A Stirling Example of Incorporating Hands on Analysis of a Model Engine in Thermodynamics

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Abstract:

Thermodynamics is often seen as one of the more challenging courses in Mechanical Engineering, sometimes even being referred to as a "gateway" course. This difficulty, in part, owes to many of the concepts being harder to visualize for students than in a typical solid mechanics course, where a solid body can be readily referred to. To try and combat this perception, Dunwoody College of Technology has worked for the past six offerings to incorporate the analysis of a model Stirling Engine into the curriculum as a multi-stage project. Aspects such as the history and development of the cycle, taking physical measurements and relating them to a p-V diagram, and building and testing a regenerator are incorporated into the project.

This paper reviews lessons learned from administering the project in its most recent offering, along with some reflection on prior offerings. The authors will also present guidance on implementing the project and tying it into a typical Thermodynamics semester-based schedule. An anonymous end of semester survey was administered asking for both qualitative and quantitative responses. Findings for student learning as a result of participating in the project will also be discussed.

Introduction and Project Goals:

The Thermodynamics course at Dunwoody College of Technology is required for 3rd year Mechanical engineering students. While Thermodynamics isn't the student's first theory intensive course, having completed both Statics and Mechanics of Materials in their 2nd year; Thermodynamics has the reputation of being more abstract and challenging to understand [1], [2]. The effective teaching of Thermodynamics is an ongoing topic of study [3]. Here we bring some of those abstract concepts into the student's hands with an individual/partner project utilizing a model or toy Stirling engine. We assign the project when entropy is being studied, the chapter before gas-power systems are introduced. As a note, we deviate from the order of the textbook (Fundamentals of Engineering Thermodynamics, by Moran [4]) to introduce gas-power systems before vapor power systems to better tie into the project. We've found that students can more readily draw from their own experiences with automobiles, small engines, and commercial flying for these cycles as opposed to relating to the Rankine cycle. To provide some familiarity before the project is introduced, we use the model Stirling engine to demonstrate the ideal gas model and again when introducing the second law and Carnot's reasoning for a maximum efficiency of heat engines. Overall, the goal of the project is to help students learn several of the course objectives that are denoted by an asterisk below.

Course objectives (asterisks indicate objectives addressed in the project)

1. Evaluate the thermodynamic state of a fluid*
2. Apply the ideal gas law to determine the properties of a gas*
3. Apply the first law of thermodynamics to evaluate closed systems*

4. Apply the second law of thermodynamics to evaluate thermal processes*
5. Apply control volume energy analysis to evaluate steady state open systems.
6. Calculate entropy change in thermodynamic processes
7. Evaluate properties using computer software.
8. Analyze vapor power cycles.
9. Analyze gas power cycles*
10. Analyze refrigeration systems.
11. Explain the behavior of ideal gas mixtures and psychrometrics.
12. Apply energy balance to analyze systems*

In addition to the above, we had the goal of having the students practice writing short technical briefs. For each of the written portions of the project, the specific format was intentionally left open versus providing a document template to fill in. This approach was taken as it forced the students to consider document structure, what content is needed to convey the results in a concise yet complete manner. This reasoning for our approach is conveyed to the students. In a professional setting, you aren't often provided with a template to fill in.

The importance of project-based learning in education has long been recognized [5] and is a frequent topic of discussion in the field of engineering education. The specific evidence on the benefits of project-based learning is mixed in the literature. Findings range from it being "unlikely to see improvements in student test scores" [6] to significantly improving learning outcomes, based on variables such as subject matter, class size, and course type [7]. While there may be disagreement on direct increases in assessment methods such as exams, there is agreement on project-based learning's positive influence on student's attitudes toward the topic itself, longer retention of the material, and increased participation [6], [7].

Lastly, the Stirling engine was chosen for several reasons that are advantageous for our above goals. The temperatures required are safe and accessible with basic equipment found in the home or on campus. The cost to run the project is minimal (details in Appendix C), with an initial cost of approximately $63.00 and decreasing with each offering. Because the Stirling cycle and engine are esoteric when compared to other gas-powered cycles, it's unlikely that students have been exposed to the cycle before the course. Due to this, any learning related to the cycle can be attributed to the project itself, as there isn't any significant coverage in lecture or the textbook; two shorter paragraphs and an idealized pair of cycle diagrams.

Assignment details:

The project was structured to take place primarily over the second half of the semester. The assignment was broken into a series of shorter deliverables to provide opportunities for feedback, and an early deliverable was able to be revised to recover a portion of the missed points. In total, there were four deliverables, each averaging 25 points. The course itself is graded based on categories or specifications grading, i.e. each major component in the course must be completed to achieve the desired grade, so the importance of the project is clear from the beginning as one cannot pass the course without earning a minimum grade in the project category [8]. We have found this approach to be successful in making the students take each aspect more seriously as opposed to a traditional grading scale where an item such as a project worth 20% overall could be ignored near the end, at least in part. The other categories were Homework and Quizzes. Table 1 displays each deliverable and its description along with the class topic or activity occurring in the timeframe. Each project deliverable is expanded upon each in the section that follows. Full assignment handouts are contained in Appendix B

Table 1: Summary of deliverables and due dates for Thermodynamics project

Week	**Class Topic(s)**	**Description**
Week 6	2nd Law / Entropy	Project Assigned (during entropy discussion)
Week 10	Gas-Power Systems	Due: SolidWorks model of Stirling Engine
Week 12	Finishing Power Cycles	Due: History of Stirling Engine – p-V diagram
Week 14	Psychrometrics / Power Plant Tour	Due: Measurements and initial calculations
Week 16	Finals Week	Due: Final write-up and results

<u>Deliverable 1: SolidWorks model of Toy Stirling Engine</u>

The first project deliverable was an individual assignment that required each student to disassemble, measure, and model in SolidWorks the Toy Stirling engine shown below in Figure 1 (left-hand side). The example of a student made model is also shown in Figure 1 (right-hand side). We elected to use a gamma-style low temperature difference model. There are several reasons we require students to do this as the first deliverable exercise. First, 3D modeling generates interest and buy-in from the students as they get hands on experience with the engine and tend to find the exercise enjoyable; it should also be noted that it is emphasized that points are assigned for functional and dimensional accuracy, not aesthetic! As you can see in Figure 1, the students like to take it a bit further.

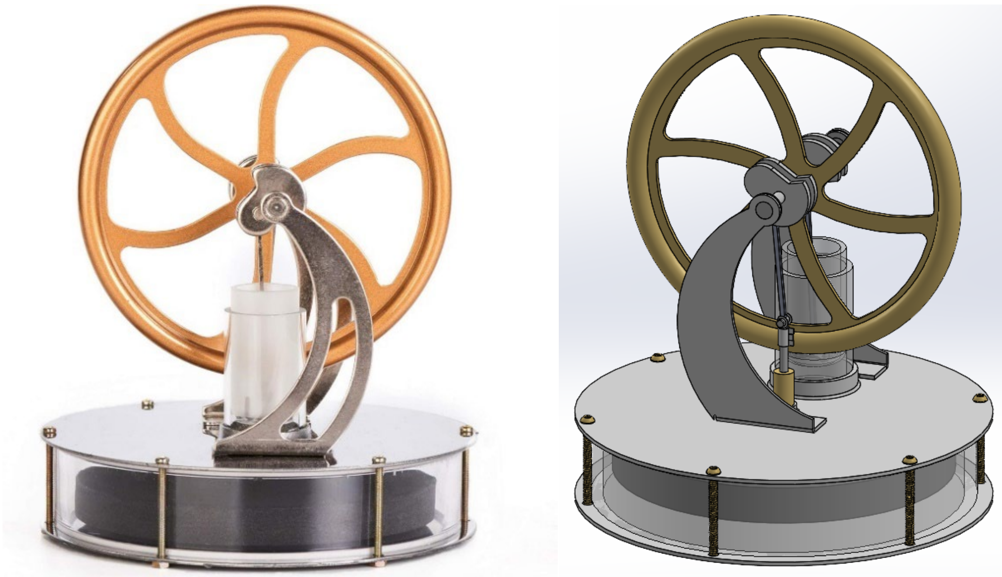

Figure 1: Image of Model or Toy Stirling Engine on the left-hand side. Each student was given a low temperature gamma style Stirling Engine that can run while heated with a hot water source. The right-hand side shows an example of a student made 3D model in SolidWorks.

Second, subsequent deliverables ask for a p-V (pressure-volume) diagram, which requires accurate values for the volume of the system at each location. During this exercise students describe experiencing an “aha” moment regarding the operation of the engine. This is often when students realize how little the overall volume in the engine is changing due to the power piston cycling up and down, along with the insight that the key to its operation is the shuffling of the air between the hot and cold plates by the larger displacement piston (Figure 1 for model). Additionally, we’ve found that manually rotating the engine around its shaft helps clarify for students why a real p-V diagram can’t be the rectangular shape shown for the ideal Stirling Cycle. Although we discuss and demonstrate the operation of the model in lecture, for many, the hands-on experience is required to truly understand.

The assessment of the model also provides some guidance on items that are important (examples numerated below)

1. Connection angle between two pistons on crank shaft is correct
2. Engine has correct volume and displacements with proper clearances
   - There will be a tolerance on this, but it should be reasonably correct
3. The pistons move between the appropriate positions (e.g. the stroke length or travel of the power piston is correct)
4. Mates between parts are properly done to allow for the model to freely rotate through all positions

Deliverable 2: History of Stirling Engine, Initial p-V diagram

At this point in the project, the students are asked to pair up with another student and explore the history and development of the Stirling engine, its early and modern uses, along with common configurations and identifying the configuration that was provided. This stage of the project has recently presented itself as a good opportunity to discuss the use of AI/LLMs. While there is a longer discussion contained in Appendix A, the authors' set aside a short time in lecture to go over how we approach its use and the potential downsides.

At this point in the project, we've provided feedback on their initial 3D models and confirmed their initial measurements. Using this model, we ask them to develop an estimate of the real p-V diagram of the toy Stirling engine. We also require them to show a few screenshots to indicate the status of the engine at key points in the diagram, e.g. a screenshot of the power piston and displacer piston orientations at the maximum volume state. A few examples of student generated p-V diagrams using the ideal gas model with dry air are provided below in Figure 2. This portion of the project is historically where a number of students struggle. While the students can directly determine the system volume at each location with their 3D model, calculating the corresponding pressure requires assumptions for mass of air contained in the engine and the temperature profile as the engine rotates. This deliverable is the first written deliverable where the students are asked to guide the reader through their process up to this point (Full details in Appendix B).

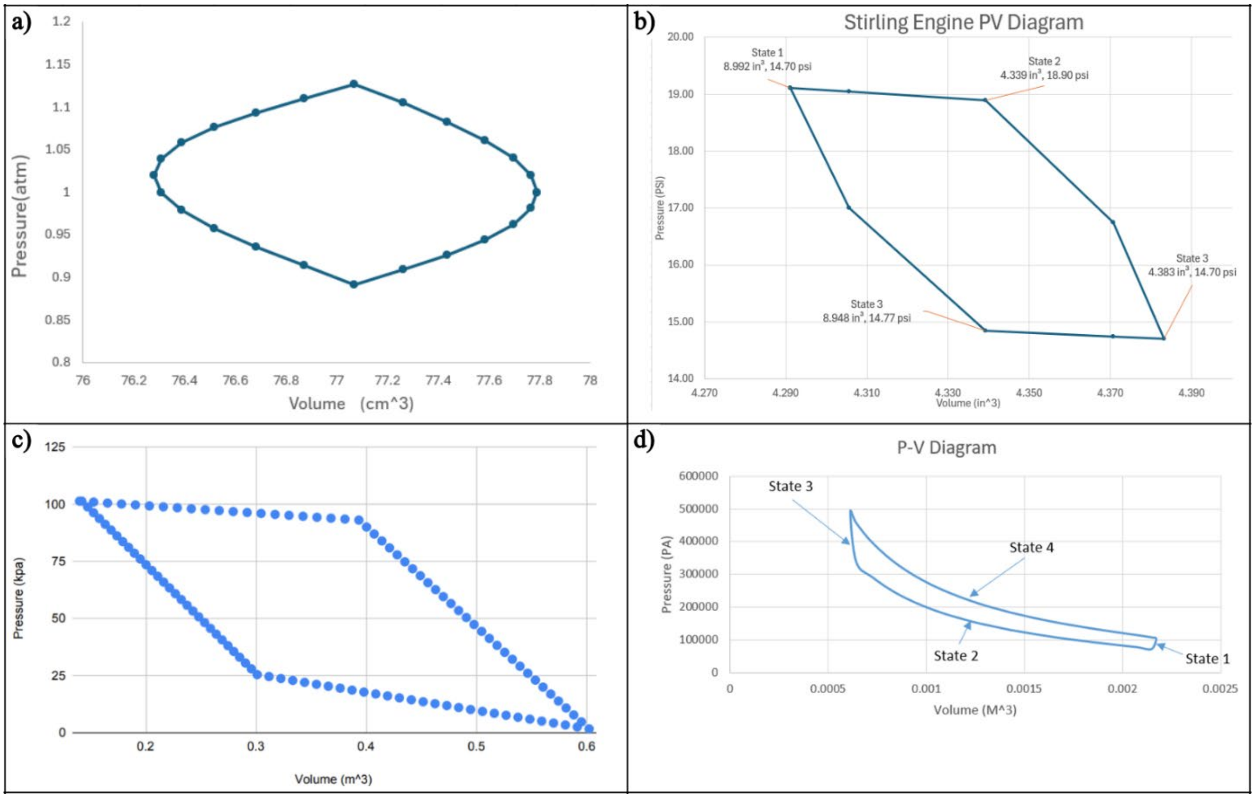

Figure 2: Examples of initial p-V diagrams constructed by project teams. **a)** This example shows a result where a student assumed a smooth temperature transition between the states on each of the temperature extremes, but not a smooth transition on either side. **b-c)** Teams in these examples assumed linear profiles between their chosen states; each diagram has a few errors, e.g. improper pressure, which feedback is provided on. **d)** Last example where the magnitude of the pressure is much larger than reality, which upon review resulted from a numerical error in the student's spreadsheet.

<u>Deliverable 3: Measurements and Initial Calculations</u>

The third deliverable asks students to do a series of initial measurements that help quantify some performance characteristics for the engine, primarily work output and input heat to estimate the operating efficiency. During one of the lecture periods, the author(s) lead the students in measuring the power output of a typical engine running on a hot cup of water. To accomplish this, a lightweight sewing thread is attached to the rotating shaft of the engine to enable the lifting of a small weight. The time taken to lift the weight over a set distance is noted and used to directly calculate the power being delivered. We've elected to use this method over more sophisticated methods such as connecting to a basic electric motor as it directly corresponds to the thermodynamic definition of work as given in the textbook used for the course [4]: "*Work is done by a system on its surroundings if the sole effect on everything external to the system could have been the raising of a weight*" and originally stated by Carnot [9].

To quantify the input heat rate, each group is supplied with an Arduino, a Type K thermocouple, and a MAX6675 Module to interface between them. Detailed guidance, along with a FAQ section, on how to interface the peripherals with the Arduino are provided with the assignment (see Appendix B). An example student plot of temperature versus time for several cases is shown below in Figure 3. This data and chart, along with measuring the mass of the water allows the students to determine the amount of energy leaving the water and going into the engine in a given time period. We recommend the students use a well-insulated container, e.g. a double-wall vacuum insulated mug to more closely follow the assumption of no heat loss through the walls of the container. We also ask the students to 3D print a single regenerator, i.e. heat exchanger to replace the larger displacement piston, to do some initial testing and to force the students to start this portion earlier as the final deliverable asks them to do three different configurations. In previous offerings this was left until later in the semester and students ran into issues, with some running out of time for testing. Examples of regenerators are provided in the next section.

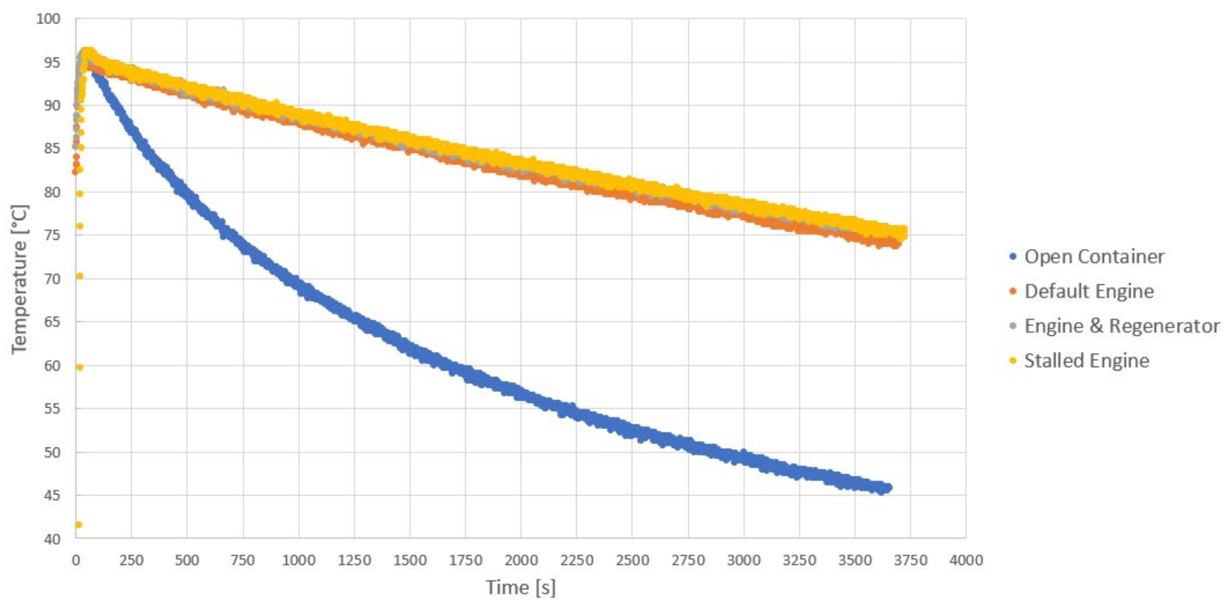

Figure 3: Temperature vs Time for several configurations. The open container case demonstrates the unconstrained heat transfer case. The Default Engine case demonstrates how the Stirling Engine acts as a controlled release of energy from the heat source, thereby enabling work to be usefully extracted. The Engine & Regenerator and Stalled Engine are additional cases to help elucidate how the engine and its operation impact the heat transfer.

The last portion of this deliverable asks the students to combine the heat transfer estimates with estimates of power to derive an engine efficiency. Two main approaches were taken to estimate the power output of the engine. These are enumerated below:

1. During one of the lectures, a small 3 g mass was attached to the axle of the engine. The amount of time it took to raise the weight over a distance of 1 m was timed and averaged over 5 tests. This testing resulted in an average power output of 1.2 mW. It should be noted that the power measurement is dependent on the mass used, with a single trial of a 20 g mass resulting in approximately 4.5 mW.

2. A differential pressure gage was installed and used to measure the pressure as the engine ran fully unloaded. A difference of 1200 Pa was measured between the minimum and maximum pressure while operating at a rate of approximately 3 cycles per second. If this pressure difference is used as the bounds on the p-V diagram and an area inside the diagram is calculated, an estimate of 3 mW is attained. With these measurements, the final p-V diagrams students construct can be adjusted to have realistic pressure differences.

The calculated heat transfer rates students presented varied between 10 & 20 W, depending on the particular container and starting temperature. Using the values above, the resulting engine efficiency, i.e. $\eta = W_{out}/Q_{in}$ varies between 0.006 % & 0.045 % on the high end. As we expect, there are a number of irreversibilities reducing this value well below the Carnot efficiency of $\eta_{carnot} = 1 - T_c/T_H$. As a check, we require the students to compare this to the Carnot efficiency and ensure it's not exceeded. Again, we review and provide feedback on calculations and results prior to the last deliverable presented below.

<u>Deliverable 4: Final writeup and results, regenerator results</u>

The final deliverable tasked the students with writing a cohesive document summarizing their efforts throughout the semester and what they've learned during the process. One additional element was added, which is designing and 3D printing three configurations of regenerators using the provided steel wool or another material as the mesh and testing the speed of the engine. A low-stakes competition to see which group could attain the highest unloaded RPM was conducted at the end of the semester, which many students tend to appreciate. Some of the grading criteria were flexible points for going more in-depth on an area of interest to the team. For example, a couple of groups measured power with the regenerator installed. An example set of results are provided below in Figure 4. As we can see, this group was able to increase the speed of their engine from the default configuration from 140 RPM to 320 RPM. Additionally, Figure 4 shows two of their regenerator configurations. Figure 5 shows an example of a final p-V diagram; much improved from the typical initial p-V diagrams that were illustrated in Figure 2.

Figure 1: Steel Wool Regenerator

Figure 2: Steel Mesh Regenerator

Assum. Heat Transfer	15 W			
Assum. Work / Cycle	0.0016 J/Cyc			
Configuration	**Peak Engine Speed (RPM)**	**Estimated Peak Work (mW)**	**Estimated Peak Efficiency**	**Efficiency Increase from Default**
Default Engine	140	3.73	0.025%	+0%
Steel Wool	320	8.53	0.057%	+128.6%
Hybrid Wool/Mesh	220	5.87	0.039%	+57.1%
Steel Mesh	220	5.87	0.039%	+57.1%

Figure 4: Example results from a student report.

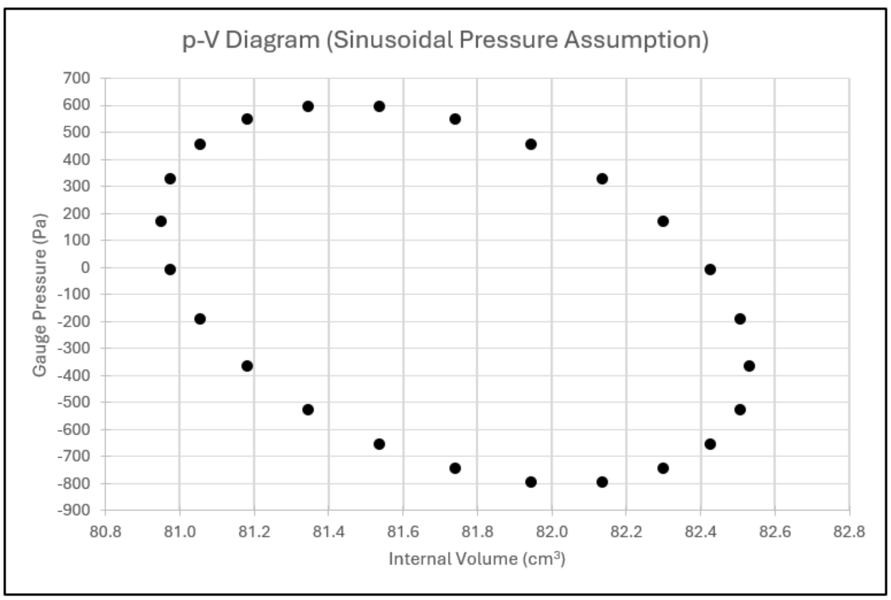

Chart D-1: p-V diagram for standard engine.

Figure 5: Refined student p-V diagram for final deliverable.

Assessing the project effectiveness with student feedback:

The students' perception of the project and its effectiveness in helping them achieve the course objectives was measured quantitatively and qualitatively with a survey at the end of the semester. The anonymous survey was optional, but all students present on the day it was administered completed it. A total of 15 responses were received from a total of 20 enrolled students for a response rate of 75%.

Below we have listed a sample of the open-ended responses with a summary of the quantitative results afterward.

<u>Student responses to “Do you have any comments that you’d like to share regarding the semester project? For example: suggestions for things to change or aspects you enjoyed, items you struggled with that we should be more aware of, etc.”</u>

1. “The project was very fun to complete and learn from as well”
2. “More outlined and direct instructions for assignment[s]”
3. “It would be nice to do the memo earlier in the semester and condense it down into one or two submissions. The memos were great and gave a thorough understanding of applied thermo, but I believe the last weeks of the semester did not allow enough time to fully explore alternative testing configs and builds of the engine”
4. “I really enjoy 3D modeling, so I particularly liked modeling the engine. I'd say the hardest part of this project is writing good content for the memo [deliverable] and formatting it properly”
5. “No comments, good project, change nothing!”
6. “I feel like there should be a better defined and instructed way of collecting the temp data. I didn't have much of an issue figuring it out, but I know many who did.”
7. “Stirling project was a huge time sink, and some things could be streamlined. Good: Optimizing engine forced students to understand material and apply it hands on. Bad: Arduino thermometer was a time waste, didn't feel like it helped learning. Memo [deliverable] format didn't make sense to me. A report may make more sense for this.”

The quantitative portion of the student survey requested students to anonymously rank the prompts in Table 2 on a 5-point Likert scale from 1 being strongly disagree to 5 being strongly agree [10].

Table 2: Compiled results from anonymous end of course project survey. Students were asked to rank their agreement to each prompt based on a Likert Scale: Strongly Disagree = 1, Disagree = 2, Neither Agree Nor Disagree = 3, Agree = 4, Strongly Agree = 5. Responses were averaged based on this numerical conversion.

Prompt	**Average**	**Std Dev.**
Analyzing a physical Stirling engine model, specifically constructing a p-V diagram, has helped me to understand how a real cycle differs from the perfect cycles presented in the textbook.	4.4	0.51
You are asked by a friend or relative (that has not had engineering training) to explain the operating principles of the model Stirling engine in simple or plain terms, do you feel confident in your ability to do this?	4.1	0.52

As Table 2 indicates, the students found value in working with the Stirling engines. No students ranked the first prompt below 4 and only one student ranked the second prompt as a 3. In general, the aspects of the project the students didn't enjoy or would change relate to the amount of work or how well defined the project is. As mentioned earlier in the initial assignment details, we deliberately were less prescriptive on certain elements to force students to consider layout and presentation; a factor we stress when initially presenting the project.

Lastly, Figure 6 summarizes the results of our asking which activity they stated helped them learn or understand the ideal gas model the best. The most frequently chosen category by a good margin is the weekly quizzes we give (referred to colloquially as Skills Exams by the students), with lectures being 2nd. Overall, beyond the quizzes, the rest of the activities were seen as equally useful to the students. In terms of the project, we see this response as a good opportunity to incorporate the toy engine more into the ideal gas section earlier on.

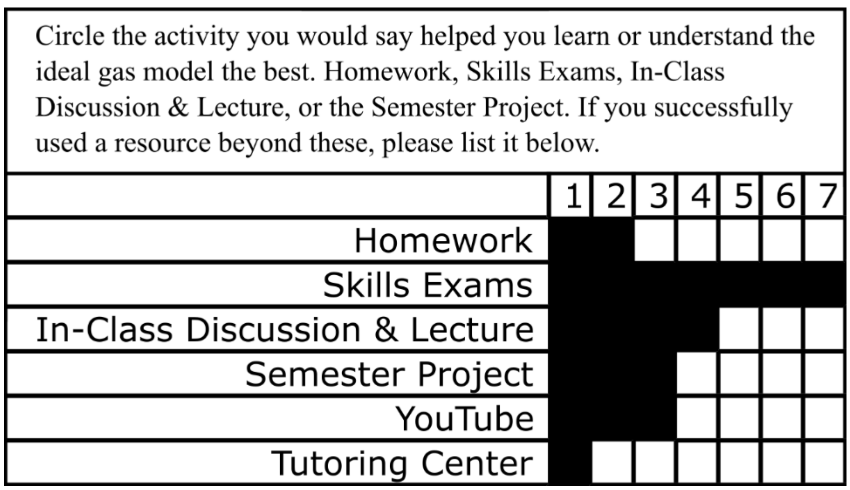

Figure 6: Compiled responses from anonymous end of course project survey. Most students chose one of the presented options, several chose an additional resource: YouTube & the on-campus tutoring center.

Lessons Learned & Project History:

While the current iteration of the project has been well received, there have been lessons learned from the current and past offerings. The incorporation of a Stirling engine project has been part of the course since Fall 2020. Below the authors share some of the project history and how it shaped the current project setup, along with some improvements we plan to implement in the next offering.

<u>3D Modeling</u>

In the first iteration of the project, the students were asked to design and model a Stirling engine. There was an accompanying page on Canvas that contained examples of successful builds from around the internet, along with other technical resources to help guide the students. Lastly, the authors made glass cylinders available to the students if they elected to use it for the displacement or larger cylinder. Overall, the 3D modeling portion of the project has always been well received, however, we moved away from designing the engine from the ground up as it was quite challenging for students to translate this model to a working engine, unless they were quite careful at reducing friction and keeping certain dimensions within a reasonable range; essentially copying existing designs. The task of building a functional Stirling engine as a project in a lab course dedicated to manufacturing is challenging in itself, with the cited paper stating only 50% of students were able to achieve a functioning engine in one semester [11]. As a point of comparison, our first offering in fall 2020 had one successfully operating engine, albeit impressive as this student wasn't working from given plans as was the case in the dedicated fabrication course!

The current project, which relies on an easily purchased toy Stirling engine is preferable for our purposes: hands on experience with the engine, getting a sense of the displacements and volumes involved, and analyzing the operation of the engine within safe and attainable temperatures. Details on the deliverable are given in Appendix B. The content of the deliverable works well, however, in future offerings, we see some value in having the students start and complete this portion a bit earlier. This timeline would allow for more direct discussion with the students when Gas Power Cycles do get introduced.

<u>p-V Diagram</u>

Earlier versions of the project asked the students to do a full idealized cycle analysis utilizing Python. However, we shifted away from this approach fairly quickly as it wasn't well received and seemed to detract from the learning of the fundamental principles of the cycle itself. Relying on Excel, a tool which all students would benefit from practicing more, more than serves our purpose. For example, instead of focusing on understanding the relationship between pressure, displacement volume, speed, etc., students were spending time on coding details and debugging. Further, a truly idealized analysis required the students to veer fairly far away from the "real" p-V diagram that we were actually seeking. We would suggest keeping the analysis of the cycle itself fairly basic as we've done here so the big picture isn't lost. This more simplified approach also enables more rapid and directed feedback to the students.

<u>Temperature Measurements & Data Collection</u>

While there are always going to be some students that struggle with getting the hardware setup for the measurements; those students also benefit from getting another exposure to Arduino and interfacing sensors. Over the years, the amount of guidance and up-front documentation has increased, which we recommend giving as much as possible in terms of tips, tricks, and instruction here. From our perspective, the point of the project wasn't the struggle through this section, but the output is valuable to their understanding.

Technical Writeups

The open-ended nature of the writing portion of the project has always received mixed responses from the students. Over the years, we have provided additional resources for presenting graphs and making them readable in Excel, general guidance for what we look for when judging their writing, etc. We've tried to keep the guidance as straightforward and in plain language so it's easy to assess. A few examples are below:

Opening Paragraph

- Did you say anything helpful or meaningful to the reader? What is the document about?

Main body of document

- Clarity and accuracy: Was it complete and accurate? Is it clear that you understand what you are writing about? Was the length appropriate for the material being covered?
- Comments throughout document: Were your comments accurate and useful? Was the information valuable or mostly fluff that didn't contribute to the memo content?

Figures and Charts

- Points will be subtracted for lack of discussion of any figure / table placed into memo with no discussion. As a rule, a figure or table should never be included in a report or memo unless it is referenced in the text.
- Did you discuss what was learned?

While we recommend this approach, it does require more time investment on the grading side to give both technical and document structure feedback. Given this downside, we think it's valuable to the students and should be kept if able. There is typically a marked improvement between the initial writing and the final deliverable.

Conclusion:

Throughout this paper, our goal is to convey a low barrier to entry Thermodynamics project that can be readily adjusted to meet the needs of a particular offering. Since first incorporating the use of a Stirling engine in Fall 2020, we've made changes each year to improve student engagement and focus on learning the operating principles of the engine itself. Shifting towards making basic measurements, away from more sophisticated analysis has been well received and better meets our goals of understanding the process itself.

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Appendix A:

This appendix contains and continues the reasoning behind discussing the use of AI & LLMs in the project. I use the introduction of Deliverable #2 as an opportunity to discuss AI & LLMs, primarily as a discussion on their limitations and where their use may limit the students' learning. As described earlier in Assignment details, the students are required to provide a short writeup on the history and development of the Stirling engine. I've found that I need to directly address the topic as more frequently students are asking for guidance on policy or directly seeking out their use. Additionally, AI tools are being used by default since several major search engines provide a short summary as a top response before listing any other results. While there often is a small warning or caution listed below the initial result: e.g. "Auto-generated based on listed sources. May contain inaccuracies", it's easy to overlook.

To date, my discussion has started with stressing the importance of visiting the original source and confirming the information summarized by the tool. While some tools do provide a list of sites or links by default, one of the most popular tools ChatGPT at this time doesn't appear to have this default behavior and must be prompted to provide more primary sources. While the tools are continuously improving, I emphasize limitations on the complex computations side and their connection to "hallucinations" or false confidence when providing incorrect information [12], [13].

Lastly, there is a brief discussion on the downsides of relying on or offloading their thinking to their long-term learning [14], [15]. This author's advice was if you offload some aspect of your thinking or critical thinking, it will tend to atrophy, so be conscious of doing so. While not 100% analogous, I asked the students to think about how many phone numbers they know. This brief tangent from traditional lecture content has generated valuable conversation and students have expressed that it was helpful to address it directly since it can be challenging to navigate what are acceptable versus unacceptable or unhelpful uses of AI in the modern classroom.

Appendix B:

Note each of the deliverables below are as complete as reasonable. There are aspects omitted, typically specific guidance, for example how to perform some specific operation such as Pack-and-Go in SolidWorks that is useful to the student in the course, but would be too lengthy for here.

Thermodynamics Stirling Engine – Project Deliverable #1

This is an individual assignment designed to reinforce thermodynamic concepts by analyzing a model Stirling engine. This is the first of several project assignments in the course that determines your overall grade as shown in the syllabus and categories.

(20 pts) SolidWorks Model of Physical Stirling Engine & Matching p-V Diagram

This portion of the project is meant to give you a sense of the physical dimensions of the Stirling engine. Further, it will help you to approximately match the physical position of the engine with the states shown on your state diagram (see appendix for p-V diagram). You will need to carefully disassemble and measure dimensions, so use a caliper. Requirements are below. The entire assembly will be submitted on Canvas using the "pack and go" feature in SolidWorks. The rubric for this portion of the project is below in Figure 7.

1- Connection angle between two pistons on crank shaft is correct
2- Engine has correct volume and displacements with proper clearances
    - There will be a tolerance on this, but it should be reasonably correct
3- The pistons move between the appropriate positions (e.g. the stroke length or travel of the power piston is correct) – note the power piston is the small piston and the displacer is the larger piston
4- Mates between parts are properly done to allow for model to freely rotate through all positions

Note: You'll be using your model to help construct a p-V diagram based on the physical engine and show the position of the model at a series of points to illustrate and step the reader through the diagram in the main body of the text.

Thermo Stirling Deliverable #1

Criteria	Ratings					Pts
Assembly (Pack and Go)	4 pts All parts assembled	3 pts Most parts assembled	2 pts Some parts assembled	0 pts No Points, completely missed		4 pts
Part Interferences Present	2 pts No parts are interfering with each other in the model	0 pts Parts interfere with each other in model				2 pts
Number of items (1 - 4) from list done correctly in SW Model Section	14 pts All Items done correctly	11 pts 3 of 4 done correctly	7 pts 2 of 4 done correctly	3 pts 1 of 4 done correctly	0 pts None	14 pts
						Total Points: 20

Figure 7: Deliverable 1 Rubric

Thermodynamics Stirling Engine – Project Deliverable #2

This is partner assignment designed to reinforce thermodynamic concepts by analyzing a model Stirling engine. This is the second of several project assignments in the course that determines your overall grade as shown in the syllabus and categories. The memo and the appendices should be submitted as a single word document. The rubric for this portion of the project is below in Figure 8

(10 pts) Brief history and background of the Stirling Engine (approximately 1-2 pages)

It should, at a minimum, contain the information below. Make sure to properly cite sources. Wikipedia is a fine place to begin, but I expect you to go beyond that and not to cite it directly.

- What are the basic types or configurations and what type is the one you were provided
- Invention and early use and applications

(10 pts) p-V Diagram & Matching Positions of Modeled Engine

- Use your model to help construct a p-V diagram based on the physical engine and show the position of the model at a series of points to illustrate and step the reader through the diagram in the main body of the text. Also make sure to indicate the direction of rotation through the cycle.
- While you have submitted the full SolidWorks assembly, I still expect you to utilize that model in this writeup to provide the reader with a good sense of the Stirling Engine and its dimensions. Remember, you are using the written portion to guide the reader (me) through what you've done and demonstrate that you have gained familiarity with the engine.

(10 pts) Grading for technical writing quality and memo layout

This portion of the grade is determined by how well you present the requested items. The document should be tied together with some explanation. If it is hard to follow, you will not get full credit as an important part of engineering is communication. See the "Engineering memo format.pdf" on Canvas. Because I am asking you for approximately 2 pages of history, you should expect a longer memo than the 2-3 page guideline, but don't forget to use appendices.

Note: The students were provided additional resources for guidance on judging writing and layout expectations in the "Engineering memo format.pdf" document.

Thermo Stirling Deliverable #2

Criteria	Ratings				Pts
Brief history and background of the Stirling Engine (approximately 1-2 pages) It should, at a minimum contain the basic types or configurations, and some information on invention and early uses / applications. Make sure to properly cite sources. Wikipedia is a fine place to begin, but I expect you to go beyond that and not to cite it directly.	10 pts Everything that was requested is included. The length is appropriate. Visuals should also be present to help explain configurations / history. Citations are done as requested. Overall, is well written and gives the reader a good sense of the history and background.	7.5 pts Missing one of the requested items and still well done. Or all items are present, but the writing / clarity isn't enough for full credit or the length is not sufficient, etc.	5 pts Half credit, at this point and below, it is clear that minimal effort was put into this part of the report.	0 pts No Credit	10 pts
Relative positions of power piston and displacer accurately shown with snapshots of model and Indicate where they match on the p-v diagram (this can be shown with numbers). Also direction of rotation is clear. Note that you will be indicating positions that don't align exactly with the shown chart as your engine smoothly progresses through the cycle, so consider that when indicating locations. Hint, your pistons are attached to a rotating shaft!	4 pts Sketches of the relative positions are clear and match the physical engine. The position at each state matches accurately to the p-v diagram as requested.	3 pts Sketches are harder to follow or positions aren't clear of how they match physical engine. Still matches fairly well with p-v diagrams (what can be understood)	2 pts One of the two elements requested is missing	0 pts No Points, completely missed	4 pts
p-V Diagram	6 pts The diagram and corresponding numerical values of pressure and volume are reasonable and accurate. The diagram is fully labeled (axis titles, units, points of interest, etc)	4 pts The diagram and corresponding numerical values of pressure and volume are reasonable and accurate. The diagram is missing some elements for full credit.	2 pts The diagram is present, but lacking many elements	0 pts No Points, completely missed	6 pts
Written narrative or explanation to guide the reader through memo Also, the overall formatting of the document is being judged with this rubric item (Points can be removed if all of the sections aren't included)	10 pts There is sufficient written guidance to follow the presented information. You may assume that the reader has a working knowledge of thermodynamics. Overall, formatting and organization of the report is well done.	5 pts Written guidance is not easy to follow or contains errors in explanation. May not be clear what assumptions were used.	0 pts There is no written guidance to follow the calculations or guidance is very hard to follow and detracts from report		10 pts

Total Points: 30

Figure 8: Deliverable 2 Rubric

Thermodynamics Stirling Engine – Project Deliverable #3

I've also put helpful notes at the end of this assignment

The rubric for this portion of the project is below in Figure 9.

- Turn in raw data and spreadsheets. Be reasonable with formatting data and work, but that is not the focus here. Get the data submitted. If you are doing hand calculations, scan them and include them as well.

This deliverable is focused on initial measurements to help ensure that you are able to get the hardware initially setup and measurements done correctly. I will provide detailed feedback / guidance on submission.

Deliverables:

1. Temperature vs Time measurements of the water (i.e. heat source) for the following cases:

- Open container measurement (the unconstrained heat transfer case)
- Default Stirling Engine Configuration - i.e. out of the box configuration
- Stirling Engine with Regenerator installed
- Stalled Engine (i.e. the engine is sitting on top of the water source, but isn't spinning)

*Note, for each of the above, I would recommend a minimum of 30 mins of recording time

2. Calculated rate of heat transfer from the heat source in each of the above instances (Hint, remember you can draw your CV however you want)

3. Estimated rate of work output for the Default and Regenerator installed configurations

- Most phones now have a "Slow Motion" feature that will allow you to count the number of revs in a given time period
- Upload those videos as well
- As a check, make sure you aren't estimating a rate of work that is higher than the theoretical maximum
    - Remember to use the p-V diagram you made in the previous deliverable.
- Utilize the data collected in class of the engine raising a known mass.

Files, Hardware, and initial Guidance

[This section is omitted from the paper as it is quite lengthy and simply provides guidance on setting up the Arduino hardware, printing out the regenerator, and collecting and saving data]

Frequently Asked Questions: (I show one below as an example)

Do I need to use all of the steel wool provided?

No! Remember, the regenerator is a heat exchanger, so the mesh needs to be sparse enough for air to flow easily through it, otherwise you won't gain the benefit of it.

Thermo Stirling Deliverable #3

Criteria	Ratings		Pts
Temperature Vs Time Measurements	10 pts Full Marks	0 pts No Marks	10 pts
Calculated Rate of Heat Transfer	5 pts Full Marks	0 pts No Marks	5 pts
Calculated Efficiency	5 pts Full Marks	0 pts No Marks	5 pts
			Total Points: 20

Figure 9: Deliverable 3 Rubric

Thermodynamics Stirling Engine – Project Deliverable #4

The rubric for this portion of the project is below in Table 3. You should now have the following from the previous deliverables:

- From Deliverables #1 & #2
  - All the relevant dimensions of the engine: e.g. min volume, max volume
  - An "oval" shaped p-V diagram - remember this is a real engine and can't have a rectangular p-V diagram as it's attached to a shaft
- From Deliverable #3
  - A sense of the rate of heat transfer for several scenarios
  - A comparison of the work measured in class vs. the heat input you measured for the stock condition.

In this last deliverable, you are asked to use your measurements and calculations, along with some provided information to give a fuller picture of how the Stirling Engine performs. In deliverable #3, you were asked for the values, here you should present what you did in a clear way, along with the following

Deliverables:

- Write up what you did in Deliverable #3 and put those results in the memo
  - Make sure you are including what you learned! Include your observations about what changed when the regenerator was installed.
  - Remember to make use of appendices
- For this deliverable, focus on the following:
  - Optimize the regenerator to increase angular velocity. I suggest using three configurations (Light fill, Medium fill, Dense fill)
  - Report the angular speed for each case (can use slow mo function on your phone or a laser tachometer, if using video, take 10+ seconds to even out variations)
  - Estimate the efficiency of the engine in the above cases using your calculated values
  - Again, make sure you aren't estimating an efficiency above the theoretical maximum!
  - If time allows, we'll have a regenerator speed tournament one day in class. Install your optimal regenerator and be ready for some testing!

Table 3: Deliverable 4 Rubric. This rubric was too cumbersome to directly copy from Canvas in a single image. The Rating area has been reduced to just show the Full Credit Rating for each Criteria.

Criteria	**Full Credit Rating**	**Pts**
Writeup of Temperature Vs Time Measurements Note, for some of these categories, I can only gage reasonableness as I didn't have your exact setup and do the measurements myself. There is inherent variability and it would be difficult to audit every line in a spreadsheet	The writeup is clear and useful to the reader, providing good value, along with reasonable results	3 pts
Writeup of Calculated Rate of Heat Transfer Note, for some of these categories, I can only gage reasonableness as I didn't have your exact setup and do the measurements myself. There is inherent variability and it would be difficult to audit every line in a spreadsheet	The writeup is clear and useful to the reader, providing good value, along with reasonable results	3 pts
Writeup of Measured rate of work Summarize the work we measured in class.	The writeup is clear and useful to the reader, providing good value, along with reasonable results	3 pts
Regenerator Configurations List three configurations you used to try to optimize rotational speed. It may be listed by mass of steel wool added, gauge of steel wool, or some other designation.	Clearly described configurations. At least three were listed.	6 pts
Regenerator speed results	Results are measured in some way (tachometer, slow mo camera) and clearly presented.	3 pts
Efficiency calculations Note, for some of these categories, I can only gage reasonableness as I didn't have your exact setup and do the measurements myself. There is inherent variability and it would be difficult to audit every line in a spreadsheet	Method is clear and is based on calculations presented earlier, along with estimate of maximum efficiency	3 pts
Flexible points You may have decided to focus more deeply on one aspect or another These points are awarded based on the overall technical content of the memo - reasoning given in rubric comments	Full Credit	4 pts
Written narrative or explanation to guide the reader through memo Also, the overall formatting of the document is being judged with this rubric item (Points can be removed if all of the sections aren't included)	There is sufficient written guidance to follow the presented information. You may assume that the reader has a working knowledge of thermodynamics. Overall, formatting and organization of the report is well done.	5 pts
		Total Points: 30

Appendix C

This appendix provides additional details of total project cost. Table 4 illustrates the specific items used for the project, excluding the ABS filament used for the 3D printed regenerators. We excluded this cost as it's difficult to estimate since several students used their own printers and the remaining used the on-campus printers for minimal cost. Also note that we typically run this as a partner project and Table 4 represents the partner cost. In our program, each student purchases an Arduino kit in their 1st year but we include the cost here for completeness. Finally, we reuse much of the supplies aside from the natural attrition that occurs with parts being lost, damaged, or warn out.

Table 4: Initial Cost of Project Materials. Several of the items can be reused from one course offering to another.

Item	Brand	Vendor	Part Number	Cost
Model Stirling Engine	Sunnytech	Amazon.com	LT001	$40
Steel Wool	Homax – Rhodes American	Amazon.com	Various	$0.50
Type K Thermocouple	Weewooday	Amazon.com	Weewooday-Temperature Probe-01	$2.00 each (based on order volume)
Max6675 Thermocouple Module	Weewooday	Amazon.com	Weewooday-New supplies-SL121	$5 each
Arduino Uno Or Equivalent	Various	Amazon.com	Various	$15
Total Initial Cost	*Note most of the above costs are non-reoccurring			**$62.5**