Computer Models Using Spreadsheets to Study Heat Engine Thermodynamics

Kenneth L. Tuttle
U.S. Naval Academy

ABSTRACT
Marine Power Systems is the second term of a two term course in thermodynamics at the U.S. Naval Academy. This is an applied thermodynamics course and is taught by the Marine Engineering faculty. One of the primary objectives of this thermodynamics course is to teach the thermodynamics of heat engines. Marine Power Systems takes the study of Heat Engine Cycles beyond the first step, introduction of how to work the Heat Engine Cycles. The Midshipmen at the Naval Academy write computer models of the heat engine cycles to study the thermodynamics of heat engines. The best example of the thermodynamic cycle modeled is the Brayton Cycle. The Marine Engineering students use a spread sheet program on their personal computers to model the Air Standard Brayton Cycle and run experiments by varying the independent variables.

INTRODUCTION
Traditionally, engineering students learn most or all of the thermodynamic cycles that are in common use to model heat engines. They may learn to work around the Air Standard Cycle for Otto, Diesel and Brayton by assuming air behaves as an ideal gas with constant specific heats. They may also treat the working fluid as a real gas and use Gas Tables or in the case of the Rankine Cycle, Steam Tables. However, it is possible they may never exercise the models to run experiments because that requires working the cycles repeatedly. Learning to work all of the thermodynamic cycles fills up much of the course and working any of the cycles repeatedly is both laborious and very time consuming.

In order to learn what causes the cycle efficiency to increase and what does not, it is necessary to use the thermodynamic model to run experiments. The best way to study the thermodynamic cycles is to use the computer to solve the equations and find the net work and efficiency of the Air Standard Cycle. Assuming the working fluid is air and that it behaves as an ideal gas, allows the prediction of temperature in an isentropic process such as compression or expansion. Using constant specific heats it is possible to calculate the work and the cycle efficiency. Once the model is written, it is very easy to solve the cycle repeatedly using the computer while varying any independent variable of interest. Most of the work is in plotting the results of the experiments. The students learn the results of varying the parameters and at the same time develop a variety of computer skills.

The Marine Engineering Majors study applied thermodynamics in a second term course titled Marine Power Systems. They learn to work the ideal Otto, Diesel, Brayton and Rankine Cycles, even though they learned them to some degree during the first term of thermodynamics. In

Marine Power Systems, the Midshipmen learn both the ideal cycle and the actual cycle for Brayton and Rankine. They make the ideal gas assumption, the Air Standard Cycle, for Otto, Diesel and Brayton. In addition, they treat air as a real gas in the compressor of the gas turbine and use the products of combustion for the working fluid in the combustor and turbines of the gas turbine engine and the Brayton Cycle that models it. They use steam for the Rankine Cycle and use the Steam Tables and Mollier Diagram to solve the ideal cycle, actual cycle and the Rankine Cycle with Regeneration.

SCOPE OF ASSIGNMENT

Only the gas power cycles with the ideal gas assumption are used for the student modeling efforts. In house computer models are used to study the Brayton Cycle with air as a real gas as well as the Rankine Cycle. Then students write their own models to study the variables affecting the gas power cycles in greater depth.

The Marine Engineers are assigned five different computer projects with the later assignments build on the earlier models unless the assignment entails switching to a new gas power cycle. The current and most common assignment is for five levels of the Brayton Cycle. The students start by writing a computer model of the Air Standard Brayton Cycle and vary the pressure ratio from a minimum to a maximum value encountered in gas turbines. They use a spread sheet because it is easier and fairly similar to programming in Basic only without the Read and Write statements. They are able to complete more assignments and plots of results.

COMPUTER MODELS OF CYCLES

Marine Power Systems is organized such that the Marine Engineering students do a computer project consisting of five assignments. One of the five computer assignments is included below in its complete form as an example, in Table 1. As can be seen in Table 1, the problem is defined for the students within a realistic range of existing gas turbine operating parameters. In fact, this problem is set up at the design conditions of the navy's most common main propulsion system, the LM2500 Marine Gas Turbine. This fulfills one of the objectives of the project, that the project will help the Marine Engineers learn about existing marine propulsion systems.

In the initial computer assignment, the student must use a spread sheet, the one they are issued or any other they may have, to solve the equations necessary to work the Air Standard Brayton Cycle. They must calculate the temperature of the air after compression and the work of compression. The spread sheet must calculate the temperature of the air after expansion and the work of expansion. They must find the net work of the cycle and combine it with the heat supplied to find the cycle thermal efficiency and then with the mass flow rate of the working fluid to find the power produced by the gas turbine engine. This touches several objectives. The students learn how to work the Brayton Cycle and they learn how to use a spread sheet and a computer to solve problems and write a simple mathematical model.

The students learn to copy the one line model to work the cycle over a range of values for the independent variable. They run an experiment using the model to determine the effect of varying the pressure ratio on the cycle efficiency and on the cycle net work, the work of compression, the work of the turbine and on the power produced by the gas turbine for the mass flow rate at the design conditions.

Table 1. Example of a Computer Project Using a Spread Sheet.

Marine Power Systems

COMPUTER ASSIGNMENT #1 EN361, 1998

K.L. Tuttle

OBJECTIVES:

To determine the effect of varying pressure ratio in the Air Standard Brayton Cycle on the following dependent variables:

- Compressor Work
- Turbine Work
- Cycle Net Work
- Power Produced by the Cycle Net Work
- Cycle Thermal Efficiency

GIVEN:

Air Standard Brayton Cycle

- Constant Specific Heats
- Air as the working fluid
- Input parameters:
  - a) Atmospheric Pressure: 14.7 psia
  - b) Inlet Air Temperature: 100 °F
  - c) Turbine Inlet Temperature: 2138°F
  - d) Air, mass flow rate: 140 lb_m/sec

REQUIREMENTS:

Use a personal computer and a spreadsheet to write a computer program that will perform a thermodynamic analysis of the Ideal Brayton Cycle. For the information supplied in the section above and a pressure ratio of 2, assume that air is an ideal gas and calculate the temperature at each state point. Find the compressor work, the turbine work, the net work produced by the cycle, the power developed by an engine following the cycle, and the cycle thermal efficiency.

Modify your spreadsheet, computer program to repeat the above calculations holding all input parameters constant with the exception of the pressure ratio. Vary the pressure ratio from 2 to 30 in increments of one unit.

Use the graphics capability of your spreadsheet to produce properly scaled and labeled plots of the following results keeping Pressure Ratio as the independent variable:

- Compressor Work, Turbine Work and Net Work, show on one graph.
- Horsepower
- Cycle Thermal Efficiency

Discuss your results as they appear on your plots and as tabulated and draw your conclusions as they relate to each stated objective. As a minimum, the discussion shall include the objectives demonstrated by the curves, such as:

- the effect that increasing the pressure ratio has on cycle efficiency, power and net work as well as compressor work and turbine work,

- any other pertinent observations you may have made based on your plots and table of data.

Table 1. Example of a Computer Project Using a Spread Sheet. (cont.)

FOR YOUR REPORT: Create a typed cover sheet with your name, course, section, due date and date submitted; turn the cover sheet into an executive summary. An Executive Summary should describe the project and stand alone by stating the following: Title, Objective, Conclusions and Recommendations. Make up an appropriate title(please include CP1), state the conclusions as given or list in separate statements starting each with "To determine the effect of varying .... on..." Place the material in the following order:

- Executive Summary, one page.
- The required plots
- The tabulated data, spreadsheet.
- The typed discussion of results
  - State what each graph is a plot of
  - State what each graph shows in terms of what effect the independent variable has on the dependent variable.
  - Mention any significant observations or results

The final part of the computer work is to plot the results of the experiments. The results are most meaningful if the students are able to see the cycle net work superimposed on the plots of compressor work and turbine work. Since the scale is common to all three lines, the relative values of the numbers is obvious as is the rate of change in each of the plots. The fact that the cycle net work peaks at some intermediate value is also prominently displayed. The students learn computer plotting skills for data presentation for reports or publications and for effective presentations. They also learn to talk to their figures and to discuss their results.

One of the most important aspects of the assignment is the Executive Summary. The Executive Summary consists of the title of the project, the objectives of the experiment and the conclusions that the student was able to draw from the experiment and any recommendations of what to do further or differently. It is critical for a researcher to have a clear idea of the objectives of and experiment. The best indication of that is a clear statement of the objectives.

A student needs to learn to draw and state conclusions from the experimental results. Here they learn to state one conclusion for each objective that was stated. If it is an objective to determine the effect of varying the pressure ratio on the cycle thermal efficiency, then state what happened to the efficiency when the pressure ratio was increased. Did it increase? Did it decrease? Did it remain unchanged? Once they get the basic description, they can elaborate on linearity or other conclusions that can be drawn from observing the results. The students are taught to write each objective and each conclusion in as brief and as clear and concise a statement as possible.

At the conclusion of the first computer assignment, the students have a working model and plotting skills and have completed one experiment on the Brayton Cycle using their own computer model. The assignments are easy to check for errors as the plots flag any computational errors. The students correct any errors and incorporate any improvements to the plots on the second computer assignment. Rarely do any errors make it past the second computer assignments and usually the errors are caught by the students if they feed the model a problem to which they know the correct answers. There is usually an example problem in their textbooks or they will have had the problem on a quiz or exam by the time they need a known problem.

RUNNING EXPERIMENTS

The first computer assignment leaves the students with a model of the ideal Brayton Cycle. The follow up assignments ask them to modify that model to vary other parameters or to add features such as compressor efficiency and turbine efficiency. The follow up assignments also allow the students to vary more than one independent variable and to look for interactions of the independent variables.

For example, the push in gas turbine development is to raise the turbine inlet temperatures. Raising the temperature increases the power produced by the engine, which is understandable, but also it increases the efficiency of the engine, which is in apparent conflict with the theory. The student has learned from the Carnot Cycle that efficiency is a function of the temperature of the heat source and of the heat sink. Either the raising of the heat source or the lowering of the heat sink temperature results in higher cycle efficiency. The student is primed to expect the efficiency of the Brayton Cycle to increase if the turbine inlet temperature is increased. In the second computer assignment, they learn that it does not increase. The follow up assignments help the students to sort through these apparent contradictions.

In Computer Assignment two, the students are asked to determine the effect of varying the ambient air temperature, the heat sink, on the cycle thermal efficiency as well as on the compressor work, net work and engine power. The air temperature actually affects power in two ways. The compressor work changes as does the mass flow rate of the air. Both affect the net power of the engine. The effect of temperature on mass flow rate can be put off until a later assignment or worked in here by assuming that the volume flow rate of the air entering the compressor is constant rather than assuming the mass flow rate of the air is constant if the temperature changes. The former is a better assumption.

The students also vary the temperature of the gases entering the turbine. They can see the effect on turbine work, net work and power, however, to see the effect on cycle efficiency, it is necessary to present the data with the temperature on the x-axis. Several levels of pressure ratio can be used to show the effects of both independent variables and to check for interactions. One of the objectives of the second assignment is “to determine the interactions between temperature of the heat sink and temperature of the heat source and the pressure ratio as they may affect the peak net work of an Ideal Brayton Cycle”. Does the net work peak at a higher pressure ratio if the temperature of the source is increased or if the temperature of the sink is decreased?

Computer Assignment three moves from the ideal cycle to the actual cycle. The assignment is shown in Table 3 as a second example. As can be seen in Table 3 the temperatures are not varied but pressure ratio and compressor and turbine efficiency are. The compressor efficiency is varied separate from the turbine to determine its effect on compressor work, net work, power and efficiency. Then the turbine efficiency is varied to determine its effects. The component efficiencies are varied from the ideal case, one hundred percent efficient, to the low end of a

Table 2. Example of the Project to Model the Actual Brayton Cycle.

Marine Power Systems

COMPUTER ASSIGNMENT #3 EN361, 1998

K.L. Tuttle

OBJECTIVES:

To determine the effects of compressor efficiency and turbine efficiency on the following dependent variables in the Brayton Cycle:

- ○ Compressor Work
- ○ Turbine Work
- ○ Cycle Net Work
- ○ Power Produced by the Cycle Net Work
- ○ Cycle Thermal Efficiency

Determine whether there are any interactions of compressor and/or turbine efficiency with the pressure ratio.

GIVEN:

- ○ Constant Specific Heats
- ○ Air as the working fluid
- ○ Input parameters:

a) Atmospheric Pressure:	14.7 psia
b) Inlet Air Temperature:	100°F
c) Turbine Inlet Temperature:	2000°F
d) Air, mass flow rate:	140 lb_m/sec
e) Compressor Efficiency:	70%, 85% & 100%
f) Turbine Efficiency:	84%, 92% & 100%

REQUIREMENTS:

Using the computer program developed in Computer Assignment #1, modify the program to include the Actual Cycle, actual work and efficiency, then conduct a parametric analysis of the Actual Brayton Cycle to determine the effects of varying compressor and turbine efficiency, or inefficiency since CP1 and CP2 were parametric analyses at compressor and turbine efficiency of 100% and will be used as one level of efficiency in CP3. The lowest setting for the compressor efficiency will be 70% and for the turbine efficiency, 84%. You should leave the turbine at 100% while you reduce the compressor efficiency and leave the compressor at 100% while you reduce the turbine efficiency. In addition, compare the ideal case, CP1, with the actual case with the compressor at 85% and the turbine at 92%.

Use the graphics capability of your spreadsheet to produce properly labeled plots of the following graphs:

- ○ Compressor Work and Net Work vs Pressure Ratio at three Compressor Efficiencies.
- ○ Horsepower vs Pressure Ratio at three Compressor Efficiencies.
- ○ Cycle Thermal Efficiency vs Pressure Ratio at three Compressor Efficiencies.
- ○ Turbine Work and Net Work vs Pressure Ratio at three Turbine Efficiencies.
- ○ Horsepower vs Pressure Ratio at three Turbine Efficiencies.
- ○ Cycle Thermal Efficiency vs Pressure Ratio at three Turbine Efficiencies.
- ○ Compressor Work, Turbine Work and Net Work vs Pressure Ratio (Ideal and Actual)
- ○ Horsepower vs Pressure Ratio at Ideal and Actual Cycle Conditions.
- ○ Cycle Thermal Efficiency vs Pressure Ratio at Ideal and Actual Cycle Conditions.

Discuss your results as graphed on your plots and as tabulated. As a minimum, the discussion shall include the trends demonstrated by the curves, such as:

- ○ the effect that decreasing the compressor or turbine efficiency has on cycle efficiency, power and net work as well as compressor work and turbine work,

- the effect that increasing the pressure ratio has on cycle efficiency, power and net work as well as compressor work and turbine work,
- the interactions that appeared between the independent variables, pressure ratio and the efficiency of the compressor and the turbine.

realistic range of values. In addition the ideal case is compared to the actual case with both components at the approximate efficiencies found on shipboard gas turbines. The graphics requirements increase from the initial assignments.

Because there is more than one independent variable, the data must be examined for interactions between independent variables. The fact that net work and power go negative at a high pressure ratio demonstrates the influence of the component efficiencies. The cycle efficiency, unlike the ideal cycle, does not continue to increase indefinitely and approach a limit of one hundred per cent asymptotically. The pressure ratio at which net work and power peak shifts under the influence of the component efficiencies as well. It is necessary to add one more variable to fully understand the parameters affecting the gas turbine engine.

The fourth assignment asks the student to vary the temperatures as they did in the second assignment and determine whether the effects of air inlet temperature and turbine inlet temperature are different for the actual cycle than they were for the ideal cycle. The fifth assignment has the student incorporating the effects of the ambient air temperature on power produced by the actual gas turbine with the compressor and turbine efficiencies set at the expected values. In the end, it can be seen what the optimum pressure ratio would be to operate a gas turbine engine at under certain conditions of combustor temperatures and compressor and turbine efficiencies.

CONCLUSION

These computer model assignments have been polished over a number of years and many variations have been tried in order to cope with the confusion the students have following the instructions. The students are allowed as much help as they need getting started, as long as it is their fingers running the keyboard and they do not copy. It is not necessary for every student to complete every assignment, only the first assignment is required of all students. The grade for the project, however, is a straight function of the number completed. This allows a student to do extra work for extra credit and it allows the best students to stretch. The projects can be broken into smaller assignments or the project can be taken further if more experiments are conceived. The packet the students return is nice, very impressive, especially the best students.

DR. KENNETH L. TUTTLE

Dr. Tuttle graduated from the U.S. Naval Academy in 1967 with a major option in Mechanical Engineering and went to Oregon State University for an M.S. in 1974, and a Ph.D. in 1977, both Mechanical Engineering. After six years industry experience, he joined the Naval Academy faculty. Currently an Associate Professor in the Department of Naval Architecture, Ocean and Marine Engineering, Dr. Tuttle has served as Director of the Marine Propulsion Laboratories, taught Thermodynamics, Combustion and Design, and is a Past Chairman of the Ocean and Marine Engineering Division. He is the Chairman of the Environmental Panel for SNAME and is a member of the National Research Council's Committee on Shipboard Wastes. Dr. Tuttle has consulted part time since 1972 and markets expertise in automotive emissions, waste-to-energy conversion, gasification and other combustion related specifics. He holds one patent for a method of firing a wood-fired boiler to meet emissions standards and helped develop the first commercial fixed-bed wood-gasifier, the first pulverized-wood swirl-burner, and the first low-underfire-air technology to allow grate fired boilers to pass emissions tests.

Kenneth L. Tuttle
Marine Engineering
U.S. Naval Academy
Annapolis, Maryland 21402
410-293-6454 voice or fax
tuttle@nadn.navy.mil
http://eng.usna.navy.mil/~naomeweb/