the project components and deliverables of this design-based lab. The five-part project, completed over the course of the semester, challenged students to design and build a functional Stirling engine, guided by specific technical and reflection questions. In addition, the project was designed with the intention to create a stress-free opportunity for students to fail, to ensure that student time-on-task was minimal and meaningful, and to provide meaningful teaching and learning opportunities for graduate teaching assistants.

This paper presents student feedback to the design-based lab, and lessons learned from the instructors and facilitators. Overall, this work provides insight into an active learning, design-based approach to a second-year thermodynamics laboratory (Design-implement experience, Standard 5).

KEYWORDS

Design-based learning, thermodynamics lab, active learning, Stirling Engine, Standards: 5.

INTRODUCTION

Second-year thermodynamics courses provide foundational skills for chemical engineering students that they will build on during the rest of their education. Laboratories makes up a large component of these courses, and are intended to help students visualize and gain a deeper understanding of the material taught in lectures.

We noticed that the lab components of these courses, many of which had not changed for many years, were set-up so that students could passively follow a lab manual to achieve pre-determined results, and then write a lengthy lab report that was disconnected from the rest of the course material. Students found the labs to be “make-work” projects that were time consuming and did not contribute to their understanding or application of the technical material.

At our University, a CDIO approach was used to redevelop one of the second-year thermodynamics labs into a Stirling engine design-implement experience (Crawley, 2014). The five-part project, completed over the course of the semester, challenged students to design and build a functional Stirling engine, guided by specific technical and reflection questions. Deliverables included thermodynamics calculations and reflections on their experience.

This paper will be structured as follows. First, a brief discussion of how the Stirling engine project aligns with the requirements of a CDIO design-implementation experience. Following this, will be a full description of the five-part project, as well as reflections from the course instructor and TA. The paper concludes with lessons learned and future work.

DESIGN-IMPLEMENT EXPERIENCES

The CDIO initiative is designed to support increased technical understanding of material, and also put students in real world engineering situations to foster professional skills. Students work through four stages: conceive, design, implement, and operate. For a full description, see Rethinking Engineering Education (Crawley et al., 2014). This paper will focus on the design-implement experience, which is standard 5 of 12 of the CDIO program, and is considered a critical opportunity to teach both engineering skills and technical fundamentals.

These experiences mimic the real world and set a foundation for disciplinary skills which help students in their early careers as engineers. They are designed to reinforce understanding of product, process, and system development, set a foundation for deeper conceptual understanding, and increase connections between technical material and professional interests. The design stage focuses on creating the plans, working drawings, or algorithms that describe the project. The implement stage involves transforming the design into the product solution. The experiences strengthen fundamentals through repetition, are active and experiential, and tend to be motivating and fun (Crawley et. al., 2014).

The CDIO conference proceedings showcase many examples of successful design-implement projects. Kontio et. al., 2017 found improved student satisfaction and self-esteem, deepened understanding of material, and professional growth including communication. Vo et. al., 2017 found the experiences to improve self-learning, problem solving, communication, teamwork and knowledge acquisition, and in Piironon et. al., 2017, students felt more prepared for careers in the workplace or in research. Design-Implement experiences are one of the CDIO standards, and they are distinct in their requirements (Crawley et al., 2014):

- Resemble engineering practice in the field of the discipline
- Are realistic enough to challenge students when relating theory to practice
- Develop working modes relevant for students' professional development
- Are aligned with a set of explicitly formulated learning outcomes primarily related to – Integrating, applying, and reinforcing disciplinary knowledge – Developing engineering skills, such as product, process and system design and implementation skills – Developing personal and interpersonal professional skills, such as teamwork and written, oral and graphical communication
- Emphasize and assess these learning outcomes rather than the project goals per se
- Include aspects of design, implementation, and verification
- Are open-ended and allow alternative paths to alternative solutions
- Are fully integrated into the curriculum

Other Considerations to Foster Student Learning

In addition to the design-implement criteria, other factors were taken into consideration in the design of the experience. Specifically, we will discuss three main principles that we aimed to achieve in the project execution: stress-free opportunity to fail, student time-on task and teaching assistant training and mentorship.

Stress-Free Opportunity to Fail

In increasingly complex technical environments, learning to manage, embrace, and learn from failure is increasingly important (Marinovici 2005). Traditionally, in design-implement experiences, the difficulty is chosen so that success is possible if the work is done well, but finding this level of difficulty has been a challenge for previous researchers (Vo, 2017).

This project chose a Stirling engine because it relates to the primary technical components of the course, and is an interesting project. However, the task of building a Stirling Engine is quite challenging for second-year students, and we did not want students to perceive a non-working engine as a failed learning experience (Marinovici 2005).

For this reason, we designed our assessments to help students understand the difference between product performance and learning performance. We did not give credit for fully working engines, and instead gave credit for each step of the design process. While ultimately engineering students must learn to build working designs, we opted to give students a more interesting design task, and remove the stress of complete functionality. Students were expected to complete a Stirling Engine, that is, they were expected to procure or build and assemble all components of the engine. In their meetings with other students and the instruction team, students were expected to describe the functionality of each component, discuss what was not working in the engine, and suggest modifications that could fix the problems. To give credit to teams with working engines, we had a competition with prizes.

This non-traditional assessment helped students understand the primary learning outcomes for this project were to solidify knowledge and increase confidence through the application of theory in a practical project. It also provided an opportunity for students to learn that it is possible to experience positive learning benefits even if a product is not functional (Vo, 2017).

Student Time-on-Task

One of the challenges of design-implement experiences as mentioned in Crawley et al., 2014, is that students have competing demands on their time, and time on task for any project must be carefully monitored. Lichtenstein et al., 2010 further state that the demands of an engineering curriculum often force students to choose between acquiring practical skills and other enriching experiences.

There was concern if too much time was focused on building a functional engine, students may feel overwhelmed by the design aspect of the project and would lose sight of the connection to the technical material. To prevent this, students were given worksheets each lab session that helped focus their attention for that working period, as well as explicitly make connections back to the material from lectures. These worksheets were completed collaboratively with their team, which further encouraged students to reason, explore, and reflect on the project, an important aspect of design-implement experiences (Crawley et al., 2014).

Teaching Assistants Training and Mentorship

To further assist in student construction of knowledge, teaching assistants (TAs) were given training to help them support and mentor students in the project. A training workshop was developed for the TAs to help with the Stirling Engine concepts. During the semester, several of the TAs assembled a Stirling Engine of their own to compare to the students designs. The instruction team met informally to discuss specific technical content and mentorship strategies.

DESCRIPTION OF STIRLING ENGINE PROJECT

The first simple engine which used heat from fire to produce work is credited to Thomas Savery in 1698. Despite utilizing energy in the form of heat, that heat was not converted to useable work for tens of thousands of years. In this project, students were given a few lab sessions to accomplish this goal by creating a Stirling engine that will do work to raise a quarter. Their challenge came from the constraint in time, budget (and therefore the use of rudimentary materials) and minimal amount of heat. The act of designing and testing the device gave them the opportunity to analyze the conversion process using concepts learned in thermodynamics and provided valuable hands-on experience.

Students were assigned to teams of 4-5 students for the design project. Each lab section had 100 – 125 students registered. The teaching team consisted of the course instructor, an undergraduate student teaching assistant, and 5 – 7 graduate student TAs.

Description of the Five-Part Project

Lab 1:
The end goal of this lab session was for the student teams to come up with the preliminary design of their Stirling engine. For the last 20-25 minutes of the lab, the teams were directed to present their design in a "Network" of 2-4 other student teams.

During the lab, the students watched a classroom demo of a store-bought Stirling engine rigged up to raise a quarter. During the demo they recorded the necessary data to calculate work done on the quarter, heat released by the heat source and thermal efficiency of the Stirling Engine. The worksheet completed in the first lab session consisted of questions about the theory of the Stirling engine, calculations of the classroom demo, and finally descriptions of their preliminary design. After deciding on their design, students completed a worksheet regarding the safety hazards and mitigation strategies for their design. They had to think about the safety hazards present during the construction of the engine (depending on what tools they were going to use) as well as the hazards in the heat source chosen (if there were any).

Completion marks from this lab session came from the Stirling Engine worksheet and the safety worksheet.

Lab 2:
The end goal of this lab session was to have the first design built. For the last 20-25 minutes of the lab, the teams met with their network to discuss their progress.

This lab session was primarily unstructured building time for the students. We provided some basic materials needed such a balloons, cardboard, wires, tools, etc. and the students were also encouraged to bring their own. The only worksheet for this lab session was about safety hazards. Lastly, before leaving, groups completed a peer evaluation for their group members.

Completion marks from this lab session came from the safety worksheet, testing their design, and the peer evaluation.

Lab 3:
This optional lab session was provided as unstructured building time for the students. This session had no deliverables, so the students just focused on completing their engine.

Lab 4:
The end goal of this lab session was for students to perform a preliminary test of their machine in their networks.

In the lab session, teams had to complete a worksheet, which consisted of specific and reflective questions about their design process, as well as descriptions of the final Stirling engine design and sample calculations for amount of heat transfer from their heat source. Finally, they needed to update their safety hazards and mitigation strategies if their design had changed from last time.

Completion marks from this lab session came from the design analysis worksheet, the safety worksheet, and testing their design.

Lab 5:
This was the final lab session of the semester. This is when the final testing of the Stirling engine took place!

The groups tested their engine right away in the beginning of the lab. Right after testing, they got started on the thermodynamic analysis worksheet which had to be completed before the end of the lab session. This worksheet consisted of thermodynamic calculations for their engine, the PV diagram of a Stirling cycle, and a reflective analysis. They also had to update their safety hazards and mitigation strategies if their design had changed from last time. Also, the groups needed to show their bill of materials sheet along with the receipts to ensure they did not pass the budget. Lastly, the groups were required to complete another peer evaluation, but they had one week from the final session to complete that.

Completion marks from this lab session came from testing the final design, the thermodynamic analysis worksheet, the safety worksheet, showing the bill of materials, and the peer evaluation.

Exams:
An exam question on the Stirling Engine was included in both the final exam and the midterm exam to evaluate student learning. The midterm exam took place after the first Stirling engine design lab and before the second. Class average on the midterm exam question was 60%, which indicated that many students were not understanding the application of the course concepts to the working Stirling Engine. Class average on the final exam question relating to the Stirling Engine was 75%, indicating that the students became more comfortable with the concepts as the term progressed.

Using the Stirling Engine Project as Design-Implement Experience

Overall, the Stirling Engine Project was a great case study application of a design-implement experience. Below, in Table 1, a mapping is showing of the activities in the Stirling Engine Project to the essential attributes for design-implement experiences as outlined by Crawley et al., 2014.

Table 1. Mapping of Stirling Engine Project Activities to CDIO Guidelines on Design-Implement Experiences (Crawley et al., 2014)

Essential Attributes of Design-Implement Experiences	**Application in Stirling Engine Project**
Resemble engineering practice in the field of the discipline	• work collaboratively in group, and work with deadlines • design solutions for open-ended engineering problems • use a variety of tools • safety training
Are realistic enough to challenge students when relating theory to practice	• students required to use appropriate knowledge and skills to formulate, analyze, and solve engineering problem (ie. build Stirling engine)
Develop working modes relevant for students' professional development	• develop interpersonal skills as well as team working skills such as leadership and working with others • student had to work efficiently and manage their time in order to complete the worksheets within the lab session.
Are aligned with a set of explicitly formulated learning outcomes primarily related to: *– Integrating, applying, and reinforcing disciplinary knowledge* *– Developing engineering skills, such as product, process and system design and implementation skills* *– Developing personal and interpersonal professional skills, such as teamwork and written, oral and graphical communication*	• Most students had never heard of a Stirling Engine, so it was a learning opportunity where they got to research and learn more about it as they faced the challenge of building one. • Students reinforced their knowledge in every step from the planning to the execution, and finally the analysis. • Working collaboratively with colleagues and friends also improves interpersonal skills such as speaking and listening as well as supporting professional growth.
Emphasize and assess these learning outcomes rather than the project goals per se	• success of Stirling engine was not graded • the worksheets testing knowledge of theory were marked • students to focused less on making the engine work, and more on understanding the concepts behind it
Include aspects of design, implementation, and verification	• Creating a device that converts heat to work, such as a Stirling Engine, requires a plan, design, and execution. • Although not marked, the engines were also tested at multiple steps see if it could raise a quarter.
Are open-ended and allow alternative paths to alternative solutions	• Project was designed open-ended so the groups got a chance to research, discuss, and plan together • We also encouraged them to use their own materials, 3D print parts, etc. to create an engine any way they wanted
Are fully integrated into the curriculum	• This design project allowed students to get a apply the classroom theory to their hands-on experience of building an engine.

FEEDBACK AND REFLECTIONS

Student Feedback

When a significant change is made to a course, there are often many bumps and kinks to work out and student feedback can see a huge decline in the first year. The instructor teaching the ENGG 311 course had previously received scores on her end-of-year evaluation around 6.4/7.0. The first year of the Stirling Engine Project, her scores maintained a 6.0/7.0, which is still above the faculty average. This shows student perception of the new lab was very positive. Students were prompted to complete an online survey about their experience. Major results are highlighted in Table 2 below.

Table 2. Summary of Student Feedback

Question	**Summary of Responses**
Did the design lab help you understand the following course concepts?	90-95% of students responded "agree" or "strongly agree" on all questions: • Evaluating the efficiency of a power cycle • Performing energy balances on closed systems • Evaluating the maximum theoretical efficiency of a power cycle
What did you learn from the lab section?	48% said helped with course content 20% mentioned teamwork skills 15% learned challenges of design and complex problems
What could improve the lab component?	25% different building materials available 17% more guidance/ better TA support 20% no changes were necessary 5% more time 4% marks for a successful working engine
How many hours outside of scheduled labs did you spend working on Stirling Engine?	28% zero hours 51% 1-5 hours 13% 6-10 hours 0.7% 10-19 hours 3% 20+

One of the teaching assistants provided the following feedback comment, which is a good summary of the student feedback:

> When I went around and asked the students if they preferred this lab structure over our traditional labs, they unanimously agreed. They said this gave them hands-on experience which they found useful as an engineer in the making. They also said they feel like they learnt more doing this because they got to build a device on their own, do trial and error to fix their mistakes, and while doing so, they got to understand in depth what is happening. Some of the replies I got when I asked around were:
>
> *"I would have this lab over any of the previous labs I have done in engineering, this was a lot of fun and I actually feel like I learned something."*
>
> *"I think the best way to learn something is to do it, and this is exactly what this lab was. You really had to understand everything that was going on in order to make any changes".*
>
> *"Thank god you changed it for our year."*

From the instructor perspective, she observed students generally were having fun in the lab, there was always a high-level student engagement and energy in the room, and there was a higher rate of attendance. While working with the students, she was also able to observe those “aha” moments with respect to their understanding of energy balances on multiple systems that interact with each other. A colleague and previous instructor of the course, wandered through a few of the lab sessions and said, *“the students are very engaged in the projects, and are clearly enjoying the opportunities these sessions provide in creativity, design, teamwork, and the hands-on active learning.”*

Instructor and Teaching Assistant Reflections

At the completion of the course, reflections were gathered from the teaching assistants who facilitated the lab and the instructors. They were given the following questions for their reflection, but these were meant as prompters and they were not limited to these questions or required to answer each:

- How did it go?
- How did it feel?
- What worked well?
- What would you change?

Generally, the comments from the teaching assistants and instructors on *what worked well* fell into four categories: Learning Thermodynamics, Hands-On Experience, Level of Engagement, and Teamwork. In Table 3, we included sample reflections and quotes to highlight each of these four categories. Overall, the students seemed to have a good time and were able to apply the technical concepts they were learning in class. Generally, most teams seemed to work well together and benefit from the teamwork. Perhaps this was an outcome of having only completion marks associated with the worksheets, so there was less pressure on team members contribute towards getting marks and they were just able to focus on learning.

In terms of areas for improvement, the feedback focused on two main areas: more emphasis on technical concepts, and that not all team members were engaged. See a summary of comments in Table 4. Most of this feedback stems from the fact the lab was designed with team assignments for completion marks only. Although most students were engaged and motivated by the hands-on project in itself, this type of design allowed for some students to not participate and be “loafers” or “free-riders”. The feedback below also indicates that there would be opportunities for improvement in ensuring the students are able to apply the concepts they are learning in lectures to the labs with more thermodynamics problems required in the lab.

Table 3. Summary of TA and Instructor Feedback on What Went Well

What Went Well	Feedback from Teaching Assistants and Instructors
Learning Thermodynamics	I found it very exciting and highly related to the thermodynamics. This taught them patience and a life lesson that ‘failure is okay’ [while learning technical concepts], and that is something everyone needs to accept and learn from. First session about compression and expansion of gasses was really good. especially the calculations and questions part. I think after doing all calculations they could figure out the main concept of that part. The idea of practical implementation of what the students learn in class is great as it emphasizes the importance of the concepts taught class. Some students had “aha” moments with respect to energy balances on multiple systems that interact with each other.
Hands-On Experience	I think the best part about this design lab is the fact that students got hands-on experience with various building tools and collaborated with one other to try to build a functioning device; and that is what engineering is truly about. They learn how they should start a project (even by searching in YouTube) and make progress. Also, they learned other engineering knowledge like Mechanical and Civil engineering which was unique. It also paves the way for the students to picture how real life projects are being built starting from theory and going through the design phase and ending with actual construction.
Level of Engagement	High level of students interacting with each other. Watching the students so confused and annoyed in the first lab, to happily making a 2nd or 3rd prototype of the engine by the end really showed that they cared about this lab. High level of student engagement. High energy in the room.
Teamwork	Students have the experience to create an engine in a cooperative group, work together, find problems, collaboration and solving them. Very few groups had group dynamics problems (2-3 out of 55) The Stirling engine part were really interesting. It helped them to work in a group and improve their teamwork skill.

Table 4. Summary of Feedback on Areas for Improvement

Areas for Improvement	Feedback from Teaching Assistants and Instructors
More Emphasis on Technical Concepts	Several students asked me that they could be given some instructions how to make the engine? In my opinion, it would be good to remind them reducing the fractions and making it airtight, etc. If the students could find the chance to do the experiment themselves or provide a video to show a complete experiment procedure and make them to watch before, would help them to understand it more. Many students still struggling with energy balance concepts. I think if we could give them one question (related to thermodynamic and stirling engine) to solve at the end of each session would help them to find the relation between theory and practice.
Not All Team Members Engaged	There were some students who did not involve so much and did not collaborate with other members of the group but it was in minority. I had to ask my groups to go and take a look at the setup and some of them refused to do so. They just finished their worksheet calculation with the provided data. In my opinion, since it is just completion marks, I would have each student fill a worksheet (even before the lab) as oppose to a group worksheet because some groups just divided the work and not all the members were involved in filling the sheet.

DISCUSSION AND CONCLUSIONS

The second-year engineering thermodynamics labs were re-designed from a scripted laboratory exercise to a design-based experience.

The lab session deliverables were intentionally designed to give students a hands-on design experience, to specifically tie the design experience to the course material, to allow the students an opportunity to fail in a low-stress environment, to ensure that student time-on-task was minimal and meaningful, and to provide interesting teaching and learning experiences for the graduate teaching assistants.

Overall, the lab re-design was successful. Each lab session was designed with specific deliverables, including performing thermodynamic calculations learned in lecture and describing the engine in terms of the definitions learned in lecture. Students self-reported that this technique helped them understand course content. In addition, TAs and the instructor saw some “Aha!” moments when working with students in the lab. A question on the Stirling Engine was included in both the midterm and the final. Class average on the midterm question was 60%, and class average on the final exam question was 75%, indicating that student understanding increased through the semester.

The task of building a working Stirling Engine was suitably challenging for second year students. All of the students were able to build a Stirling Engine in the semester, however only 3 of the 55 teams were able to build a *working* Stirling Engine. In order to create an environment where students were safe to fail, (and to minimize the de-motivation that can happen from such a challenging task) completion grades were assigned for the completion of the engine, not its final performance. In addition, the instructor gave a “pep talk” on failure in the middle of the term. Student feedback did not seem to indicate that de-motivation from not being able to make the engines work significantly impacted their experience.

Student time on task was an important consideration in the design of the labs. Student feedback indicate the time spent on this project was reasonable. It was possible for teams to complete the project entirely in the 5 scheduled 3-hour labs. This is great for teams who cannot find time to meet outside of class, or students who would prefer to focus their time on other courses. On the other hand, the few students who spent large amounts of time outside of class (6 students reported spending 20+ hours) were students who were passionate and excited about the project. These few students who were excited about the project took to opportunity to 3D print components, visit welding shops, or develop matlab simulations of their machines.

A training workshop was designed for the graduate student TAs at the beginning of the semester. Student feedback indicates that the TA support was helpful, but it was not as significant a help as it could be. Recommendations for future offerings include:

- Ensure that several of the TAs assigned to this course have been involved it the Stirling Engine design course at least once
- Continue TA training workshop. Increase the focus on mentorship strategies.
- Require that the TAs build a Stirling Engine themselves with the students.

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BIOGRAPHICAL INFORMATION

Shiza Syed is an undergraduate student in Civil Engineering at the University of Calgary who worked with Dr. Johnston over the summer to develop the Stirling Engine labs and worksheets.

Robyn Paul is a first-year PhD student at the Schulich School of Engineering, University of Calgary where she also works as the team lead on all matters related to the engineering accreditation processes. Robyn recently completed her master's degree in engineering education where she studied engineering leadership development's impact on career success.

Monique Sullivan is a mechanical engineering graduate studying Engineering Education at the University of Calgary.

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