# AC 2011-2004: CONVERTING HEAT TO WORK: A THERMODYNAMICS DESIGN PROJECT

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# Converting Heat to Work: A Thermodynamics Design Project

Abstract: The conversion of heat into work is a fundamental concept addressed in the study of thermodynamics. While the concepts involved in the conversion process are developed thoroughly through course work and lecture there remains a disconnect between learning the subject on paper and fully appreciating how difficult the conversion is to accomplish. This paper discusses an open-ended design project in which students bridge the gap by designing a device that converts heat produced by a candle into the work of raising a quarter vertically. The act of designing and testing the device allows students the opportunity to analyze the conversion process using material learned in class and provides a valuable hands-on experience dealing with the physical phenomena involved (i.e. friction, heat loss, sudden expansion, etc). The project has been administered at multiple universities with students participating in small teams and feedback gathered through post-project surveys. Several iterations of the project have been administered with variations in the analysis required, in-class time dedicated to the project, budget provided and final testing procedures. The lessons learned regarding these different iterations are synthesized, an overview of some of the different design concepts is presented and suggestions are provided for successful implementation of the design project.

## Introduction

Laboratory components to engineering courses are valuable for providing students hands-on experiences, demonstrating principles learned during lecture and developing basic experimental and measurement skills. Depending on the target learning outcomes, students in a lab class may take part in a variety of experiences including demonstrations, "cookbook" type experiments, guided inquiry exercises, and design, build, test (DBT) projects [1, 2, 3, 4].

In DBT projects a student has the valuable opportunity to learn the complications and compromises engineers must face while trying to convert an idea into a reality during the design and build phases. The testing phase provides concrete feedback on how well a design functions. This in turn generates discussion of errors in judgment during the design process and potential improvements on the design. DBT projects also allow students to incorporate analysis techniques developed during lecture both in the design phase, and following the testing phase; further cementing fundamental concepts and demonstrating their relevance.

In this paper a DBT project is discussed in which teams of 2-3 students must convert heat into work as part of an introductory thermodynamics course for junior level engineers. Incorporation of the project promotes multiple Accreditation Board for Engineering and Technology (ABET) specified program outcomes[5] including:

outcome a. Ability to apply mathematics, science and engineering principles
outcome b. Ability to design and conduct experiments, analyze and interpret data
outcome c. Ability to design a system, component, or process to meet desired needs
outcome e. Ability to identify, formulate and solve engineering problems
outcome j. Knowledge of contemporary issues
outcome k. Ability to use the techniques, skills and modern engineering tools necessary for engineering practice

Two approaches to the project were undertaken at different universities under the instruction of two faculty members; one approach was implemented in a lab class and the other in a lecture-based course. Surveys were used to assess student attitudes towards the exercise and possible improvements.

**Project Overview**

The project goal was to convert heat into work. The heat source consisted of a tea light candle and the work to be produced was the raising of a quarter ($0.25). At first glance this may not seem all that difficult to a student, but in reality this project goal is deceptive in its simplicity. Consider, for example, that humans in their modern form have been around for roughly 50,000 years however the use of fire actually predates modern time. The first simple engine which used heat from fire to produce work is credited to Thomas Savery in 1698[6]. Despite utilizing energy in the form of heat, that heat was not converted to useable work for tens of thousands of years. In this project students are being given a few weeks to accomplish this goal. Since the introduction of the heat engine, technology has expanded quickly so that currently the conversion of heat to work is commonplace. Inexpensive engines are very sophisticated and take advantage of modern fuels and materials to output power at relatively high efficiencies. As the current project is constrained by time, budget (and therefore the use of rudimentary materials) and minimal amount of heat available the students find themselves between these two extremes, facing an open-ended problem whose solution is not guaranteed.

**Project Constraints**

Perhaps the single most important part of this project is laying out the project constraints. While some students will give the project their full effort, there are some who will instead spend their time trying to find loopholes in the rules.

Heat source – Students were only allowed to use one or two tea light candles as their heat source. They were not allowed to modify the candle in any way other than to reduce the overall weight by removing some wax. Using such a modest heat source forces students to be creative in their design, lowers the overall costs of the project and makes the project safer.

Embedded energy – Students were not allowed to design other sources of energy, (i.e. kinetic, potential, electrical or chemical) into their project. This meant no other fuel sources may be ignited, no springs, catapults, sling shots, fly-wheels, etc. that are pre-loaded and simply need to be triggered, or other similar shenanigans. The candle could not be used to combust any other material. The goal for the students was to come up with a design which converted the candle heat into work.

Design exceptions – Two exceptions allowed were counterweighting and the use of a cold sink such as ice. Accepting a counterweight gave many designs a much greater chance of success, while hopefully not detracting from the learning. Ice was allowed to be used as a low temperature sink, in conjunction with Sterling engines or Peltier devices.

Safety - Each design required measures to be taken to remove any safety risks that could potentially cause injury. Students were required to submit preliminary design drawings to ensure the design adhered to project constraints. Also, to ensure that this was taken seriously students could lose points if their final design was seen to have safety hazards.

**Additional Project Components**

Though this project was done multiple times by different instructors, the goal for the project and project constraints largely remained the same throughout each of the different iterations. In one case the project was implemented during the lab component of class with 7.5 hours of class time dedicated towards designing and building the project (Case 1). A total of 44 students participated in Case 1 in which the project was a class requirement. In the other case the thermodynamics class of 37 students was purely lecture based and the project was used as an optional extra credit opportunity (Case 2). Some of the specific project components that accompanied each case are described below.

**Quantifying Heat Transfer Rate**

Case 1 - Each team had to independently quantify the rate of heat release from a candle prior to completing the final test. Students designed an experiment to accomplish this and submitted a report to the instructor for approval prior to running the experiment. The report was a single page which described the set-up, measurements, and equations that would be used. Most students settled on using the candle to heat water in an insulated soda can and monitoring the temperature change of the water with time. Teams were required to repeat their experiment multiple times to verify their results.

Case 2 - In order to reduce the amount of outside time required to complete the project the quantification of heat transfer rate from the heat source was determined in class. The experiment was set up the same as mentioned in Case 1 by measuring temperature change as a function of time for a known quantity of water.

**Grading Criteria**

Case 1- Each team received a grade based on the performance of their final product in terms of height reached, accounting for half of their project grade. Each team also received a grade based on a final report, accounting for the other half of their project grade. Overall, this project accounted for 10% of a student's course grade. Points could be lost for failure to design within the project constraints and for not adhering to the due dates for the different aspects of the project. The performance grading rubric is shown in Table 1.

Table 1. Project performance grading rubric (Case 1)

| Grade | Performance Criterion |
|---|---|
| 100% | Quarter raised over 6 ft. vertically |
| 90-100% | Quarter raised from 4-6 ft. vertically |
| 80-90% | Quarter raised from 2-4 ft. vertically |
| 70-80% | Quarter raised from 1-2 ft. vertically |
| 60-70% | Quarter raised, but less than 1 ft. |
| 0-50% | Design showed promise, but did not perform |

Case 2 - The project in the lecture course was given a weight equivalent to a homework assignment as extra credit. The final demonstration was designed as a competition where the winning team won by lifting a quarter approximately 12 ft and received a single step in their final grade. For example, a final grade of B was increased to a B+. In the event that there was a tie, the quality of the analysis was used as a tiebreaker. The extra credit points were divided in half between the demonstration and the analysis. A quarter of the points were awarded for simply showing up at the competition with a design in hand with the other quarter awarded for a successful demonstration. Points were distributed in the analysis similarly to a homework problem, i.e. problem statement, sketch, assumptions, governing equations, work shown and arrival at a reasonable answer.

**Final testing**

Case 1 - Teams were given one hour to perform the final test of their design and produce work. Timing started when the candles were lit and the total work was calculated based on the change in position of the quarter. Once the candles were lit the design had to operate on its own and could not be interfered with in any way. If a team had maxed out their work earlier than the hour provided they could elect to conclude their test early. Testing was done on a team by team basis in the lab. If during the final test the team encountered a problem and wanted to request a re-test, this was allowed, but their final performance grade dropped 7% each time. Of the 16 teams that faced this performance grading, 14 successfully raised their quarter above 6 feet, one team raised it two feet, and one team's design did not function.

Case 2 - The main difference in Case 2's final demonstration was that every team competed at the same time. The students were given one hour to demonstrate their design. It was set-up as a department event that faculty and students from other classes were encouraged to attend. The faculty were given ribbons to award to their favorite designs. If the design failed the students did not receive a quarter of their potential extra credit points. Fourteen of the 15 teams initially created competed in the demonstration. Of the fourteen that competed, only 2 were able to reach the maximum height of 12 ft, 2 teams reached a mid-level height and the remainder were unable to make their designs work the day of the demonstration.

**Budget**

Case 1 - Each team had a budget of up to \$60. This money came out of the lab fees which accommodate the course. Students were allowed to spend more money, but above \$60 they would not be reimbursed. Students were also allowed to find free items, but had to account for what those components would have cost if purchased in their bill of materials. In so doing, designs could be compared on a performance/cost basis even if free materials were used.

Case 2 - The budget in this case was limited to \$20. The students were expected to come up with this amount on their own. The idea behind the limit was to prevent any unfair advantages if students had access to highly engineered parts or exotic chemicals from their internships or current jobs. Students had to account for the estimated cost of every part in their apparatus even if they received the part for free.

**Deliverables**

Case 1- A final report for this project was required which included three major sections. In the design analysis section of the report a team discussed how their final design was reached. This included the main problems trying to be fixed, alternative designs considered, compromises made, initial testing problems and solutions, detailed presentation of final design (either descriptive photographs or Solid Works), bill of materials, and any other relevant information considered or resources used in the design process. A thermodynamic analysis section included data collected during the final testing and the calculation of heat, work and efficiency submitted in a professional manner. This section also described in detail the method used to quantify the heat transfer and asked students to recognize any causes of irreversibilities in their design. The final section was a reflective analysis in which each team discussed the process of designing and testing their improvements; specifically what worked well and what did not. This section also included proposed future improvements for their design. Ideally, the students would recognize that many of the irreversibilites in their design presented an opportunity for potential improvement. Finally, this included a comparison with other sources of conversion technologies in terms of capital costs, fuel costs, and efficiency while including proper citations. A comparison with current technologies demonstrated that the efficiency of the student designs were roughly 1000-10,000 times less than modern engines and power plants, thus adding some perspective to how difficult it is to reach high efficiencies.

Case 2 - The deliverables included competing in a final demonstration and an efficiency analysis. Any team that participated in the demonstration and completed an analysis received extra credit even if their design failed at the final demonstration. The analysis was to be written similarly to a homework problem. The students were to utilize the 1$^{st}$ and 2$^{nd}$ law of thermodynamics to predict the height they could lift the quarter. They also needed to determine the overall thermal efficiency of their conversion process.

**Student Design Ideas**

In that the project was open-ended, there was a large variety of designs used. These designs often centered on a few ideas: Stirling engines, hot air balloons, piston-cylinder devices, Peltier devices, and designs that forced mass from a counter-weighted object. Some samples of these different designs which were successful are presented in Figure 1. Each of these design concepts had their own challenges, but showed that students were clearly approaching the project from many different directions.

Although a number of different approaches were taken to successfully complete the project a few of the designs were prone to failure. The most common design that failed was the Stirling engine design. Many students attempted to build a Stirling engine out of a pop can however to date only about 15% were built well enough to lift the quarter. They failed due to poor sealing, excess friction and improper balancing. The other common failures occurred when using the candle to pressurize a vessel partially filled with water. These vessel frequently sprung leaks requiring resealing before another attempt was made.

a.  b.  c. 

d. 

Figure 1. Student designs - a). Sterling engine, b). hot air balloon, c). piston-cylinder device, d). Peltier device with motor

**Student Feedback**

Following the project a survey was administered to get feedback from the students on this experience. The first part of the survey had students rate certain aspects of the experience on a Likert scale. The results are shown in Table 2. It is seen that students responded very positively to the exercise and how it was administered in both cases. Over 75% of the responses agreed or strongly agreed that the project sparked their interests in the thermal fluid sciences. This is of particular importance in thermodynamics as it is often the first of a 3 part required course series in this field.

Table 2. Survey questions and results

| **Statement rated from 1-5 (1=strongly disagree, 5= strongly agree)** | **Case 1** | **Case 2** |
|---|---|---|
| The design project helped me better understand practical constraints in engineering | 4.49 | 4.3 |
| The design project helped me appreciate the difficulty in converting heat into work | 4.67 | 4.54 |
| I prefer the open-ended structure of the project to one with a more rigid structure | 3.7 | 4 |
| Group based projects are an effective tool for improving engineering skills | 4.47 | 4.23 |
| My learning was improved by having multiple groups design for the same problem | 4.23 | 4.23 |
| The project sparked my interest to learn more about the thermal/fluid sciences | 3.91 | 4.23 |

Certain questions on the survey were included to assess student reactions to some of the differences in project delivery as shown in Table 3.

Table 3. Survey questions and results comparing delivery differences

| **Statement rated from 1-5 (1=strongly disagree, 5= strongly agree)** | **Case 1** | **Case 2** |
|---|---|---|
| I understand how to quantify the rate of heat release from a candle | 4.35 | 3.92 |
| The time provided for the project was adequate | 4.14 | 4.23 |
| The budget provided for the project was adequate | 4.23 | 3.84 |
| The total amount of points for the project was fair for the work required | 3 | 4 |
| The performance requirements and grading were fair | 3.68 | 4.08 |
| The project requirements were at an appropriate level of difficulty | 4 | 4.38 |

The most apparent difference in feedback for the two cases displays the student opinion that the project should be worth more points if implemented as in Case 1. This stems from students feeling that the grade weight should reflect the amount of work and effort put in to create a functioning design. While there was mixed reaction to the performance grading in Case 1, its value was in providing large motivation for coming up with a working design, and testing it to the point where it worked reliably.

Surprisingly, the time provided for the project, and the budgets were shown to be adequate. In fact, some students commented that the $60 budget should have been even less, so as to prevent groups from buying a design, such as a Sterling engine, from ebay.

A few key points can be summarized from the answers to the open-ended questions at the end of the survey.

The Best Part of the Project

- In both cases, students felt the best part was: the hands on building, testing their design, freedom in design, the challenging concept of the project, seeing their final product work, learning how to work in a group and from failure. One student commented that the best part was "The feeling of excitement and pure joy when we successfully raised the quarter. I never knew I could get a feeling like that from thermo!!"
- Specific to Case 2, students uniformly liked having the other faculty members watch the final demonstration. Also, 100% of the students who filled out the survey liked having the project as extra credit. They felt it still motivated them but that they could be more creative without the stress of receiving a grade.

The Worst Part of the Project

- In both cases, students felt the worst part was: seeing many designs fail, choosing a design, having such a small heat source, finding time for their groups to meet, and completing the analysis.
- Specific to Case 1, the students did not like the large weight on performance.

Student reflection on what they could have done differently

- Students realized they could have gotten more out of the project if they had: spent more time on it and managed their time better, come up with and tested multiple designs, and done more research on potential designs.

**Lesson Learned**

It is reiterated here that the biggest lesson learned is the need to have an original set of constraints that are very clear, and do not leave room for interpretation. This, it turns out, can be quite difficult as students can be very clever in trying to find a way to interpret the rules in a way that could allow a design to fit the constraints. Any changing of the rules after initially announcing them can also be interpreted as unfair by other groups despite an intention to simply clarify something or perhaps even make the project easier. If possible, this should be avoided and again stresses the need for being clear upfront.

Additionally, students should be explicitly told that no flammable liquids can be used. Many students considered designs in which the candle heat is used to convert a liquid into a vapor, either to build pressure or move the liquid mass. While the candle will boil water when care is taken, students often first look for fluids with boiling points lower than water. Unfortunately most of these fluids are highly volatile which creates a very dangerous situation in the presence of an open flame. Simply stressing safety in the final design will not prevent risks as students often preliminarily test their concepts carelessly and at home where an instructor cannot put a stop to a bad idea.

Instructors should further be aware that YouTube sometimes led students into a false confidence behind certain designs such as homemade Sterling engines, candle powered hot air balloons, and put-put boats just to name a few. Videos showing designs which seemed to work well at converting heat into some small form of mechanical motion mislead students who would sometimes not test their design until just before its completion date only to realize that their design did not produce the needed lift, or torque, to move the quarter. To address this potential problem it is recommended that students be given a deadline for demonstrating the potential for their design prior to the final test. This forces teams with a poor design to recognize that fact early, and permits time to react accordingly.

Another lesson learned from the implementation of this project is that students would benefit in the future from more guidance on the analysis portion. Book problems have the comfort of being prescribed and students struggle when things become less defined, as is the norm in open-ended problems. Students would benefit from more time in the classroom spent on learning how to estimate or make assumptions regarding variables that are hard or impossible to measure. This is a challenge they will face in the work place and it is a learning goal of open-ended problems. Figuring out how to make these kinds of assumptions and decisions are often left up to the students to figure out on their own. Instead, instruction on decision-making should be addressed in greater detail in the classroom.

A final insight can be gained from comparing the successful completion of the designs in the two cases. In Case 1 the project was weighted as a portion of the grade, in Case 2 the project was given as extra credit. The two cases appropriately weighted the project according to the type of class, lab vs. lecture, however the outcomes of the different grading is significant. Case 1 had a success rate of 87.5% whereas Case 2's success rate was 13.3%. In Case 1 the students were not as happy with the project assessment; however the higher weight may well have had a significant impact on the successful completion of the project. One caveat should be noted, in Case 1, there was significantly more class time dedicated to the project which likely had an impact on the difference in number of working designs. Students who received extra credit indicated in the survey that they felt more comfortable exploring riskier, more creative designs because their grade did not hinge on a working apparatus. A balance must be struck within each engineering course between stressing the importance of achieving a successful result and rewarding creative effort. The two different cases of implementation presented in this paper show that this project is flexible enough to be tailored to help instructors achieve this balance in their own class.

## References


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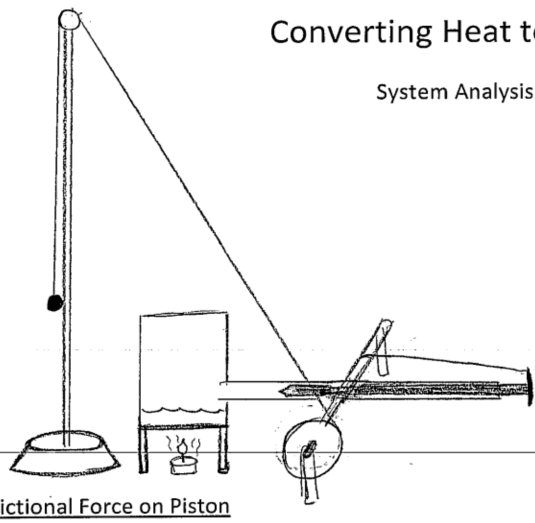
## Appendix

The following is an example report from a Case 2 project.



Converting Heat to Work

System Analysis

Frictional Force on Piston

One source of work is the piston overcoming friction. To estimate this frictional force, we held the piston vertically and hung small weights from the end—increasing the mass until the piston started to move. From this, we were able to estimate the frictional force on the piston.

$$F_f = ma = (.0301\ kg)\left(9.81\frac{m}{s^2}\right) = .295\ N$$

Force to Move Pulley and Quarter

Similarly to the frictional force, we estimated the force required to turn the pulley and moved the quarter upward by hanging weights from the small-diameter pulley.

$$F_{pulley} = ma = (.420\ kg)\left(9.81\frac{m}{s^2}\right) = 4.12\ N$$

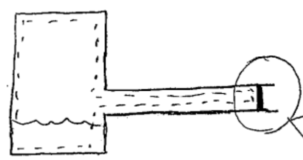
Force to Move Piston

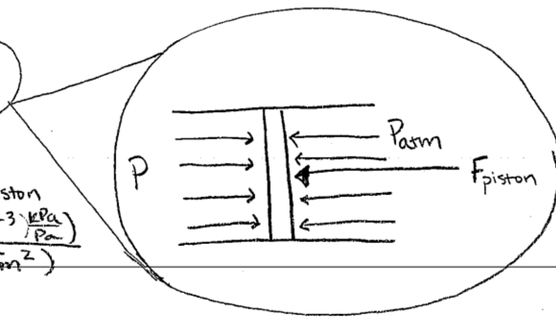
To find the total force required to move the piston, we added the force the move the pulley and the frictional force.

$$F_{piston} = F_f + F_{pulley} = .295 + 4.12\ N = 4.42\ N$$

## Pressure

Based on the total force by the piston, we are able to calculate the pressure inside the container.






$$\Sigma P_x = 0 = P - P_{atm} - F_{piston}/A_{piston}$$

$$P = 101.325\ kPa + \frac{4.42\ N\ (10^{-3}\ \frac{kPa}{Pa})}{(\pi/4)(.0055^2\ m^2)}$$

$$P = 287.365\ kPa$$

## Heat Transfer Rate

Using specific volume to find the mass of the water

$$v = \frac{V}{m_w}$$

$$.00100186\ m^3/kg = \frac{200\ cm^3 \left(\frac{m}{100\ cm}\right)^3}{m_w}$$

$$m_w = .1996\ kg$$

Using table values for u (using the temperature values found during the in-class candle heat experiment), calculating Q

$$Q = m_w(\Delta u)$$

$$Q = (.1996\ kg)\left(245.814 - 80.982\,\frac{\text{kJ}}{\text{kg}}\right)$$

$$Q = 32.905\ kJ$$

Experiment took 20 minutes

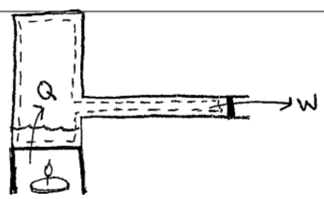
$$\dot{Q} = \frac{32.905\ kJ}{(20\ min)(60\ s/min)} = .02742\ kJ$$

Work

Taking the control volume to be the area inside the container, the total work is boundary work.

$$Distance\ piston\ moves = 1\ ft = .3048\ m$$

$$Diameter\ of\ piston = .0055\ m$$




$$W = P(\Delta V) = (287\ kPa)\left(\pi/4(.0055\ m)^2(.3048\ m)\right)$$

$$W = .00208\ kJ$$

Test run took 32 minutes to raise quarter to ceiling.

$$\dot{W} = \frac{.00208\ kJ}{(32\ min)\left(\frac{60\ s}{min}\right)}$$

$$\dot{W} = .000001082\ kJ/s$$

Efficiency

$$\eta_{th} = \frac{\dot{W}}{\dot{Q}} = \frac{.000001082 \frac{kJ}{s}}{.02742 \frac{kJ}{s}}$$

$$\eta_{th} = .0039\%$$

Our efficiency is very low, as expected. It is far from an ideal system, and this shows that very little of the candle's heat energy actually goes into raising the quarter