**ME 370B**
**Energy Systems II:**
**Modeling and Advanced Concepts**

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Winter 2023

Project #3: Natural Gas Combined Cycles and System Exergy Analysis

**Group assignment, due as a PDF file via Canvas, Thursday, February 2, 11 PM**

Natural-gas, combined-cycle (NGCC) power plants have become the standard against which alternative fossil-fueled electrical power generation strategies are judged. This is because natural gas is about as easy to work with and environmentally friendly as a fossil fuel can be (very low particulate, very low sulfur, and relatively easy to achieve low NOx), and the combined-cycle nature of the plant—losses from one part are used to advantage in the other—leads to high efficiency at moderate capital cost.

At the heart of any NGCC system are the two types of engine that you considered in the first project: gas- and steam-turbine engines. All a combined cycle power plant is, is a steam-turbine engine which is fed hot gas by a gas turbine engine instead of a boiler. The gas turbine moves the air, burns the fuel, and extracts some exergy as work, and then passes the hot, still-exergetic fluid to the steam turbine to take another whack at capturing the exergy. This pass-off occurs in a heat recovery steam generator (HRSG) that is really no more than a heat exchanger that transfers exergy from the gas turbine exhaust to high-pressure steam flowing through its tubes. This steam carries the exergy to the steam turbine where another portion is converted to work. The exergy that was not captured from the exhaust in the HRSG is carried out the stack and lost, as is any exergy in the steam that is not extracted by its turbine.

In order to get on top of NGCC systems quantitatively there are a couple of things we need to do. The first is to take a slightly closer look at the gas turbine engine itself. If we are to design a combined cycle system we must be in a position to make choices about each of the two cycles that are to be combined. In the first week's project you began this process by developing codes that model simple-cycle gas- and steam-turbine engines. In the first part of this assignment you will further your gas-turbine understanding by using your code to explore the tradeoffs between efficiency and specific work as a function of pressure ratio and firing temperature.

In the second part of the project you will link your understanding of exergy and gas-turbine engines by performing an exergy flow and destruction analysis of a simple-cycle gas turbine engine. The engine you will use is based on the best of today's technologies (at least in the heavy-frame world) and will permit you to see just why and where combining cycles provides advantages that are hard to beat. We have discussed in class how it is that engines are really exergy-management devices. This is where you get to quantify that discussion.

The next part of the assignment is to develop a simple-but-complete, combined-cycle power plant. We will the MS6001 gas turbine that used to operate here on campus (as "Cardinal Cogen") as inspiration for our plant, but eliminate many of the details that are not essential to understanding. We will also focus just on the electricity generation of the plant. That is, we will consider this more from the combined-cycle power rather than cogeneration (simultaneous delivery of electricity and heat) point of view.

The last part of the assignment is to consider a STIG plant. While it is true that steam injection is in common use for both power augmentation and NOx control, we are going to push this a bit further by considering what might be possible if you used very large amounts of steam injection in a state-of-the-art gas turbine. To that end, we will get rid of the steam turbine (significantly reducing capital cost) and use a simpler, lower-effectiveness HRSG just for the purpose of raising steam to inject into the gas turbine. As such, all of the electrical power (or shaft work) will be generated by just the gas turbine, and the steam will be used in an open cycle such that no condenser, cooling tower, etc., are needed. Although this is really just a simple STIG plant, we will see that if we can pull this off (i.e., make the gas turbine tolerate all of the steam) then an interesting possibility exists for how to generate power in an efficient, cost-effective manner. This last part is less of an "analyze what is out there" exercise than an "explore what is possible" one and is in keeping with where we are ultimately headed in this class—teasing out new possibilities for how to engineer efficient, environmentally sound approaches to capturing exergy for a growing, developing world.

This probably goes without saying, but now would be a good time to look through the GE Combined Cycles handout and to browse through the wet-gas-turbine cycle excerpt from Horlock. Neither is critical to getting the assignment done, but both will help you to frame the systems squarely in your mind and are well worth a quick read.

## The Objectives

(1) to gain understanding and experience with gas turbine carpet plots,

(2) to gain experience with tracking exergy and its destruction in complex energy systems,

(3) to gain insight into how exergy analysis can help decision making in energy systems, and

(4) to develop understanding of combined cycle and cogeneration systems.

## The Assignment

As with most of our projects, this one comes in four parts. The first two are relatively straightforward and provide linkages between what you have already done and what we want to learn about combined cycles this week. As you can see from the point assignments, they are the lighter end of the assignment, but getting them right—particularly Part 2—is essential since we will build directly on these in the subsequent two parts.

Parts 3 and 4 are the major new pieces for this week. Part 3 has a lot in it, but much is cut, paste, and integrate from what you already have from Project 1 and from Part 2 above. Part 4 is new ground and will require some thinking as well as calculating, and so you should begin to wrap your mind around it from the get go. That being said, my recommendation would be to read through Parts 3 and 4 to see where you are going and to begin to discuss how to attack the STIG problem, but then begin with Parts 1 and 2 to get going and add perspective to your thinking about the other two. Again I would advise you to work in two teams of two within your group—half the group attacks Part 1, the other half Part 2—then share results, methods, meanings, before again splitting up to tackle Parts 3 and 4. (But this is only a suggestion…)

(1) 15 Points Decisions about the optimal pressure ratio to choose for a gas turbine are often made using a *carpet plot* of efficiency vs. air-specific work. Take your code from the first assignment, strip out anything superfluous, and make a function that reports back the first-law efficiency (LHV basis) and air-specific work of a simple-cycle gas turbine with a specified combination of pressure ratio and turbine inlet temperature.

Write a carpet-plot-generating script to perform a series of calculations showing how efficiency and air-specific work trade off with each other as pressure ratio is varied at fixed turbine inlet temperature. (In other words, make a carpet plot.) Show curves for three levels of permissible turbine inlet temperature: 1600, 1800, and 2000 K. Use the same fuel and performance metrics from the first project (except for turbine inlet temperature) and choose a range of pressure ratios that covers the interesting part of the performance space.

(2) 15 Points Again building on your gas turbine code from the first week, construct semi-extensive plots of fuel-specific internal exergy and fuel-specific flow exergy vs. station number for each of the streams (air, fuel, mix) of the turbine. Use a turbine inlet temperature of 1700 K and a pressure ratio of 23:1 (specs. corresponding to the GE H turbine). Since you will have to construct a more realistic model of air to do your exergy calculations, operate your combustor on environmental air that includes argon, $CO_2$ and water vapor (50% RH) instead of engineering air.

Perform an exergy balance for each component and construct a bar graph that shows exergy destruction by device (compressors, combustor, etc.). Print the first-law (LHV) and exergy efficiencies of the engine on this bar graph. (Is all of the exergy accounted for?)

(3) 35 Points Develop a Cardinal Cogen-inspired, combined-cycle power plant analysis by adding a HRSG and steam turbine to your gas turbine code. Use the device performance parameters listed below, and adjust the steam pressure and flow rate to achieve the steam turbine exit quality and HRSG pinch-point temperature specifications given below. These specifications are drawn from a combination of GE literature for the MS6001 gas turbine and some informed guesses about the state of technology for the plant.

Show both cycles on a temperature vs. fuel-specific enthalpy difference diagram by offsetting the enthalpy of both the gas and steam sides such that they are aligned at the hottest point in the steam cycle (state 5). Print the net power produced by the gas and steam turbines on the diagram.

Borrowing from the codes you generated in Part 2, construct a fuel-specific internal exergy-station plot, a fuel-specific flow exergy-station plot, and an exergy loss (by device) bar graph. Print the first-law (LHV) and exergy efficiencies of the combined-cycle engine on the bar graph. For graphing purposes, treat the HRSG as a single unit (no need to break it up into economizer, boiler, etc.), and assume the water for the Rankine cycle is drawn from cold storage at ambient conditions and without feedwater heating (i.e., omit the deaerator). Since we are "mining the flue gas" for its enthalpy, assume that it is the high-capacity fluid in solving for the heat transfer in the HRSG using the specified effectiveness.

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Turbine Inlet Temperature              = 1410 K
Gas Turbine Pressure Ratio             = 12.2
Burner Pressure Ratio                  = 0.95
Air Compressor Polytropic Efficiency   = 0.86
Fuel Compressor Polytropic Efficiency  = 0.86
Gas Turbine Polytropic Efficiency      = 0.82
HRSG Effectiveness                     = 0.90
Economizer Pressure Ratio              = 0.92
Boiler Pressure Ratio                  = 0.92
Superheater Pressure Ratio             = 0.92
Condenser Pressure Ratio               = 0.92
Steam Turbine Polytropic Efficiency    = 0.75
Condensate Pump Polytropic Efficiency  = 0.85
Feed Pump Polytropic Efficiency        = 0.85
Condenser Pressure                     = 6.80 kPa
Turbine Exit Quality                   = 0.88
Pinch-Point Temperature Difference     =   20 K
Air Mass Flow Rate                     =  144 kg/s
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(4) <u>35 Points</u> Transform the relatively advanced gas turbine engine from Part 2 into a STIG turbine. Assume that the effectiveness of the HRSG is 85%, that the gas turbine exhaust is the high-capacity fluid, and that the steam pressure at injection into the combustor equals that of the fuel gas (twice compressor pressure). Adjust the fuel flow rate as needed to maintain the turbine inlet temperature at 1700 K. Cover a range of steam-air mass ratios from 0 to 0.4 and make the same assumptions about pressure losses going through the HRSG as you used in Part 3 above. Note that finding the correct steam injection temperature will require iteration. (If I were you, I would make a function that reports back the exhaust exit temperature for a given amount of steam injection and a prescribed injection temperature and then use this as a tool in an iteration loop to find the actual temperature based on HRSG effectiveness. But that's just what I would do…)

Plot the first-law efficiency (LHV) and air-specific work vs. steam-air mass ratio. Also plot the gas temperature at the inlet and outlet of the HRSG, the steam temperature exiting the HRSG, the temperature difference between the steam exiting the HRSG and the hot gas entering it, and the pinch-point temperature difference in the HRSG.

Assuming that the combustor can actually tolerate this amount of steam injection (not necessarily the case!) perform an exergy analysis for the case of 0.4 steam/air mass ratio. Construct an exergy-station plot, a flow exergy-station plot, and an exergy loss bar graph. Print the first-law (LHV) and exergy efficiencies on the bar graph. Again, treat the HRSG as a single unit in your exergy-loss analysis.

The Write-Up

Only the plots are required.  Also please include a brief statement of how much time was spent on each part of the analysis and what you thought were the most and least useful aspects.

The Deliverables

(1) Carpet plot of efficiency vs. air specific work
    - Include lines varying pressure ratio for the three specified turbine inlet temperatures

(2) Fuel-specific exergy vs. station number
    Fuel-specific flow exergy vs. station number
    Exergy destruction bar graph
    - LHV efficiency
    - Exergy efficiency

(3) Combined *T-h* diagram for air and steam cycles
    - Semi-extensive based on the fuel, offset for zero difference at state 5
    - Net gas turbine power
    - Net steam cycle power

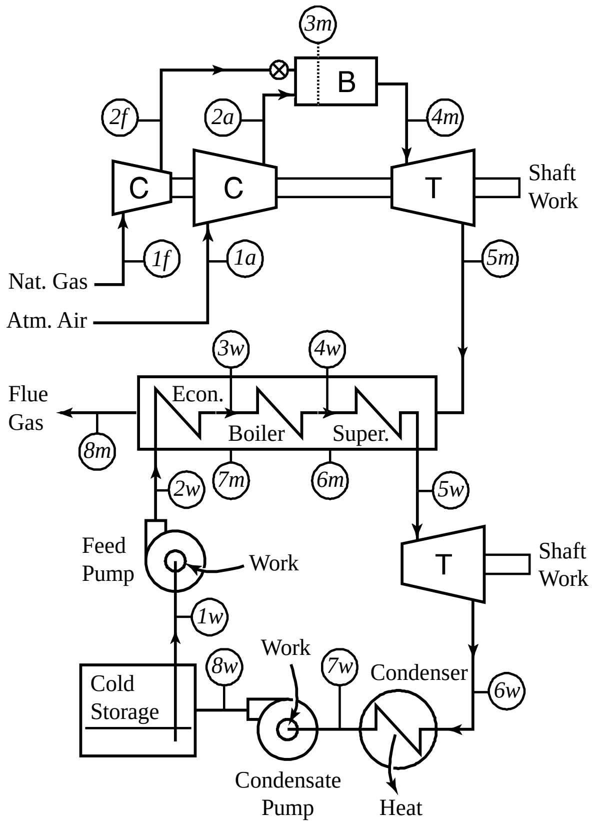
    Fuel-specific exergy vs. station diagram for gas turbine and steam cycle
    Fuel-specific flow exergy vs. station diagram for gas turbine and steam cycle
    Exergy destruction bar graph
    - LHV efficiency of combined cycle
    - Exergy efficiency of combined cycle

(4) Plot the following vs .steam-air mass ratio:
    - LHV efficiency
    - Air-specific work
    - HRSG gas inlet temperature
    - HRSG gas outlet temperature
    - HRSG steam outlet temperature
    - HRSG steam-outlet/air-inlet temperature difference
    - HRSG pinch point temperature difference

    For the 0.4 steam-air mass ratio case:
    - Exergy-station plot for the air and steam cycles
    - Flow exergy-station plot for the air and steam cycles
    - Exergy destruction bar graph
    - First Law (LHV) efficiency
    - Exergy efficiency

The Schematics

Combined Cycle (Part 3)




STIG Turbine (Part 4)