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# Development of a Real-World Thermodynamics Course Project

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## Abstract

This paper outlines the development of a real-world based project in a thermodynamics course in a mechanical engineering program at a large university. In the first few iterations of the project, students worked in teams to analyze a combined power cycle. While this project gave students additional experience with thermodynamic calculations and required them to apply knowledge learned in class to new situations (vapor and gas power cycles were covered separately in lecture, but combined cycles were not explicitly discussed), the project was not strong in assessing ABET Student Outcome 2, "an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors." The instructor has worked to improve the project to better meet this student outcome and provide more thorough real-world context for the students. The university has an on-campus simple-cycle power plant that provides peak-shaving power for a local power company. Inspired by prior work presented at ASEE conferences, the project in this thermodynamics course was altered to assign students the task of convert the simple-cycle plant into a combined-cycle plant. Students in Spring 2023 completed a basic version of this project. In Fall 2023, students started the project by touring the on-campus power plant. Then students worked in groups to design a vapor cycle to integrate into an existing gas cycle to create a combined cycle. The project included formative assessments to help students learn more about the design process before completing summative assessment of a final report. In addition to teaching about the engineering design process, the format of the project also yielded a deeper understanding of the material.

## Motivation

At the 2022 Annual ASEE Conference, Andrew Lutz presented the Rankine Cycle design project that he created and implemented in class [1]. He used this assignment to assess ABET Student Outcome 1, "an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics [2]." For the project, students were required to design a Rankine cycle that met prescribed constraints. Per Lutz, "this project was designed to be open-ended, challenging, and contain no clear solution." In discussing how the project went, Lutz mentions how students went through multiple iterations of the design before arriving at a final design.

The author of this paper had previously taught two semesters of the thermodynamics II course, which focuses on thermodynamic cycles. Per the departmental-set ABET requirements of the course, Thermodynamics II was slated to assess ABET Student Outcome 2, "an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors [2]." Previous instructors of the course had assessed the outcome with an exam question, but the author wanted to introduce a project inspired by industry and incorporated more of the engineering design process. In the Spring 2022 semester, they introduced a project that was heavier on analysis than design, leaning the assessment more towards Outcome 1 than 2. After reading Lutz's paper about the Rankine Cycle design project, the author worked toward improving their course project to integrate portions of Lutz's project design. Each semester saw small improvements with the Fall 2023 iteration of the project being the most heavily focused on the engineering design process to date.

**Explanation to Students of the Engineering Design Process**

As the overall goal of the project was to assess ABET Student Outcome 2, which focuses on engineering design, the author structured the Final Technical Submission (report) using language from ABET's definition of engineering design. Additionally, the author provided an explanation of the engineering design process in the project documentation to create transparency with students of the goals and expectations for the project. Below is the explanation of the engineering design process as provided to the students.

*Overview: Engineering Design*
The technical submission of the project requires you to employ the process of engineering design.

Per the Accreditation Board for Engineering and Technology (ABET), engineering design is an iterative, creative, decision-making process that involves the following for the purpose of obtaining a high-quality solution under the given circumstances:

- Identifying opportunities
- Developing requirements
- Performing analysis and synthesis
- Generating multiple solutions
- Evaluating solutions against requirements
- Considering risks
- Making trade-offs

Through the process of engineering design, basic sciences, mathematics, and engineering sciences are applied to convert resources into solutions.

Engineering design is measured by ABET Student Outcome 2, which is "an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors."

Your group's performance on the technical submission will be assessed based on the criteria of engineering design as prescribed by ABET. Rubrics will be provided as appropriate throughout the design process with relevant performance indicators. Additionally, your group will be provided a table to complete that shows the changes you made to your cycle throughout the iterative process of engineering design.

*Final Technical Submission*

The Final Technical Submission will include a section dedicated to each of the following:

- ***Summary*** **–** Provide a cycle device diagram, T-S diagram, operating conditions and relevant performance data, and bill of materials for the final cycle
- ***Identifying Opportunities*** **–** outline the design goal and introduce relevant vocabulary (explain each power cycle, provide cycle device diagrams)
- ***Developing Requirements*** **–** outline the prescribed criteria and limitations of the design
- ***Performing Analysis and Synthesis*** **–** provide steps required for analyzing the cycle and selecting operating conditions. Provide all equations used in analysis. *Do not include the operating conditions in this section.*
- ***Generating Multiple Solutions*** **–** provide tables showing the operating conditions selected in each iteration of cycle analysis (see example technical submission and provided table file). Operating conditions that do not meet the system requirements should be highlighted red.
- ***Evaluating Solutions Against Requirements*** **–** for each solution, evaluate the solution against the requirements. Discuss the strengths and weaknesses of the solution. If the solution does not meet one or more of the requirements, discuss approaches to correcting the issue (which should be reflected in the subsequent solution). *At minimum, you must have three iterations. There is always a way to improve your design.*
- ***Making Trade-offs*** **–** Discuss any trade-offs made throughout the design iteration process. Discuss any other changes that were made throughout the design iteration process and why they were made.
- ***Considering Risks*** **–** For the vapor power cycle installation, discuss any risks or strengths for each of the following:
  - Public health, safety, and welfare
  - Global factors
  - Cultural factors
  - Social factors
  - Environmental factors
  - Economic factors

**Project Overview**

The assignments of the project spanned across the latter half of the Fall 2023 semester. The project included multiple deliverables with submission deadlines spread across the two months. Whether the specific assignment was completed individually or as a group is indicated in parentheses.

- Power Plant Visit (individual grade, class went together)
- Power Plant Visit Q&A assignment (individual)
- Technical Submissions (two checkpoints and one final submission) (group)
- Excel File for Calculations (group)
- Reflection (individual)

*Power Plant Visit*Mississippi State University has an on-campus power generation site. With two gas turbines, it is capable of producing 26 MW of power, which is integrated into the grid of the Tennessee Valley Authority (TVA). After first touring the facility in Spring 2023, the author brought the students of Thermodynamics II to tour the facility during class in the Fall 2023 semester. Students were able to see what a functioning power plant looks like and get perspective on what it takes to operate a facility.

*Power Plant Visit Q&A assignment*

Prior to the Power Plant visit, students were provided a list of questions to answer throughout and after the tour. The questions ranged from specific to the campus power plant to general information about power plants and considerations to be made in maintaining them. The goal of this assignment was to help keep students focused during the tour but also to get them in the mindset of the various considerations they would need to make and discuss in the latter part of the project. Specifically, some questions of the assignment were focused on "making trade-offs" and "considering risks" from the list of requirements for the engineering design process. Students completed this portion of the project individually. The questions and rubric for this assignment are provided in the Appendix.

*Technical Submissions*

The bulk of the project included the Technical Submissions. There were three Technical Submissions (two checkpoints and a final), with each adding more analysis and discussion leading to the final submission. For each submission, students were graded on the accuracy of their calculations and the relevancy and accuracy of their discussion.

Throughout all Technical Submissions, each group was working toward a final design of a basic Rankine Cycle to be integrated into an existing simple cycle power plant to create a combined cycle power plant. Operating conditions of the gas cycle were provided as well as operating parameters of the vapor cycle components. These conditions and parameters for the Fall 2023 project are provided in the Appendix.

As specified in ABET's definition of the engineering design process, the process is iterative, requiring the generation of multiple solutions that should be evaluated against requirements. Groups were required to show at minimum the data associated with three iterations of designing the Rankine Cycle. In all iterations, groups indicated results that were out of range of the system requirements. Such instances were not discouraged, as the iterative process allowed for refinement of the cycle to get all values within the specified range.

The first iteration was required for the first Technical Submission along with a discussion of results that were not within the specified range and what steps were going to be taken to get the value within range (i.e. which operating conditions were going to be changed and how). If a group's values were all in range on the first iteration, the focus was then optimization, and discussion included the steps to be taken in that process. Students were encouraged to structure their discussion based on the paragraphs required for the final technical submission. After submitting the first Technical Submission, groups received written feedback from the instructor.

Groups also had the option to schedule a meeting with the instructor to discuss the submission and feedback.

The second iteration was required for the second Technical Submission. The discussion on this submission included comments on the changes made between iteration one and two and if the changes were expected as well as plans for the third iteration.

The final Technical Submission included the results of the third iteration and the final discussion of the engineering design process. The final Technical Submission included all sections as outlined in the previous section of this paper titled Explanation to Students of the Engineering Design Process.

*Excel File for Calculations*

As the project by design was iterative, utilizing a spreadsheet to complete calculations was advantageous in addition to being in line with calculation software commonly used by practicing engineers. Groups were required to submit the Excel file used to calculate various values for the cycle such as the energy balances. The Excel was independent of a specific iteration, so any parameters for the Rankine Cycle could be entered, and the calculations would be completed. An additional challenge students had to overcome in creating the spreadsheet was handling units. As Excel does not innately account for units, students had to have a full understanding of how the various units throughout the analysis process interacted.

*Reflection*

Upon completion of the project, each student completed a reflection about how the project went. This reflection intended to encourage students to take inventory of what was involved in the engineering design process of the project and any strengths/weaknesses present for themselves or their groups. Additionally, as the author continues to improve the project from semester to semester, the reflections were helpful in determining strengths and weaknesses of the project design. The questions asked are provided in the Appendix.

**Discussion of Student Submissions**

*Power Plant Visit Q&A Assignment*

Overall, student submissions for this part of the project showed broad comprehension of what was shown at the power plant and showed that students were making the considerations that the assignment was designed for. The last question asked if there were any further questions about power generation or related material, and the responses here gave the instructor a good pool of topics to either integrate into lecture or the power plant tour in future semesters.

*Technical Submissions*

As the project was designed to assess the engineering design project, the results of the Technical Submissions were a large focus for the instructor on the success of this iteration of the course project.

One aspect of the Technical Submissions that was unique compared to typical assignments in their engineering courses was that values being out of the specified range on earlier iterations was not penalized. Such a process was an adjustment for some students, as many are accustomed to assignments with only one submission attempt. The answers must all be correct on the first try. In meeting with some students, the instructor ascertained that the "first iteration" presented was not the first as students had played around with numbers to start with to get values that mostly worked.

A common error for the first Technical Submission was incorrect math in the calculations. The instructor built a spreadsheet that would run the calculations for the cycle depending on certain input parameters from the students' proposed cycle. The instructor then compared the numbers that should have been calculated to compared to values that students presented. With multiple calculation errors, an unforeseen action item for many groups between iteration one and two was to correct issues in their calculations. Without the correct calculation process, changing parameters would be moot and would yield wrong results as well. In future iterations of the project, the instructor is considering a Pre-Technical Submission where groups can test their spreadsheet calculations. However, it may not be an issue to leave the first Technical Submission as-is and anticipate groups having issues to be corrected. In this case, a larger amount of time between Technical Submissions 1 and 2 will account for the extra time to correct any necessary calculations.

In both the first and second technical submissions, most groups had at least one calculated value outside of the specified range. While groups did have the required discussion, it was not as thorough as the instructor anticipated. Future iterations of the project should provide more structure and guidelines for what the discussion should include. Many discussion sections were lacking in intentionality of changes to be made to the cycle.

As the final Technical Submission was supposed to have all values within range, it was observed that many groups would end up with iterations "2a," "2b," etc. depending on how close their second iteration was to being within the requirements.

The content and quality of the final Technical Submission varied across groups, as was expected. With the course's current placement in the mechanical engineering curriculum, there was a mix of how many students had completed the college's technical writing course. Additionally, this project was probably one of the students' first experiences with a more in-depth engineering design project, so amateur data presentation and discussion was expected. In future iterations of the project, the instructor may provide more instruction on data presentation, but the focus will continue to be on exposure to the engineering design process.

*Excel File for Calculations*

Overall, groups did well in putting together the Excel file and met the expectations outlined in the project documentation. Some groups had excellent worksheet organization, and others showed a need for additional practice. The instructor is considering incorporating more Excel-based assignments prior to the project to give students more experience in organizing worksheets. Examples could also be provided.

*Reflection*

A common theme among responses was that the project allowed students to gain a deeper understanding of thermodynamics calculations. This makes sense, as the format of the project provided much practice in this area. One added bonus of the project was that students got to see how the different cycle parameters affected other areas of the cycle. Students remarked how being able to observe how the devices and parameters interacted with each other strengthened their overall knowledge. The focus on design in addition to the typically expected analysis helped grow conceptual understanding.

When responding to the question, “Which parts of the project were explained well? Which parts of the project were unclear?” many students had little to share and praised the organization of the project documentation. Common suggestions were better clarity on what calculations the Excel sheet was supposed to accomplish. Such comments were anticipated, and they will be taken into account in future iterations of the project.

**Conclusion**

The latest iteration of a project in a thermodynamics course included a heavy focus on assessing ABET Student Outcome 2, which is centered around the engineering design process. The engineering design process was defined and explained in project documentation to students. The bulk of the project that focused on the engineering design process included three Technical Submissions. Each Technical Submission required the results of an additional iteration of selecting operating parameters for a Rankine Cycle. Additionally, the final Technical Submission required a discussion of multiple factors of the engineering design process. Overall, the course instructor is pleased with the outcome of the project for the Fall 2023 semester. The new structure of requiring students to show the results of their iterations and provide discussion about the iterations and the effects of changes made showed a deeper understanding of the Rankine cycle and the biggest contributors to overall cycle performance. Additionally, students saw how engineering design decisions can be limited by factors outside of the control of the engineers. Not all designs operate under optimal conditions. These factors are additional considerations in the design process.

**Future Iterations and Plans**

A common concern when assigning group projects is how can the instructor assess the ability of all students. Without clear structure in workload, it is possible for a portion of the group to take more responsibility of the work than another portion. However, group work for large projects have benefits to the students and instructor. In the workforce, engineers typically work on large projects in teams, thus providing that environment in school can be beneficial to student development. At large universities, such as the one described in this paper, class size is a challenge for large projects. The class described in this paper had a total of 90 students, which is a significant grading load for a project of this size if completed individually. The author continues to refine this project from semester to semester, and a next goal includes finding a balance between student accountability and grading load.

As discussed previously, updates will be made to the expectations for the Excel file and potentially additional practice with the software will be given throughout the course.

The next iteration of the project will benefit from what the instructor learned in Fall 2023 about the timing of due dates for the project assignments.

**References**

[1] A. Lutz, “A Rankine Cycle Design Project for Assessment of ABET Student Outcome #1”.
[2] “Criteria for Accrediting Engineering Programs, 2021 – 2022 | ABET.” Accessed: Apr. 20, 2023. [Online]. Available: https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2021-2022/

**Appendix**

*Power Plant Visit Questions*

1. What kind of cycle does the Mississippi State University Power Plant currently have? What company is the main manufacturer of the equipment present on site?

2. What is the MW output of the Mississippi State University Power Plant? Put this amount in terms of how many homes this can power or a similar comparison.

3. What is the role of the Mississippi State University Power Plant in power generation? Who do they supply power to?

4. Describe the layout of the Mississippi State University Power Plant and explain how each portion contributes to the overall goal of power generation.

5. Explain what it means to “black start” a site. How can a failure of the black start system affect a power generation site and the overall power grid?

6. How does the Mississippi State University power plant compare to other power generation facilities? Consider factors such as location, type of cycle, size, etc. Explain the pros and cons of the Mississippi State University power plant’s differences and similarities to other power plants.

7. What considerations are made in the maintenance of a facility like the Mississippi State University Power Plant?

8. What emissions concerns are there with a site like the Mississippi State University Power Plant? What about other power generation facilities?

9. What did you find most interesting about the visit to the Mississippi State University Power Plant?

10. After your visit to the [university] Power Plant and completing this assignment, what other questions do you have about thermodynamics/power generation?

*Power Plant Visit Questions Rubric*

| **Question** | **1 point** | **2 points** | **3 points** |
|---|---|---|---|

| | | | |
|---|---|---|---|
| 1 | Partial answer and is incorrect | Partially correct or partially answered | Fully answered and correct |
| 2 | Partial answer and is incorrect | Partially correct or partially answered | Fully answered and correct |
| 3 | Partial answer and is incorrect | Partially correct or partially answered | Fully answered and correct |
| 4 | Layout is not completely correct and lacks explanation | Layout and/or explanation are lacking | Layout is correct and explanation is thorough |
| 5 | Partial answer and is incorrect | Partially correct or partially answered | Fully answered and correct |
| 6 | Response is lacking in evidence of research and/or correctness | Response shows evidence of research but is either not thorough or contains incorrect information | Response shows evidence of thorough research and presents correct information |
| 7 | Partial answer and does not show evidence of much research | Partially answered and shows some evidence of research | Fully answered and shows evidence of thorough research |
| 8 | Partial answer and does not show evidence of much research | Partially answered and shows some evidence of research | Fully answered and shows evidence of thorough research |
| 9 | Vague response without a specific example(s) | N/A | Provides a specific example(s) |
| 10 | Vague response without a specific example(s) | N/A | Provides a specific example(s) |

*Technical Submission – Cycle Conditions and Parameters*

***Overview: Design Goal***

Mississippi State University Facilities Management is accepting bids for the construction of a vapor power cycle to be integrated into an existing gas power cycle via a heat recovery steam generator (HRSG).

Organizations are encouraged to prepare a bid that outlines:

- The proposed operating conditions of the combined power cycle
- A bill of materials outlining the purchase cost of additional devices required
- Explanation of the improved performance of the combined cycle compared to the gas power cycle

<u>Design Criteria:</u>

Your group will select the devices and operating conditions for the vapor power cycle. Additional design criteria specific to each individual device is provided below, but design criteria for the vapor power cycle as a whole include:

- Power output of the vapor power cycle cannot exceed 25 MW
- Vapor power cycle cannot have more than three operating pressures
- Exiting state of the cooling water in the condenser should not exceed the conditions of a saturated liquid
- Temperature difference of the exhaust of the gas turbine and the exiting air of the HRSG cannot exceed 400 K
- Total cost of the vapor power cycle installation should not exceed $35,000,000

***<u>Overview of Current System:</u>***

The current gas turbine cycle operates under the following conditions. The air flows at 200 kg/s.

| **Location** | **Measured temperature (K)** |
|---|---|
| Entering compressor | 400 |
| Pre-combustion | 500 |
| Post-combustion | 1000 |
| Exhaust | 700 |

When analyzing the Brayton cycle, utilize the most accurate of air-standard or cold air-standard analysis.

***<u>Vapor Power Cycle Restraints:</u>***

The manager does not want to incorporate a reheat process or utilize a feedwater heater. Options for the devices are provided below.

***Turbine***

The model of turbine has been selected, and the operating parameters are provided below. Three options for the turbine, each of a different age and thus isentropic efficiency, are presented. The cost varies based on the age of the turbine.

The turbine system should have no more than two pressure drops (three or less operating pressures in the cycle). A combination of models can be selected.

*General Turbine Operating Conditions:*

- Power output: 2 to 25 MW (cannot exceed maximum output)
- Inlet pressure: up to 120 bar
- Inlet temperature: up to 540 °C
- Final exhaust pressure: Between 0.05 and 0.15 bar

*Turbine Models Available for Selection:*

| **Model** | **Cost (per unit)** | $\eta_T$ |
|---|---|---|
| Turbine A | $1,000/kW | 0.94 |
| Turbine B | $800/kW | 0.88 |
| Turbine C | $500/kW | 0.79 |

***Condenser***

The cycle should have one condenser. You can assume the fluid exits the condenser as a saturated liquid.

The supply of cooling water will enter the condenser as compressed liquid at 20 °C, 100 bar flowing at 50 kg/s. The exit state of the cooling water should not exceed saturated liquid.

*Condenser Models Available for Selection:*

| **Model** | **Cost** | $P_{min,allowed}$ **(kPa)** |
|---|---|---|
| Condenser A | $150/kW | 3 |
| Condenser B | $100/kW | 10 |

***Pump***

The cycle should have one pump. The operating pressures should correspond to those of the turbine(s). The pump will cost $150/kW and has an isentropic efficiency of 94%.

***Heat Recovery Steam Generator (HRSG) (pronounced her-sig)***

The gas power and vapor power cycles are connected via a heat recovery steam generator (HRSG), which is a type of heat exchanger. It costs $100/kW. The HRSG will take the 700 K exhaust from the gas power cycle and transfer heat from the air to the water in the vapor power cycle. The minimum temperature of the air exiting the HRSG should be 300 K.

***Water Flow Rate***

The costs for various flow rates are provided. The mass flow rate of the water cannot be lower than 25 kg/s.

| **Flow rate (kg/s)** | **Cost** |
|---|---|
| 25-49 kg/s | $10/kW |
| 50-74 kg/s | $20/kW |
| 75-100 kg/s | $30/kW |

*Reflection Questions*

1. How would you describe your knowledge of Brayton, Rankine, and combined cycles before the project?

2. How would you describe your knowledge of Brayton, Rankine, and combined cycles after the project?

3. What skills have you improved as a result of the project?

4. What problem(s) did you/your group encounter while working on the project? What are your perceptions of how the problem(s) was addressed/solved?

5. What were your personal goals for the project? Did they change throughout the process?

6. What did you learn about yourself as you worked on the project?

7. What similarities and differences did you notice in the way the members of your group worked on the project?

8. Which portion of the project took the most time?

9. Do you believe the workload was equally distributed across your group members?

10. Which parts of the project were explained well? Which parts of the project were unclear?