Teaching Cycle Optimization in Introductory Thermodynamics Courses

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Introduction

In our competitive economic market, design optimization is crucial. In the area of thermodynamics, optimization is becoming more and more important as consumers and the government become increasingly concerned with energy usage and operating cost. Unfortunately, most students in the thermal sciences are taught little about optimization of thermal cycles and devices. In thermodynamics courses, students are typically given simple thermal cycles to analyze to introduce them to both the cycles and thermodynamic principles. In some curricula cycle design and optimization are not included at all, whereas in others these topics are included only in elective courses in thermal system design. A few schools include the topics in courses required of all mechanical engineering students. As a result, many students may never be involved in either cycle design or optimization. For those who do take an advanced course covering these topics, an early introduction will make the transition from purely analysis to design easier. Thus, thermodynamic cycle design and optimization should be introduced as soon as possible. This paper discusses design projects that allow these topics to be included in already crowded introductory thermodynamics courses.

In any design project, certain constraints must be satisfied. For example, an air conditioning system must remove X Watts of heat from a room. However, once systems have been developed that meets those constraints, how can one choose between those designs? Several optimization possibilities include minimizing first or operating cost, maximizing work output, or maximizing thermal efficiency or second law efficiency. The projects discussed here involve optimizing second law efficiency or operating cost. Maximizing second law efficiency gives the students a better idea of how good their designs are than does maximizing thermal efficiency; second law efficiency is the ratio of the thermal efficiency to the maximum possible thermal efficiency, so an ideal cycle will have a second law efficiency of one. More information on second law efficiency can be found in Bejan[1] or many thermodynamics textbooks. However, if second law efficiency and the related topic of exergy are not included in a course, the projects discussed here can just as easily involve the maximization of thermal efficiency or work output. The projects also could be expanded as desired to include first cost elements or a detailed economic analysis.

Optimization of cycles using hand calculations is very time consuming. Many properties must be looked up in charts and calculations repeated frequently. Especially as cycles become more complicated, these calculations become burdensome. However, the use of computer software to perform calculations makes this process much faster. Several different software programs can be used, or students can write their own computer programs that call thermodynamics properties. In busy thermodynamics courses that have little time for teaching new software (or reminding students how to program), the computer program EES (Engineering Equation Solver) can be helpful (although other programs can be used). EES is a simultaneous equation solver that includes thermodynamic properties. Students can develop parametric tables that allow them to quickly plot the performance (second law efficiency, work output, etc.) as they change important variables. EES is easy to learn -- the author introduces the program in two class periods -- and thus does not take a lot of time away from instruction.

In the past, the author taught cycle design and optimization and the use of EES exclusively through the design projects. While the students said they learned a great deal, some students struggled to complete the projects. They spent so much time getting a working program going and learning how to better use EES that they had little time to think about appropriate design decisions and optimization. This difficulty was a source of frustration for some. It is better to introduce the program more slowly. The author currently introduces the program in one class period held in a computer lab after finishing the lecture topics dealing with the first law of thermodynamics. A handout is given summarizing the steps needed to analyze a problem, and an example first law analysis problem is given so the students can see the necessary format. The students, who sit two per computer, reproduce the example as the instructor presents it. After completing the example, students work on an instructor-assigned problem that they must turn in. The instructor circulates around the room to answer questions. In subsequent weekly homework assignments, students are required to complete a minimum of one problem per week using EES. This process familiarizes the students with the program before the project(s) start, allowing them to focus more on the optimization process. In addition, the students can start to look at how to analyze the effects of properties on their system. For example, the students could be required to plot thermal efficiency verses compression ratio for a simple Otto cycle homework problem. Then by the time the first project is introduced, looking at the effect of cycle properties on its performance will not be a new concept. When the first project starts, a second class period is spent in the computer lab where students are taught to use parametric tables for the purpose of optimization.

The projects discussed here have been used in two different types of thermodynamics courses. At San Jose State University thermodynamics is taught in one four-unit course. The author uses one project in that course. The author previously taught at Baylor University where thermodynamics is spread across two three-unit required courses. Two more complicated projects were used in the second of those courses. The level of difficulty and complexity of the projects discussed here can easily be changed depending on the amount of time available and the level of the students. Two projects — the design of a steam power plant and a dual-temperature refrigeration system — will be discussed below.

Projects

The first project involves the design of a Rankine-cycle steam power plant. (For additional details on an early version of this project see Van Treuren and DeJong[2].) In different semesters, students are required to use different components based on available time and to prevent students from using friends' projects from previous semesters. For example, one semester at Baylor University students were required to use a superheater, two reheaters, two closed feedwater heaters, and one open feedwater heater in addition to components typical in simple cycles such as pumps, turbines, a condenser, and a boiler. At San Jose State where thermodynamics is taught over a shorter time period, the students used one feedwater heater and one reheater in addition to typical components. Students must come up with a schematic of the cycle and perform background research to determine appropriate values such as the maximum temperature that a turbine in this configuration can handle. A schematic from a student project is shown in Figure 1.

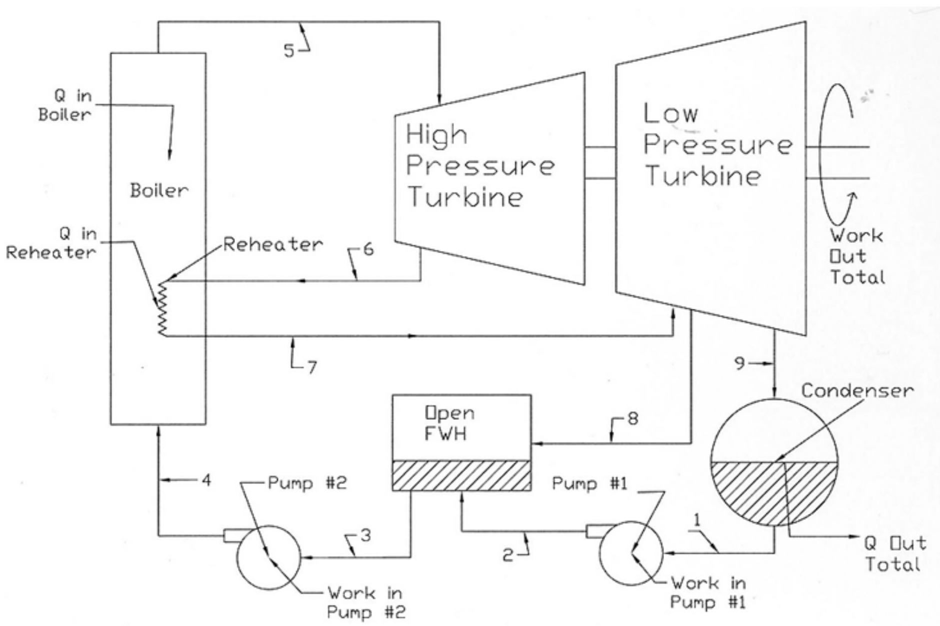

Figure 1 –A cycle schematic from a student project[3]

Based on the time available, students can be given information such as appropriate pump and turbine efficiencies, or they can be required to analyze pump curves and turbine product data to determine appropriate values. Typically students choose somewhat random pressures and temperatures based on values in textbook examples to get their programs up and running. These values are later optimized. An example of a portion of an EES program (from a student project) is shown below in Figure 2. This portion shows the analysis of one turbine where position "5" is the inlet to the turbine and "6" the exit, "turbeff" is the turbine efficiency, "h_{6s}" is the enthalpy at the exit for an isentropic turbine, and "h_{6a}" is the enthalpy at the exit for the actual turbine.

{state 6}
$s_6=s_5$
$P_6=2333 \{kPa\}$
$h_{6s}=enthalpy(steam, s=s_6, P=P_6)$
$h_{6a}=h_5-(h_5-h_{6s})*turbeff$
$T_{6a}=Temperature(steam, h=h_{6a}, P=P_6)$

Figure 2 – A section of an EES program showing analysis of a turbine

The format is quick for most students to learn. They can check their equations by calculating the net work in two different ways: turbine work minus pump work and also heat input minus heat output. If these equations give the same answer, the students know that most likely their program is correct.

Once the students have a working program, they must determine more appropriate values of pressure, temperature, and mass flow bled off to the feedwater heaters. Students must justify each property chosen for their programs. Some of these values can be determined through research or simple equations. For example, while students may not have the heat transfer background to analyze a heat exchanger in depth at this point, they may know that there should be at least a 10°C temperature difference between the condenser and the heat sink (typically river or lake water). This puts a lower bound on the condenser temperature and hence pressure. Some properties come not from research but from optimization. For example, the pressure at the exit of the first turbine (P_6 in Figure 1) can be optimized in EES using a parametric table. The initial arbitrary value of P_6 is removed from the program, and a parametric table allows the value to be varied from a low to high value. The value to be optimized — in this case second law efficiency — is then quickly calculated for each of the values of P_6. The results can be plotted as shown below in Figure 3.

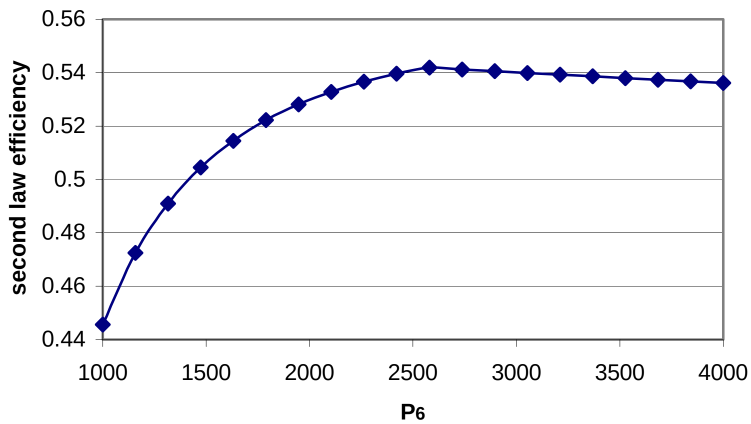

Figure 3 —Plot showing how second law efficiency varies with P_6

The pressure giving the highest value of second law efficiency is then placed in the program. Other pressures and the mass flow rates bled off to the feedwater heaters can be optimized in a similar fashion. Once later values are changed, the first values optimized can be "re-optimized" in case the optimum value has changed. This process can be continued until the optimum values do not change with additional iterations. An alternate method is to use a very large parametric table where values of all components to be optimized are varied. These two methods of optimization are cruder than a sophisticated program that searches among all parameters for optimum system performance. However, they have two benefits: they allow the students to clearly see how component properties affect system performance, and they do not require that the students be taught time-consuming methods that would take more time than is available in these types of courses.

The deliverables for the project are as follows: a two-page written summary of their system and major design decisions, a system schematic, their code showing all calculations, a spreadsheet giving pressure, temperature, mass flow rate, enthalpy, and quality at each location, a T-s diagram, and a section justifying each design decision. The last section can be difficult for many students. They are used to using values given in a textbook or any values that “work”. The students must be given instruction as to what an appropriate justification is — for example, a parametric table showing optimization, a reference listing the maximum temperature a turbine can handle or how a feedwater heater behaves, or a simple equation giving minimum condenser temperature and pressure. Students typically have had little or no experience justifying design decisions in other classes, and without this instruction the author has found that the students perform very poorly in this section. The instruction does not need to take a lot of time and can be included on the handout given at the beginning of the project.

The second project used by the author involves the design and optimization of a multipurpose refrigeration cycle. This project was used in the second required thermodynamics course at Baylor University. For this application, the students need to remove 30 kW of heat from a refrigeration room and 40 kW of heat from a freezer. The refrigerator must be maintained at 10°C and the freezer at -10°C. To facilitate this design, the students are given a brief introduction to both heat exchanger and compressor analysis. In this project students are required to analyze their compressors realistically using the analysis found in Stoecker and Jones[4] to see how cycle conditions affect compressor performance. In some ways this project is easier than the first since there are fewer variables to optimize. However, in this project the students must also do some elementary economic analysis. The students are given the choice of several compressors with various efficiencies and first costs. They must choose the compressor that results in the lowest total cost (first cost plus operating cost) over a five-year period. If an instructor wished to include engineering economics in the class to a greater degree, this portion of the design problem could be expanded.

Like the previous project, this project includes several deliverables: a two-to-four page summary describing the system, major design decisions, and two alternative designs considered; a spreadsheet showing the temperature, pressure, mass flow rate, enthalpy, entropy, and quality (where appropriate) for each state; a printout of the code; a discussion of the choice of compressor; a plot of the mass flow rate through the compressor as a function of pressure ratio across it (to show the students how a compressor operates); a cycle schematic; a T-s diagram; and a section listing and justifying all design decisions in detail. The students initially were also required to give a four-to-five minute presentation of their design in class. However, this presentation met with limited success. Many of the designs were quite similar, and thus groups that presented near the end had little to add. Thus, this presentation has been replaced with a presentation unrelated to the project at a different point in the semester.

Conclusions

The design projects presented here have been used in introductory thermodynamics classes at two different universities to teach thermodynamic cycle analysis, design, and optimization. The size of the projects can be expanded or contracted based on time available, and additional aspects such as component selection and economic analysis can be included without much extra work on the part of the instructor. These projects have been well received by the students—students overwhelmingly have said that they learned about the cycle design and analysis better than they would have using only homework problems. In an end-of-semester survey, the students listed the projects as both enjoyable course activities and effective learning tools more frequently than any other activity. What may be just as important as learning how to design and analyze a cycle is learning how to optimize a cycle and justify design decisions. With additional instruction of these two topics, the author has seen significant improvement in student projects in these areas.

References

1. Bejan, A., 1998, *Advanced Engineering Thermodynamics*, John Wiley & Sons, Inc.

2. Van Treuren, K.W., and N.C. DeJong, 2001, "Using Design to Teach Thermodynamic Cycles: Designing a 250 MW Steam Power Plant Using the Rankine Cycle," *ASME TurboExpo*, New Orleans.

3. Ladd, K., Machado, S., and A. Chauvin, 2001, "Maximum Efficiency of a Rankine Cycle Power Plant," student report, San Jose State University.

4. Stoecker, W.F., and J.W. Jones, 1982, *Refrigeration and Air Conditioning*, McGraw-Hill, Inc.

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