ME 370B
Energy Systems II:
Modeling and Advanced Concepts

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Project #1: Gas- and Steam-Turbines, Heat Pumps, and Boilers

Due as a PDF file via Canvas, Thursday, January 19, 11 PM

Gas and steam turbine engines are ubiquitous in today's energy systems. Developing a quantitative understanding of their controlling parameters is a prerequisite to understanding today's state-of-the-art systems and the potential of future energy systems that will likely incorporate many of the same components, if not complete subsystems.

Similarly, boilers and heat pumps (including chillers and air conditioners) are used to control the thermal environment in buildings, industrial processes, etc. Understanding both the ability to directly heat a fluid by using a boiler, as well as how to heat or cool a fluid by pumping heat using work, is again a prerequisite to understanding how advanced energy systems are (or could be) configured.

In this assignment, you will build thermodynamic models of four simple systems—a simple-cycle gas turbine engine, a simple-cycle steam turbine engine, a vapor-compression air conditioner using R134a as the working fluid, and a gas-fired boiler for use in providing hot water or saturated steam for space heating, or superheated steam for power generation.

In each case we will use the framework provided by Matlab and Cantera. The assignments over the next few weeks will build on the codes you develop in this assignment, both to enhance your understanding of concepts to be discussed in class and to begin to demonstrate how system integration (combined cycles) provides significant benefit without requiring new technology.

The Objectives

(1) to brush up on your experience working with Matlab and Cantera from ME370A,

(2) to be able to model systems with both two-phase real fluids and reacting ideal gases,

(3) to gain experience modeling an energy system, and

(4) to understand the basic functioning of gas- and steam-turbine engines, boilers, and heat pumps in anticipation of building on this understanding to develop more advanced systems.

The Assignment

There are four parts to the assignment—one for each member of a four-person group. (If you have a three-person group, you may skip one of the parts.) Each person should write the code for their own part. However, conversation among group members is not only *permitted*, it is strongly *encouraged*.

(1) 25 Points Construct a model of a simple-cycle gas turbine engine (compressor, burner, turbine) using the natural gas mixture specified below with dry engineering air (3.76 moles N_2 per mole O_2, no humidity, no argon, etc.):

Fuel Component	Mole %
Methane	90.7
Ethane	3.6
Propane	1.9
Nitrogen	1.8
Carbon Dioxide	1.0
Oxygen	1.0

Use a pressure ratio of 20:1 and polytropic efficiencies for the compressors and turbine of 90% and 88%, respectively.[1] In order to promote good mixing (and to make the flow rate independent of downstream pressure variations), use a separate compressor for the fuel so as to inject it into the combustor (through nozzles) at a pressure that is twice the combustor pressure. Neglect pressure losses except for across the combustor—use a 5% loss of stagnation pressure there. Assume an allowable turbine inlet temperature of 1600 K. (Note that you will have to solve iteratively to find the correct fuel flow rate to generate this temperature.)

Make a schematic diagram of your system using your choice of drawing/graphics program and indicating the state designations used in your analysis. Depict the cycle on a *T-s* diagram labeling the states with corresponding designations. Because the mass flow rate and composition vary with position in the cycle (air, fuel, air-fuel mixture, products), make the *s* coordinate of the *T-s* diagram the entropy (extensive) of the working fluid per unit mass of fuel consumed by the engine. We will sometimes refer to plots with this type of coordinate—fuel-specific entropy in this case—as being *semi-extensive*. Print the thermal efficiency on a lower-heating-value basis (use Cantera to find the LHV), the air-specific work (work per unit air consumed), and the LHV you find for the natural gas on your plot.

(2) 25 Points Construct a model of a simple steam turbine engine. Since we are mainly interested in the steam side of the cycle, we won't worry about the source of the heat needed to drive this engine (at least for this problem), so confine your analysis to the water side and assume that sufficient heat is available to implement the cycle. Use an evaporator inlet pressure of 170 bar and a condenser inlet pressure of 6.8 kPa. Assume polytropic efficiencies for the pump(s) and turbine of 85% and 80%, respectively.[1] Include stagnation pressure losses of 8% across each of the major heat exchange components—economizer, evaporator, superheater, and condenser—but neglect pressure losses in the interconnecting lines. Use a turbine inlet temperature sufficiently high to provide a steam quality of 85% after expansion through the turbine. (Note that you will have to solve iteratively to find this temperature.) After condensation, the saturated liquid water (condensate) is pumped to a deaerator (see Cengel and Boles' description of open feedwater heating) that uses steam

[1] Polytropic efficiency is the differential version of isentropic efficiency. See the handout *More than you ever wanted to know about…Polytropic Efficiency* on the class Canvas site for an explanation.

extracted from the turbine to remove dissolved gases and to preheat the feedwater. For this purpose, assume that the steam extracted is sufficient to raise the output stream from the deaerator to saturated-liquid conditions at 10 bar (storage conditions) and that the pressure loss across the deaerator is 8%.

Make a schematic diagram of your system using your choice of drawing/graphics program and indicating the state designations used in your analysis. Depict the cycle on a *T-s* diagram with respect to saturation lines and label the state points with your state designations. Print the thermal efficiency (work per unit heat transferred to the steam), water-specific work (work per unit water flow), and the maximum temperature in the cycle on your plot.

FYI: You can investigate the effect of feedwater heating on specific work and efficiency by setting the exit pressure of the deaerator to the condenser pressure in your code. If written in the usual fashion, this should effectively remove the heating from the system and re-route the extracted steam to the turbine.

(3) <u>25 Points</u> Construct a model of a vapor-compression air conditioner using HFC134a as the working fluid. Assume that the refrigerant exits the evaporator as a saturated vapor at 5°C and exits the condenser as a saturated liquid at 50°C. Use a polytropic efficiency of 85% for the compressor.[1] Include a regenerative, counterflow heat exchange between the condenser outlet and the compressor (suction line) inlet. Include stagnation pressure losses of 10% for each of the heat exchange components—evaporator, condenser, regenerator—but neglect pressure losses in the interconnecting lines. Assume an effectiveness of 80% for the regenerator.[2]

Make a schematic diagram of your system using your choice of drawing/graphics program and indicating the state designations used in your analysis. Depict the cycle on a *P-h* diagram (actually log*P* vs. *h*) with respect to saturation lines (see the plotting command *semilogy* in Matlab). Print the coefficient of performance (heat transferred from the cold side per unit compressor work), and the heat transfer per unit mass of refrigerant (capacity) on your plot.

FYI: You can investigate the effect of the regenerative cooler by setting its effectiveness and pressure drop to zero in your code. If written in the usual fashion, this should effectively remove the regenerator from the system.

(4) <u>25 Points</u> Construct a model of a natural gas fired boiler for water. Consider a system producing an outlet stream of 82-bar, 750 K superheated steam from an inlet stream of pressurized water at ambient temperature (requires an economizer, boiler, and superheater).

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[2] Heat exchanger effectiveness is the fraction of maximum heat exchange permitted between two counter-flowing streams. See the handout *More than you ever wanted to know about… Effectiveness, Capacity, and Pinch* on the class Canvas site for an explanation.

A fixed rate of natural gas (assume 1 kg/s) is burned with 10% excess air. Prior to introduction of the fuel, the air (from ambient conditions, 20°C, 1 bar) is preheated by the exiting exhaust (flue) gases in a regenerative heat exchanger with an effectiveness of 90%.[2] Assume that the flue gas exits the regenerative heat exchanger at a temperature of 60°C, which is just above its dew-point and thereby avoids corrosion in the exhaust flue.

For the boiler, assume that the stagnation pressure loss across each component (economizer, boiler, superheater) is 8% on the water side, and that there is a negligible pressure drop on the gas side. Use the same natural gas composition as in Part 1 of this assignment.

Make a schematic diagram of your system using your choice of drawing/graphics program and indicating the state designations used in your analysis. Plot the process for each fluid stream on a semi-extensive *T-h* diagram (temperature vs. extensive enthalpy rate per mass flow rate of fuel) denoting each state and connecting neighboring states with a process path. Include the vapor dome for water on this diagram, and shift the water or flue gas lines such that they are in the correct orientation relative to each other on the plot (process points align in temperature and enthalpy difference). Calculate the mass flow of the water and the first-law efficiency of the system (heat transferred to the water per LHV of fuel consumed) and print these numbers on each plot.

The Write-Up

Only the plots and system schematics are required. On the process plots, be sure to differentiate between process paths that are accurately depicted (a known path, indicated by a solid line), and process paths that are used simply to connect known states (an unknown path, indicated by a dashed line).

In addition to your answers, please include a brief statement of how much time you spent on each part of the analysis and what you thought were the most and least useful aspects of the assignment. (I will ask for this each week.)

The Deliverables

(1) Schematic of the gas turbine system analyzed including state labels
Semi-extensive (fuel specific) *T-s* diagram of the gas turbine states and process paths
- Lower Heating Value of the fuel printed on *T-s* diagram
- Thermal efficiency (LHV basis) of the engine printed on *T-s* diagram
- Air-specific work of the engine printed on *T-s* diagram

(2) Schematic of the steam turbine system analyzed including state labels
T-s diagram of cycle, including the vapor dome
- Thermal efficiency of cycle printed on *T-s* diagram
- Water-specific work printed on *T-s* diagram
- Maximum temperature of cycle printed on *T-s* diagram

(3) Schematic of the chiller system analyzed including state labels
P-h diagram (*semilogy*) of the cycle, including the vapor dome
Coefficient of Performance printed on the *P-h* diagram
Chiller capacity printed on the *P-h* diagram

(4) Schematic of the boiler system analyzed including state labels
T-h diagram showing all streams and the vapor dome for water
Thermal efficiency (LHV basis) printed on the *T-h* diagram
Mass flow rate of water printed on the *T-h* diagram

On Cantera and the critical isotherm

Cantera has a little issue with some real-fluid species when it comes to finding properties near the critical isotherm. I won't go into it here—we will see exactly what it is later when we deal with Helmholtz property fits—but suffice it to say that you can work around it by using Matlab's *try/catch* construct. So if your code has a hissy when you cross by the critical isotherm (for example, while doing a water or carbon dioxide compression/expansion) you can use this construct to skip over the offending interval and continue your process.

On *semilogy* and *hold* for plotting

Matlab has the interesting quirk that *hold* does not work the same way for *plot* and *semilogy*. For *plot* you can engage the *hold* either before or after the first *plot* command. For *semilogy* you must execute one *semilogy* command before you engage the *hold*.