AC 2011-2757: THERMODYNAMIC CONCEPTS IN A MODEL-ELICITING ACTIVITY

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Thermodynamic Concepts in a Model Eliciting Activity

Abstract

Model-Eliciting Activities (MEAs) are reality based problems for students that encourage open ended problem solving. These MEAs are currently being developed and tested to confirm that they are helping engineering students learn essential skills. This paper focuses on a particular MEA dealing with the introductory thermodynamic concepts of processes and uses an in-depth reflection tool to determine the concepts that students' learned and their opinions. The premise for this MEA surrounds the analysis of an engine cycle that needs to be modeled for thermal efficiency. The MEA was run in six separate classes in groups of four, the students were given one week to finish and turn in a memo that described their analysis of the engine cycle. The groups that modeled their cycle with at least one isothermal process calculated a work output for the cycle that was about 25% error off of the measured value while the remaining groups average a 36% error. A similar trend is seen with those groups that include an atmospheric condition state in their model, with a 15% error in those that do and a 41% error with those that do not. This provides insight into the successful methods of solving this MEA and what possible concepts the students are missing. Another method of assessing the MEA is a long reflection tool that allows the students to think about what they learned and record the troubles and successes that they experienced. From the spring to the summer the students indicated in the reflection that they learned very similar concepts; 63% of the students indicated that they learned about modeling a polytropic process from the MEA. Because the original goal was to help students understand the difficult concepts in modeling processes this reflection has shown us that there is at least 63% of students reached that goal. These questions are from the students’ point of view and must be taken as such. Even with the drawbacks, this method of analyzing MEAs has shown that the majority of students are learning the hard concepts in addition to teamwork and other engineering skills.

Introduction

Students most benefit from a group project when they are able to learn from their work. Most group projects have learning objectives that are meant to teach the students specific concepts. The following research focuses on taking complex group projects and analyzing them to determine
whether or not the learning objectives were met. A detailed analysis was conducted by categorizing each solution in conjunction with a post-project questionnaire. The categorized solutions and questionnaire responses helped to reveal the processes that students used to solve the group project. The process a student uses to complete the project is where the learning objectives can be found. By going into the detailed process of each students' solution a correlation between process and solution can be found. The group project that this research will focus on was developed at Cal Poly San Luis Obispo and is part of a larger research effort involving the development of Model Eliciting Activities.

Model Eliciting Activities, or MEAS, are group projects that were designed originally for mathematics classes to analyze student and teacher thinking in middle schools\(^1\). MEAs have since been adapted for engineering education as tools to aid the teaching of engineering concepts. Cal Poly San Luis Obispo along with Colorado School of Mines, Purdue University, University of Minnesota, University of Pittsburgh and the US Air Force Academy are part of a four-year effort toward collaborative MEA research for undergraduate engineering education.

MEAs are group projects centered around a realistic engineering problem that require some form of mathematical model to complete. MEA development is guided by six principles:

1.) **Model Construction:** Requires the development of a model or decision algorithm.

2.) **Reality:** The MEA must be set to a relevant engineering application.

3.) **Generalizability:** The resulting model should apply to other similar applications.

4.) **Self-Assessment:** The students must be able to verify the quality of their own work.

5.) **Model Documentation:** Requires a response or memo describing the model.

6.) **Effective Prototype:** Ensures the involvement of key concepts usable in future work.
These principles are maintained to ensure that the MEA research is consistent and effective. For the research in this paper, the six principles will also be used as categories to evaluate students’ solutions.

One of the objectives for the research at Cal Poly San Luis Obispo is to create a series of MEAs for an introductory thermodynamics class. Thermodynamics is a mostly conceptual class which make projects like MEAs, that must be realistic in nature, difficult to develop. The first step is to determine what concepts an MEA will focus on and how those concepts can be learned in an open ended project. In this case, the MEA will focus on the formation and manipulation of processes in a pressure volume diagram. Professor Andrew Kean with mechanical engineering students Frank Schreiber and Paul van Bloemen Waanders created a new MEA that focuses on the modeling and understanding of various processes in a power cycle.

The following research takes the MEA developed at Cal Poly San Luis Obispo and analyzes the students’ solutions by identifying the sections that relate to each of the six principles. By categorizing the solutions in this way, we can determine if the intended objectives of the MEA are realized. This analysis is not a grading method for the students, but rather, a grading process for the MEA designer.

The MEA

The new MEA comes from a real student club at Cal Poly San Luis Obispo, although the problem and the memo are hypothetically fictitious. The Supermileage club at Cal Poly San Luis Obispo designs a car that is made to get the most distance out of a finite amount of gas. With this in mind, the students are asked to evaluate the pressure-volume data from a single engine cycle for the supermileage car. This MEA is introduced in the third week of the quarter to mostly third-year undergraduate students. The students are told that they are to model this cycle with 4-6 simple processes in order to evaluate the thermal efficiency of the engine cycle as well as recommend a way to increase its efficiency. Appendix A contains the problem statement combined with the graphic of the ‘real’ cycle plotted on a pressure and volume diagram seen in Figure 1. A pre-lab with helpful information for the students to learn beforehand is listed in Appendix B. The graphic
in Figure 1 was generated from a theoretical model of a normal engine and arbitrarily sized onto the graph to allow for an atmospheric intake.

This MEA has so far been tested in six class sections, three in the Spring quarter and three in the Summer quarter. This MEA is designed specifically to reinforce the students' perceptions of how processes are shaped in a pressure-volume diagram. The hope is that the students will match the general shape of the provided curve with simplified processes they have learned in earlier in the course. The students were given one week to develop a general model of the engine cycle. Each group was told to ascertain the thermal efficiency of the given cycle and to enable their model to evaluate the efficiency once the suggested changes to improve the engine had been employed.

**Solutions**

Modeling a combustion engine is a useful skill that most engineers can use. A combustion engine is one that uses a fuel to generate work by expanding a gas. The work from the gas is captured by a piston and rotated, in this case, to turn a wheel. The supermileage vehicle that this MEA is based off of is meant to have a high efficiency engine that can travel long distances with a small amount of gas. The figure given to the students in Figure 1 represents the measured pressure inside of the engine as a function of volume. There are many standard ways to model an engine that are taught
in introductory thermodynamics, however, because the MEA is introduced in the third week of the course the students are told to develop their own model.

The students start by taking the continuous graph given to them and assigning pressure-volume functions called processes to define each part of it. By doing this, the students can then integrate their functions with respect to volume to get the total work of the cycle. There are several processes that the students have available to them. The most basic are the constant volume, or isochoric process, and the constant pressure, or isobaric process. An isothermal process is defined by the relation \( PV = \text{Constant} \). Where \( P \) is pressure and \( V \) is volume. The isothermal process does not change temperature of the working fluid, thus by the ideal gas law \( PV = nRT \), \( PV = \text{constant} \), where \( n \) is the number of moles, \( R \) is the universal gas constant and \( T \) is temperature. An adiabatic process is \( PV^k = \text{Constant} \), where \( k \) is the ratio of specific heats for the working fluid; air, in this case, has a \( k \) value of approximately 1.4. An adiabatic process is characterized by having no heat transfer in or out of the working fluid. Finally, any process that is defined as \( PV^n = \text{constant} \) is a polytropic process in which \( n \) is usually between 1 and \( k \).

Using these processes the students can develop a cycle that mathematically defines the graph given to them. In a standard combustion engine the combusted gas exits to atmosphere during some part in the cycle. This is represented by the lowest point in the graph, or atmospheric pressure defined as 14.7 psi (pounds per square inch). The students are not given this information before hand so it is something that they have to observe on their own. Because the students are developing their own model, it is not required that they include an atmospheric point. The students' analysis should reveal whether or not adding an atmospheric point is important.

The solutions that the students produced were evaluated and broken up into several major components. These components were selected to best show that the objective of the MEA was being achieved. In an effort to assess the effectiveness of this MEA, the solutions were evaluated based upon the six principles of Model-Eliciting Activities. An example of one of the students memorandums is presented in Appendix C.

**Model Construction**
In order to analyze the quality and form of the students’ solutions it was necessary to separate the solutions into categories. This allowed the identification of differences in the solutions as well as generating correlations between more correct answers and the methods that were used. Solution trees were created to help visualize the correlations between the different solutions and their methods. The main criterion for accuracy in a solution was the area inside the cycle or the total work of the system. The actual area inside of the graph was measured with a planimeter, a tool used to measure the area inside any two dimensional curve. This measured valued was subtracted from the students' calculated value and then used to divide the answer. The resulting number represents a percent error that was used as an indication of accuracy. It should be noted that several solutions had obvious mistakes or simple calculation errors that did not contribute to method-accuracy correlations. These solutions were not included in this analysis. The basic two groups that the students’ models fell into were those that included an isothermal process in their solutions and those that did not. This was chosen from all of the possible routes that could have been taken.

**Figure 2:** A breakdown of the analysis of the Spring solutions in all three classes combined. The Tree is broken into groups that included an isothermal process and groups that included an atmospheric state point in their solutions. The boxes indicate total number of solutions in each bin, the range of calculated work output error from the actual value and the average error for each bin.
have been used to model the engine because it had the highest correlation to accurate answers. As seen in the figure, the number in normal parentheses ( ) is the number of solutions in that category. The numbers in the brackets [ ] are the minimum and maximum error in total work. The number to the left of the brackets is the average error for that category. For the first two categories it is plain to see that the solutions that included an isothermal process had a lower average error by 27% for the first set of solutions and 11% for the second set of solutions.

The second type of grouping was whether or not the solution included a state point at atmospheric conditions. Using these categories the solutions were grouped and plotted to visualize the different solution paths that the students took. The results from this grouping of solutions can be seen in Figures 2 and 3. From the two figures it is observed that the average error is smaller when the students include an isothermal process and an atmospheric state. This could result because the groups that recognized a need for an atmospheric state were able to more smoothly model the cycle than those that did not. The isothermal process, depending on the starting and ending state points chosen, was generally seen to fit the curves of the provided graph more smoothly than the other possible processes. This could have resulted in the low error for the groups that included an isothermal process.

**Figure 3:** Another breakdown of the analysis of the Summer solutions in all three classes combined. The tree is broken into groups that included an isothermal process and groups that included an atmospheric state point in their solution. The boxes indicate total number of solutions in each bin, the range of calculated work output error from the actual value and the average error for each bin.
Model Documentation

The documentation of the model is an important part of MEAs. In industry, it is very important for engineering colleagues to understand each other’s work. Being able to communicate ideas through technical documents is an invaluable skill. MEAs cultivate this skill by requiring the students to document the technical models they create. Each group is expected to turn in a memorandum that is written to the client, in this case the fictitious supermileage club member Sharon Parker. The original problem statement asks them for the model in some digital form, the analysis of the cycle provided, and a simple recommendation to improve the efficiency of the cycle.

The first indication that the students understand that this activity is meant to emulate a real world scenario is who their memo is addressed to. Also very telling is the voice they choose to use throughout the memo. Table 1 summarize the students’ voice and who they addressed in their memo. The category "You" indicates that the students addressed the client in the memo by simply stating "You" without mentioning name or title. Similarly, "Dear Client" mean that the client was addressed by name but only in the beginning of the Memo. "Supermileage" means that the students acknowledged that the Supermileage club was their client. "You, Supermileage" indicates that the students used both "You" and the Supermileage indicators in their memo. "None" means that no client was addressed and "Professor" means that the professor was addressed instead of the client.

**Table 1:** A list of the different voices used to address the client in the Summer and Spring groups' memos to the client.

<table>
<thead>
<tr>
<th>How the client was addressed</th>
<th>Summer</th>
<th>Spring</th>
</tr>
</thead>
<tbody>
<tr>
<td>You</td>
<td>27%</td>
<td>31%</td>
</tr>
<tr>
<td>Dear Client</td>
<td>0%</td>
<td>13%</td>
</tr>
<tr>
<td>Supermileage</td>
<td>15%</td>
<td>25%</td>
</tr>
<tr>
<td>You, Supermileage</td>
<td>19%</td>
<td>9%</td>
</tr>
<tr>
<td>none</td>
<td>31%</td>
<td>22%</td>
</tr>
<tr>
<td>Professor</td>
<td>8%</td>
<td>0%</td>
</tr>
</tbody>
</table>
The deliverables of the project were also an important part of the documentation for the MEA. There were only three direct deliverables stated in the assignment: the model, the results and the recommendation. Table 2 summarizes for each quarter the percentage of students that included the corresponding deliverables. The tables also include the percentage of solutions that address a client in some way.

**Table 2:** The percentage of solutions in the Summer and Spring that included the listed deliverables in their final memo.

<table>
<thead>
<tr>
<th>Deliverables</th>
<th>Summer</th>
<th>Spring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Client</td>
<td>61%</td>
<td>78%</td>
</tr>
<tr>
<td>Model</td>
<td>96%</td>
<td>97%</td>
</tr>
<tr>
<td>Results</td>
<td>62%</td>
<td>78%</td>
</tr>
<tr>
<td>Recommendation</td>
<td>88%</td>
<td>94%</td>
</tr>
</tbody>
</table>

From the previous tables, 61% of the solutions in the Summer and 78% in the Spring identified that the memo is supposed to be addressed to a client, however the remaining students fail to address a client at all. 22% of the groups in the Spring and 38% in the Summer did not include the results of their model. Most of the results were hidden somewhere in the attached model with the exception of only a few who did not provide results at all. Most of the solutions, however, did include the remaining deliverables: describing the model, listing assumptions while also providing a recommendation for increasing thermal efficiency.

**Generalizability**

The assignment asks the students to create their model such that the client, supermileage team, will be able to use it when analyzing future engine cycles. This is a required to encourage the students to make their models simple to modify or generalizable. This also indicates to the students that the client expects their model to be useful and help them solve engineering problems. For this MEA there is a trade-off for making the model more generalizable. If the students use values that can be looked up in their model it limits the ability of the model to be used as a tool. In order to make the
model more flexible complex approximations can be made that lessen the accuracy of the model. Calculating the heat lost to the surroundings requires looking up values of internal energy and specific heats in tables. Without complex equations, which some students did use, the model requires the user to look up tables if anything is modified. In Table 3, several generalizable traits are listed along with the percentage of groups that employed them.

**Table 3:** The various methods used in group solutions that made the model more generalizable for the Summer and Spring sessions.

<table>
<thead>
<tr>
<th>Generalizability</th>
<th>Summer</th>
<th>Spring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input values for the model</td>
<td>65%</td>
<td>76%</td>
</tr>
<tr>
<td>No copy and paste required</td>
<td>85%</td>
<td>84%</td>
</tr>
<tr>
<td>No look up values</td>
<td>12%</td>
<td>31%</td>
</tr>
<tr>
<td>Work is recalculated automatically</td>
<td>70%</td>
<td>74%</td>
</tr>
<tr>
<td>Internal Energy is recalculated automatically</td>
<td>50%</td>
<td>29%</td>
</tr>
</tbody>
</table>

The least popular method of creating a good generalizable model was using equations to generate the values of specific heat based upon temperature. Specific heats do not change very much over temperature unless the gas that is being worked with is getting very hot, which was the case in this MEA. Most students chose to look up the specific heats and have the client do the same thing if they change the numbers. This is an easy way and accurate way to get those numbers. Other groups held the specific heats constant and regarded the resulting error negligible. A third, smaller selection of groups chose to look up the equation for determining specific heats based upon temperature and include that in the model. So while the generalizability might be lacking for some, it helped students to have to decide between accuracy and ease of use. Deciding between either a simple model or an accurate model is something engineers struggle with everyday.

Since the numbers in Table 3 are low, it is clear that making the model generalizable was a low priority for most groups. The important thing is that the groups recognized the issue and placed input areas for new data while recalculating work so the model remained updated. Recalculating
the internal energy, \( U \), required the students to do more research into different methods of calculating internal energy other than simply looking the values up.

**Effective prototype**

An important objective to confirm is whether or not the students are learning the concepts. This objective is important because MEAs are only useful tools if they are helping the students to learn, not preventing them from learning. The concepts in this MEA are intended to help students with common problematic areas in the thermodynamic curriculum. Table 4 shows the percentage of students that included the following basic thermodynamic concepts in their model: The Ideal Gas Law (\( PV = nRT \)), Integrated Work (\( \text{Work} = \int P \, dv \)), and the First Law of Thermodynamics (\( dU = dQ - dW \)).

**Table 4:** This table is a summary of the Summer and Spring groups that included the following basic but essential thermodynamic concepts correctly.

<table>
<thead>
<tr>
<th>Effective Prototype</th>
<th>Spring</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal Gas Law</td>
<td>97%</td>
<td>96%</td>
</tr>
<tr>
<td>Integrated Work</td>
<td>91%</td>
<td>100%</td>
</tr>
<tr>
<td>1st law</td>
<td>97%</td>
<td>100%</td>
</tr>
</tbody>
</table>

The numbers show that in the main thermodynamic concepts are being employed correctly by the majority of the students. Only a handful of solutions, at most 9%, fail to include the essential concepts. It is important to note that the ideal gas law, the first law of thermodynamics, and the concept of integrated work are very important concepts in thermodynamics. Students who did not finish the course with these concepts in hand would be seriously lacking in their engineering education.

**Self Assessment**

One missing part of this MEA is the ability for students to easily evaluate their own work. Of the required deliverables, only thermal efficiency of the engine was something the students could look
up to check their answers. Although the work output of the given cycle is measurable, it takes up valuable time for the groups to confirm that they have appropriate work. Simple mistakes like unit conversion or basic misunderstandings can be found through some sort of check that could be provided by the teacher. The average calculated efficiency was 43% and the measured work was 34 ft-lbs; These values might be given to the students as previous values so that they have something to compare to. Table 5, below, shows the percentage of groups that made the most common two mistakes or did not include a model.

Table 5: This table shows the common errors that were found in the Spring and Summer quarters solutions.

<table>
<thead>
<tr>
<th>Calculation errors</th>
<th>Spring</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit conversion</td>
<td>10%</td>
<td>6%</td>
</tr>
<tr>
<td>Confusing the heat energy into the engine as the total heat energy in and out of the system</td>
<td>3%</td>
<td>9%</td>
</tr>
<tr>
<td>No model</td>
<td>10%</td>
<td>6%</td>
</tr>
</tbody>
</table>

Having 6% - 10% of the groups not turn in a model for any reason is concerning. Some post MEA surveys indicated that some groups ran out of time and at least one simply did not understand that a working model was required. Even more concerning is that 3% to 9% of the students thought that the total heat transfer in was a summation of all of the heat transfer. The calculation in question was essential for determine the thermal efficiency of the system, which is the summed total work from the system over the heat delivered into the system.

One aspect of the solutions that is worthy of note is that some of the solutions included processes that were simply equations to fit the line instead of the processes that they had learned. At first, this was thought to be a significant factor for accuracy but the results showed no direct correlation. One third of all the groups chose to employ at least one process that they had not learned about in class. Of the students that chose defined thermodynamic processes the average of the total error in work output was 33% while those that chose new or otherwise made up processes had an average of 14% error. Simply put, the students that followed directions and employed only processes that they learned were more likely to have more error in their model. This method of modeling may
steer the students away from one of the main objectives which is to help the students become familiar with known thermodynamic processes.

Another point that can be seen from the difference in modeling known processes rather than undefined processes is the contrast in thermal efficiency. The thermal efficiency is a ratio of the total work produced to the amount of heat transferred into the system. The solutions that included known processes came out with an average efficiency of 43%. The accuracy of thermal efficiency is largely dependent on how the state points are chosen. The group solutions that used at least one unknown processes came up with efficiencies that were an average of 56%. The actual efficiency of the engine is unknown because the amount of heat transfer depends on the method used to model the system. The use of unknown processes rendering higher efficiencies is an interesting observation. If this in fact is a correlation then the association with higher efficiencies with unknown processes again could lead the students away from the objective of helping them with known processes.

**Reflections**

Every student was given an in depth reflection questionnaire after the assignment. These reflections are used in the MEA research to allow the students to analyze their own work as well as let the professors get a glimpse of how the students are problem solving these activities. The reflection asks the students about the process they used to solve the MEA as well as their own feelings towards their contributions and solutions. A full example of the reflection questionnaire can be seen in Appendix D. For the summer session, one question was added because of the demonstration that was given in the middle of the assignment. This question asked if the students thought that collecting PV data on their own would be beneficial.

The reflection covers many topics however the topics of interest for this particular MEA are in the concepts that the Students feel they learned. Question 10 in the reflection exercise asks the students to identify the concepts that they feel were important to this particular MEA. Among the possible concepts are processes, cycles, the first law of thermodynamics, modeling polytropic processes, thermal efficiency, ideal gases, and evaluating energy for an ideal gas. All of these concepts could have been present in the problem depending upon how the students chose to set it
up. What we are looking for is a common theme of processes because they are the main objective of the MEA.

The first step in analyzing the reflections was to take a small sample of them and read through them to determine where the revealing information is. After dissecting several of the reflections it became clear that some answers were all the same and some were greatly different. The time and graphs of the critical points in the MEA were interesting but failed to reveal the effectiveness of the MEA. However, the students were asked to reveal how much involvement they had in each critical step of the solving process. These numbers provided an excellent reference for the other answers. In one example, a student claimed that he did not believe that the MEA helped him learn, however he reported his level of involvement in each process as very low. It does not necessarily prove that the MEA would have helped him but it does provide a possible explanation as to why he did not gain much from the experience.

One of the reflection questions deals with the concepts that the students felt they learned the most. They were given a list of eight concepts and were told to underline the ones they felt they learned through the process of solving the MEA. Each of the eight concepts are involved in the MEA somewhere and someone who did the MEA alone would likely indicate all of them. The idea is that the question will reveal which concepts are learned by everyone and which ones are learned only by a few. Figures 4 and 5 show the results of all the reflections and which concepts are most selected. The graphs show that Processes, Cycles and Modeling a Polytropic Process were indicated as the most learned concepts. This means that the original goal of creating an MEA to focus on processes was most likely achieved. An interesting result is that both graphs look the same and have very similar percentages. The only difference between the presentations of the two quarters was a demonstration of pressure volume data gathering on the second day of the assignment. The consistency of the results of this MEA could indicate that this is a solid method for teaching the highly ranked concepts reliably.
**Figure 4:** The concepts listed are eight of the most prevalent concepts in the supermileage MEA. The students were asked to indicate which ones they learned by solving the MEA. This graph is generated from the three classes in the Spring.

**Concepts learned - SPRING**

<table>
<thead>
<tr>
<th>Concept</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processes</td>
<td>67%</td>
</tr>
<tr>
<td>Cycles</td>
<td>63%</td>
</tr>
<tr>
<td>First law for a process</td>
<td>61%</td>
</tr>
<tr>
<td>First law for a cycle</td>
<td>60%</td>
</tr>
<tr>
<td>Modeling a polytropic process</td>
<td>58%</td>
</tr>
<tr>
<td>Thermal efficiency</td>
<td>57%</td>
</tr>
<tr>
<td>Ideal gases</td>
<td>57%</td>
</tr>
<tr>
<td>Evaluating energy for an ideal gas</td>
<td>44%</td>
</tr>
</tbody>
</table>

**Figure 5:** The concepts listed are eight of the most prevalent concepts in the supermileage MEA. The students were asked to indicate which ones they learned by solving the MEA. This graph is generated from the three classes in the Summer.

**Concepts learned - SUMMER**

<table>
<thead>
<tr>
<th>Concept</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processes</td>
<td>65%</td>
</tr>
<tr>
<td>Cycles</td>
<td>63%</td>
</tr>
<tr>
<td>First law for a process</td>
<td>56%</td>
</tr>
<tr>
<td>First law for a cycle</td>
<td>56%</td>
</tr>
<tr>
<td>Modeling a polytropic process</td>
<td>54%</td>
</tr>
<tr>
<td>Thermal efficiency</td>
<td>53%</td>
</tr>
<tr>
<td>Ideal gases</td>
<td>45%</td>
</tr>
<tr>
<td>Evaluating energy for an ideal gas</td>
<td>42%</td>
</tr>
</tbody>
</table>
The most telling question was the last one; it asked the students how the MEA could have been improved. Figures 6 and 7 have the breakdown of the most common answers. There were many types of answers, however in the prescreening there were three that were prominent: The students needed more guidance in the beginning, they wanted some comparison to the strokes of an engine and the PV graph they were given, and they requested they the MEA not go over material that they had not covered yet. The students that requested more guidance specifically mentioned that they had no idea how to being the solution process and struggled mightily because they didn’t know how to approach the problem. The students that requested a real engine comparison did not struggle with the MEA so much as struggled with the concepts of the diagram. The students that complained about uncovered material specifically mentioned the internal energy and how it related to the thermal efficiency of the cycle.

**Figure 6:** This is a list of the six suggestions that the students listed as ways to improve the supermileage MEA in the Spring session.
After evaluating all of the reflections a significant improvement can be seen. The requests for improvement decrease and the amount of students that believe that the MEA is fine as is increases to almost 50% from the spring to the summer. This could be related to the fact that the summer students most likely have more free time to work on the MEA. It could also be due to the fact that there was a demonstration in the summer and it helped a great deal. It should be kept in mind that these are the opinions of the students and do not necessarily indicate that the MEA would improve if employed.

Several of the questions in the reflection exercise were not recorded. Although all of the questions reveal something about the MEA and the students’ solution process, the purpose of the assessment for this application was to improve the MEA and ensure that it is serving its purpose. Tables 6 and 7 list the remaining questions on the reflection questionnaire. These questions asked the students to rank their responses either 0 - 4 or 0 - 3; the scale is listed for each question.
Table 6: This table summarizes the quantitative questions that are asked in the reflection exercise.

<table>
<thead>
<tr>
<th>Spring</th>
<th>Average Student Data:</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.31</td>
<td>Satisfied with their final solution (0-4)</td>
</tr>
<tr>
<td></td>
<td>Level of Involvement (0-3)</td>
</tr>
<tr>
<td>2.53</td>
<td>Critical point 1</td>
</tr>
<tr>
<td>2.48</td>
<td>Critical point 2</td>
</tr>
<tr>
<td>2.56</td>
<td>Enjoyed the experience (0-4)</td>
</tr>
<tr>
<td>2.9</td>
<td>Would benefit from hands on lab (0-4)</td>
</tr>
</tbody>
</table>

Table 7: This table summarizes the quantitative questions that are asked in the reflection exercise. It also includes one extra question dealing with the possibility of a hands-on data collection addition to the MEA.

<table>
<thead>
<tr>
<th>Summer</th>
<th>Average Student Data:</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.11</td>
<td>Satisfied with their final solution (0-4)</td>
</tr>
<tr>
<td></td>
<td>Level of Involvement (0-3)</td>
</tr>
<tr>
<td>2.52</td>
<td>Critical point 1</td>
</tr>
<tr>
<td>2.38</td>
<td>Critical point 2</td>
</tr>
<tr>
<td>2.84</td>
<td>Enjoyed the experience (0-4)</td>
</tr>
<tr>
<td>3.15</td>
<td>Did benefit from hands on lab (0-4)</td>
</tr>
<tr>
<td>1.86</td>
<td>Would benefit from personal hands on lab (0-4)</td>
</tr>
</tbody>
</table>

The first question shows that the students were satisfied with their answers but somewhat less so in the summer. The level of involvement is what the students felt they contributed in each critical point in the solution process. These answers remain consistent showing that students feel that the contribute more in the beginning then in the end. Perhaps this has something to do with the fact that students that asked for more guidance asked for it in the beginning where they were struggling more. More students indicated that they enjoyed the MEA in the Summer rather than the Spring. Lastly the questions pertaining to the lab demonstration indicated that the demonstration was helpful. Even though the students rated a potential hands-on demonstration as 2.9 out of 4, they rated the benefit from the lab as 3.15 out of 4. This is an interesting result showing that students...
might not be the best people to ask about what they might need. With that in mind, the last question asked if they thought they would benefit from taking the pressure volume data themselves. It ranked 1.86 which is just below neutral.

Discussion

Changing misconceptions is difficult but is something of a specialty of Cal Poly San Luis Obispo which has the motto "Learn By Doing". Physical experiments and "Learn By Doing" is something that Cal Poly San Luis Obispo has always made sure to focus on in its curriculum. Research shows that students with misconceptions can be helped by a physical experiment that clarifies the concept in question\(^1\). A polytropic process can have a polytropic index or exponent of almost any value. The objective of this MEA is to associate those exponent values in a polytropic process to some sort of physical process. Specifically, the students become more familiar with processes they already know something about like isothermal or adiabatic processes. If the students focus on processes just because the processes best fit a line, they will miss one of the central learning objectives.

One of the goals of this MEA is to allow the students to think critically on their own about what processes are involved in an engine and how those processes appear on a PV diagram. The MEA does satisfy this goal as seen in the reflections, although what it is missing is some closed loop feedback that the students can use to test whether or not their solution is working. To start, the MEA needs to be made clear that only processes of a certain form should appear in an engine cycle. The main reason for doing this is to make sure that the intended goal of the MEA is realized. This might make it easier to grade as well, while ensuring that students learn about processes that they will use in the remainder of the course. A second modification would be to include the measured total work of the cycle. This is something that the client is not looking for directly so it might be easy to provide to allow the students to check their work. As long as it is clear that the students are providing the client with the model as a deliverable then they can only use that number as a guide. Another option is to provide an efficiency range so that the students can check their answer without giving the answer away. In all of the solutions 22% of the groups had some miscalculation or wrong idea that led them astray. The most common misconception
was that the heat transfer into the system was the total heat transfer, which is not the case. The heat transfer into the system is only the positive heat transfers. Because of this, some of the solutions had very wrong thermal efficiencies so perhaps it would be wiser to provide a method of assessment regarding the efficiencies since that is the location of most of the errors.

Even though some students struggled with units and heat transfer misconceptions, a similar number of them wrote in the reflection that they understood they did something wrong. The reflections showed that the majority of the students learned the important concepts and enjoyed the MEA in some way. While most group projects are beneficial for the students they are almost never very popular. To have some consistent feedback that says that students enjoy learning in this way, even in a small majority, is a successful result.

Acknowledgments

Financial support was provided by 1) National Science Foundation via Course, Curriculum, and Laboratory Improvement 071759: Collaborative Research: Improving Engineering Students’ Learning Strategies Through Models and Modeling and 2) The Donald E. Bently Center for Engineering Innovation at California Polytechnic State University, San Luis Obispo.

References


Memorandum

To: Thermodynamic Analysis Team
From: Sharon Parker, Cal Poly Supermileage Team
Date: June 30, 2010
Re: Engine Performance Analysis

Each year, Cal Poly’s Supermileage Vehicle Team competes in the Shell Eco-Marathon competition (http://www.shell.com/home/content/ecomarathon/americas/). Several years ago, we won the event when we drove our highly aerodynamic vehicle an amazing 1900 miles per gallon. We have not had as much luck recently, but hope you can help us turn that luck around.

Our vehicle is powered by a small displacement, but highly efficient, internal combustion engine. Prior to the competition, we instrumented our engine to measure combustion chamber pressure and volume. You can see sample results of our measurements on the next page. We measure pressure in the cylinder with a pressure transducer and we measure engine displacement (i.e. volume) with a Linear Variable Differential Transformer (LVDT). We are unfortunately not able to measure the work produced per cycle or the thermal efficiency of the engine directly.

We are writing to request your assistance with developing a thermodynamic model which accurately estimates the work produced by our engine per cycle, and determines the thermal efficiency of the engine. Please perform your primary analysis using the data we have provided. We plan to make frequent engine modifications out in the field which will change the cycle details, so please also make your model easy to adjust with additional p-V data. Hopefully with the help of your model, we will be able to see how making small changes to the cycle affects work produced and thermal efficiency. To keep the model easy to use, we ask that you: 1) treat the fuel-air mixture in the combustion chamber as simply air, 2) model combustion of the fuel as heat transfer into the system from the surroundings (i.e., even though this is an internal combustion engine, please model it as an external combustion engine), and 3) model the entire cycle with 6 or fewer distinct processes.

Please perform this analysis that our team has requested, and attach it to a memorandum. In your memorandum, please be sure to explain the key assumptions you have made in your analysis and state how you are choosing to model each process. Also in the memo, for the data we provided, please summarize your model calculations for each process (i.e., ΔU, Q, and W) and for the overall cycle (i.e., ΔU, Q, W and η). Based on your analysis, what modifications to the cycle would you recommend to increase the performance of the engine? We would like your memo and model by early next week. Thanks for your attention to this matter.

Sincerely,

Sharon Parker,
Cal Poly Supermileage Team
For our first Model Eliciting Activity (MEA), you will work in groups of four to develop a computational model to analyze performance of a fuel-efficient engine (i.e., work produced, thermal efficiency, etc.). I will assign students to groups. Please bring your textbook to class and note that the MEA will be easier once you have worked on HW2. In preparation for this MEA, it is worth summarizing all of the types of processes that we will commonly encounter in the early part of this course. We can model many of these processes with our polytropic process relationship, $pV^n =$ constant, with the value of the polytropic exponent, $n$, determining the shape of the curve (higher $n$ means a steeper curve on the $p$-$v$ diagram). Based on our discussion so far, the following processes should be familiar: constant pressure (isobaric, $n=0$), constant temperature (isothermal, $n=1$), adiabatic (no heat transfer, $n=k$), and constant volume (isochoric, $n=\infty$). There are infinite possibilities for the value of $n$, but these common values are shown in this figure from Chapter 6:

For now, we need only focus on the $p$-$v$ diagram. We will tackle the Temperature-Entropy ($T$-$s$) diagram later in the course. But I should clarify that on the $p$-$v$ diagram, the curve corresponding to $n = k$ is for an isentropic process, which we will learn later occurs when a process is both adiabatic and reversible. Here $k$ is the ratio of two specific heats we will commonly use. That is, $k = \frac{c_p}{c_v}$ where $c_p$ is the specific heat at constant pressure and $c_v$ is the specific heat at constant volume. See Table A-20 for values of $c_p$, $c_v$, and $k$.

As part of this MEA, you will have to analyze the internal energy of air (as an ideal gas). We will learn in Chapter 3 that for ideal gases, the internal energy is a function of only the temperature of the gas, as suggested in equation 3.40:

$$u(T_2) - u(T_1) = \int_{T_1}^{T_2} c_v(T) \, dT$$

There are several ways to evaluate this integral as described in Sections 3.13 and 3.14. Please read through these sections in preparation for our MEA. Also, please answer the following questions:

1) Is an adiabatic process the same as an isothermal process? Why or why not?

2) To what type of systems and processes does $W_{rev} = \int_{V_1}^{V_2} pdV$ apply?

3) When evaluating the integral above, is it more accurate to assume constant specific heats or to let the specific heat change with temperature? When evaluating the integral above, which method(s) appear best suited for a computer program and which method(s) appear best suited for hand calculations?
Dear Sharon,

Attached in this memo is part of our Thermodynamic analysis for the Cal Poly Supermileage team. Overall, we used a total of 6 processes to model the cycle, and after our analysis we were able to learn more about this power cycle.

In order to analyze the data from the graph that was presented, there were many key assumptions we had to make. To begin the analysis we assumed point A, the start of process one, was at a temperature of 59 degrees Fahrenheit and at a pressure of 14.7 psi (to represent standard atmospheric conditions). Using the tables in the back of the Thermodynamics textbook, the value of $C_v$ was determined to be .171 and this value was used for all cycles. As instructed, the air-fuel mixture was treated as only air, the process was analyzed as reversible and the cycle was treated as an external combustion instead of an internal combustion engine.

The following is a breakdown of the processes we chose to model the data from the Supermileage's engine testing:

- Process 1 is an adiabatic process with $k=1.401$
- Process 2 is a constant volume process
- Process 3 is a constant pressure process
- Process 4 is an isothermal process
- Process 5 is a constant volume process
- Process 6 is a constant pressure process

Calculations were completed as follows:

(Process 1) Work: $W = - \Delta U$

$\Delta U: (C_v) \times (mass) \times (\Delta T) = \Delta U$

$Q$: Zero, because it is an adiabatic process

(Process 2) Work: Zero, because it is a constant volume process

$\Delta U: (C_v) \times (mass) \times (\Delta T) = \Delta U$

$Q$: $Q = U + W$
(Process 3) Work: \( \int p \, dV \) (From \( V_3 \) to \( V_4 \)) = \( W \)
Delta U: \( (C_v) \times \text{(mass)} \times (\Delta T) = \Delta U \)
Q: \( Q = U + W \)

(Process 4) Work: \( P_4 \times V_4 \times \ln(V_5/V_4) = W \)
Delta U: \( (C_v) \times \text{(mass)} \times (\Delta T) = \Delta U \)
Q: \( Q = U + W \)

(Process 5) Work: Zero, because it is a constant volume process
Delta U: \( (C_v) \times \text{(mass)} \times (\Delta T) = \Delta U \)
Q: \( Q = U + W \)

(Process 6) Work: \( \int p \, dV \) (From \( V_6 \) to \( V_1 \)) = \( W \)
Delta U: \( (C_v) \times \text{(mass)} \times (\Delta T) = \Delta U \)
Q: \( Q = U + W \)

The following is a graph of the model processes in black on top of the original data provided from the engine testing. The number on the graph represent the different processes.
Here is a table of each process and its corresponding, calculated delta U, Q, and W values:

<table>
<thead>
<tr>
<th>Process</th>
<th>Delta U</th>
<th>Q (ft-lbf)</th>
<th>W (ft-lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.59701009</td>
<td>0</td>
<td>-11.59701009</td>
</tr>
<tr>
<td>2</td>
<td>8.311930119</td>
<td>8.311930119</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>22.04018446</td>
<td>30.87018446</td>
<td>8.83</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>37.0286</td>
<td>37.0286</td>
</tr>
<tr>
<td>5</td>
<td>-40.72651821</td>
<td>-40.72651821</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>-1.222606459</td>
<td>-1.712606459</td>
<td>-.49</td>
</tr>
</tbody>
</table>

For the full cycle, the delta U, Q, W, and efficiency calculations are:

Delta U: Sum of all Delta U for each process: $2.0792 \times 10^{-10}$ (should be zero)
Q (ft-lbf): Sum of all Q’s for each process: 33.77
W (ft-lbf): Sum of all W’s for each process: 33.77
Efficiency ($\eta$): $\frac{W_{\text{cycle}}}{Q_{\text{in}}}$ = 44.3%

Based on our analysis there are two main options for increasing the efficiency, and therefore the performance, of the engine. In the most general sense, there are two ways to increase performance, which is to either increase the amount of work produced by the cycle or decrease amount of heat to be put into the system. One specific method for increasing performance would be to change process 1 to an isothermal process instead of an adiabatic. Doing this would decrease the area under the process, meaning there would be less negative work the cycle must preform, and therefore increasing net work and performance. Alternately, by raising the temperature of the isothermal process the same conclusion will be reached with a larger area within the cycle corresponding the work being produced.

The majority of the calculations were performed using Microsoft Excel, and all of the data and final results are in the same Excel file. If requested, this file can be sent to supplement this memo.

Sincerely,
(Names Omitted)
ME 302-01
Reflections on your Supermileage Engine Performance Analysis

ME 302 Thermodynamics

Name: (omitted)

(Please answer the following questions directly in this document and email it back to me at akean@calpoly.edu as soon as possible (no later than Friday). Throughout this reflection exercise, please underline your selections from the lists provided)

Engineers play an important role in the globalized and as Thomas Friedman put it, an increasingly “flat” world. As future engineering professionals you will make decisions and designs that impact the lives of many people. A lot of your coursework and employment will be based in teams and require you to learn new concepts on your own. Reflection can be a part of your learning process, and this self evaluation will help you understand what you gained from this exercise.

More about “reflection” From Hatton and Smith:

Historically Dewey (1933) is acknowledged as a key originator in the twentieth century of the concept of reflection. He considered it to be a special form of problem solving, thinking to resolve an issue which involved active chaining, and a careful ordering of ideas linking each with its predecessors. Within the process, consideration is to be given to any form of knowledge or belief involved and the grounds for its support*. His basic ideas indicate that reflection may be seen as an active and deliberative cognitive process, involving sequences of interconnected ideas which take account of underlying beliefs and knowledge. Reflective thinking generally addresses practical problems, allowing for doubt and perplexity before possible solutions are reached.

* Adler, 1991; Cutler, Cook & Young, 1989; Calderhead, 1989; Gilson, 1989; Farrah, 1988

Process Focused Questions

1. Problem solving is a major part of engineering and designing solutions. Problem solving is thinking about and finding answers for a relatively clearly-defined situation for which there are one or more reasonable answers. We are interested in how your team solved this exercise. Please look at the graphs on the next page to help you answer the following question. Points A-H represent moments in time over the last week.

2. Select one of the four graphs from below that most closely matches the path that your team took while working on this assignment. Please select a lettered point on the graph of two critical points in your team’s problem solving process that stands out. A critical point is a major change in thinking or an “aha” moment. Please describe the strategy your team used at the start of the assignment and then how it changed at each of the two points.

   **Graph Number (select one): I, II, III or IV**

   **Critical point 1 (select letter): A, B, C, D, E, F, G, or H**
   Strategy Change: went from 6 to 4 processes

   **Critical point 2 (select letter): A, B, C, D, E, F, G, or H**
   Strategy Change: calculating works
3. In engineering problem solving you make assumptions to arrive at a solution. Assumptions are what information and/or constraints that you considered in forming your answer. Please describe the key assumptions that your team used in solving the exercise. Why did you make each assumption?

- The assumptions we made were that the initial conditions of the cylinder were at sea level and room temperature, there’s no friction inside the cylinder, and the fluid is just air. We made these assumptions so we know \( T_1 \) and we don’t need to account for friction, plus if it’s just air then we can use ideal gas.

4. While working on this group project, what did you personally contribute to the problem solving process? Please explain.

- I contributed ideas in class and on our first meeting. I missed the second meeting because I went back home for 4th of July, then on our third meeting I helped working on the memo.

5. Did your group have difficulty agreeing on a final solution?  Yes  No  Maybe

How did your group make the decision on what was the final answer?

- By using the equations based on the processes.
6. Did you have a method or suggestion that did not end up in the final solution?

Yes  No  Maybe

Please explain.

- The final solution is pretty much what we came up with.

7. I was satisfied with my group’s final solution (select one).

- Strongly disagree
- Somewhat disagree
- Neutral
- Somewhat agree
- Strongly agree

Please explain.

- We treated some processes as isobaric and isochoric but that is not 100% correct, although it’s very close.

Problem Solving Focused Questions

8. Thompson has outlined some commonly used stages of engineering problem solving that can be categorized as:

a. Problem Identification; i.e., identify and state the problem

b. Model/Solution Formulation; i.e., formulating the problem and abstraction, problem solving approaches, variables, assumptions, constraints and criteria. Modeling the problem: translation

c. Collecting Information and Analyzing Data; i.e., collect information, data and resources. Analyzing and/or solving

d. Evaluating and Revising the Solution; i.e., interpreting results, evaluating potential solutions and selects solution. Reflecting and revising; using feedback and improving

e. Documentation; i.e., writing and reporting

Thinking back to the two critical points that you identified earlier in question 2, please also identify the stage of the project, your level of involvement (none, low, medium, high) and approximate time in minutes when it occurred.
**Critical Point 1:**

*Stage (select one):*

- Problem Identification
- Model/solution formulation
- Collecting information and/or analyzing data
- Evaluating and revising the solution
- Documentation

*Level of Involvement (select one):*

- None
- Low
- Medium
- High

*Time of Critical Point:*

- Critical Point 1 at 2 days (or minutes if on Day 1)

9. **Critical Point 2:**

*Stage (select one):*

- Problem Identification
- Model/solution formulation
- Collecting information and/or analyzing data
- Evaluating and revising the solution
- Documentation

*Level of Involvement (select one):*

- None
- Low
- Medium
- High
Time of Critical Point (in days):

- Critical Point 2 at 2-3 days (or minutes if on Day 1)

Concepts Learned Questions

10. Below are some of the engineering concepts that might have been included in the exercise. Which ones do you now understand better as a result of this exercise? What prompted or helped you gain the concepts better? How did you notice this change?

Processes, cycles, first law of thermodynamics as applied to a process, first law of thermodynamics as applied to a cycle, modeling processes with the polytropic relationship, thermal efficiency, ideal gases, evaluating internal energy for an ideal gas, others____________________(fill in blank).

- Processes, thermal efficiency, ideal gases, and evaluating internal energy. Since I needed to know these in order to solve the problem it kind of forced me to do more research outside of class like read more from books, internets, etc. (which is a good thing).

11. Were there any other concepts or skills beyond those mentioned in the previous question that you discovered or now understand better? What prompted or helped you gain these skills or concepts better? How did you notice this change?

professional writing, using software (such as excel), apply engineering concepts, analyze data, interpret data, working with realistic constraints, teamwork, solve engineering problems, professional responsibility, ethical responsibility, communication skills, engineering in a global context, engineering in a societal context, engineering in an environmental context, engineering in an economic context, recognition of life long learning, other_______________(fill in blank)

- Professional writing: I took Eng 149 a while ago so my memo writing skill was a little rusty. This assignment helped me polish my writing skill.

12. Engineers must face conflicting interests and “gray areas” in decision making. Did you notice any ethical issues (“moral issues and decisions confronting individuals and organizations involved in engineering”, Martin and Schinzinger) that should be considered as part of the solution? Yes No

Please explain.

- There’re really no ethical issues in this assignment.
13. According to Bodner, Gardner and Briggs, a broad definition of the term “model” refers to a simplified or idealized description or conception of a particular system, situation, or process, often in mathematical terms, that is put forward as a basis for theoretical or empirical understanding, or for calculations, predictions, etc.; a conceptual or mental representation of something; and the term “modeling” refers to devise a model or simplified description of a phenomenon or system.

Harrison and Treagust define modeling as the essence of thinking and working scientifically.

Taking this into consideration, what other applications do you think your solution could be applied to? Or what other areas could you apply the skills and concepts you learned in this exercise?

- Maybe in Fluid Mechanics? and some BMED courses that I’m about to take in the upcoming year.

14. I enjoyed this problem solving experience (select one).

<table>
<thead>
<tr>
<th>Strongly disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly agree</th>
</tr>
</thead>
</table>

15. Did you feel that the piston-cylinder classroom demonstration showing how p-V data are obtained improved your understanding of the central concepts (select one)?

<table>
<thead>
<tr>
<th>Strongly disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly agree</th>
</tr>
</thead>
</table>

16. Would you get more out of this MEA if you were required to obtain your own p-V data, rather than have it provided to you (select one)?

<table>
<thead>
<tr>
<th>Strongly disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly agree</th>
</tr>
</thead>
</table>

17. How generalizable (i.e. applicable to similar problems) do you think your solution was (select one)?

- Not applicable to any other problem
- Generalizable to only similar other problems
- Neither generalizable, nor not generalizable
- Generalizable to similar and non similar problems

18. In what other ways could we improve this MEA the next time we assign it?

- Nothing really, I think it was quite good. The directions were clear and we knew what to do from the start.

Thanks for your time in helping improve this activity.