Thermodynamics, Quiz 2, Due at 9 PM on December 5, 2017.
Remember, you have agreed to the Honor code.

Submit the answers in the form of a report. In addition, upload the python codes for each problem as a separate file. You get points only if your code can be successfully executed by the TA or me. All your files should be named according to the following convention: `lastname_report.pdf` for the report, `lastname_problem1.py` for the code for problem 1 (similarly for problem 2 and problem 3).

Problem 1: Supercritical CO_2 power cycles offer the potential for better overall plant economics due to their high power conversion efficiency over a moderate range of heat source temperatures, compact size, and potential use of standard materials in construction [1]. To be able to analyze any thermodynamic cycle, you need to understand the thermodynamic properties of CO_2. In this problem, you are asked to use CoolProp generate a T-s diagram for CO_2, just like the T-s diagram that was supplied to you for water. To draw an useful T-s diagram, do the following:

1. Find the critical pressure and temperature, as well as specific entropy at the critical point for CO_2.
2. First draw the two phase dome on the $T - s$ diagram, i.e., plot the saturated liquid and saturated vapor entropies as a function of temperature. You will have to plot the saturated liquid entropy as one curve and saturated vapor entropy as another curve. The two phase dome exists only below the critical temperature T_{crit}. Draw the two phase dome for temperatures T (in K) such that $280 < T < 0.9999T_{crit}$.
3. Draw isobars for the following pressures: 6 MPa, 6.6 MPa, 8 MPa, 8.8 MPa, 11 MPa, 14.8 MPa, and 23 MPa.
4. Generate constant enthalpy lines for the following values of enthalpy: $\{0.8, 0.9, 1.01, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0\}h_{crit}$, where h_{crit} is the enthalpy at the critical point.
5. Use matplotlib to plot all the above curves on the same $T - s$ diagram. Make sure that the s values are in kJ/K/kg. The numerical values of the s-axis should lie between limits 1 and 2.7 kJ/K/kg. The T-axis should lie between the limits 290 K and 800 K. Use `plt.scatter` or `ax.scatter` to generate scatter plots as opposed to line plots.

Problem 2: The layout of a simple S-CO_2 Rankine cycle is shown in Fig. 1. Though it is called a Rankine cycle, there are similarities to the Brayton cycle too. For example, the use of the regenerator to pre-heat the working fluid before it enters the heat recovery vapor generator (HRVG). The word 'vapor' might be a misnomer because we're dealing with a supercritical cycle. Answer the following questions:

1. Assume that the high and low pressures are 23 MPa and 6.6 MPa respectively. The exit from the condenser can be assumed to be saturated liquid. The exit from the HRVG is at 750 K. Turbine and pump can be assumed to be isentropic. The regenerator efficiency is 0.9. Mark the states 1-6 from Fig. 1 on a $T - s$ diagram.
2. Determine the relevant enthalpies and find the specific work produced by the turbine, the specific work consumed by the pump, the heat supplied to the working fluid in the HRVG (per kg of CO_2), and the overall efficiency of the cycle.
3. Compare the efficiency of a simple S-CO_2 with the efficiency of an ideal steam Rankine cycle with superheat operating between the same turbine inlet temperature (750 K) and condenser temperature (you should/could have determined that in the

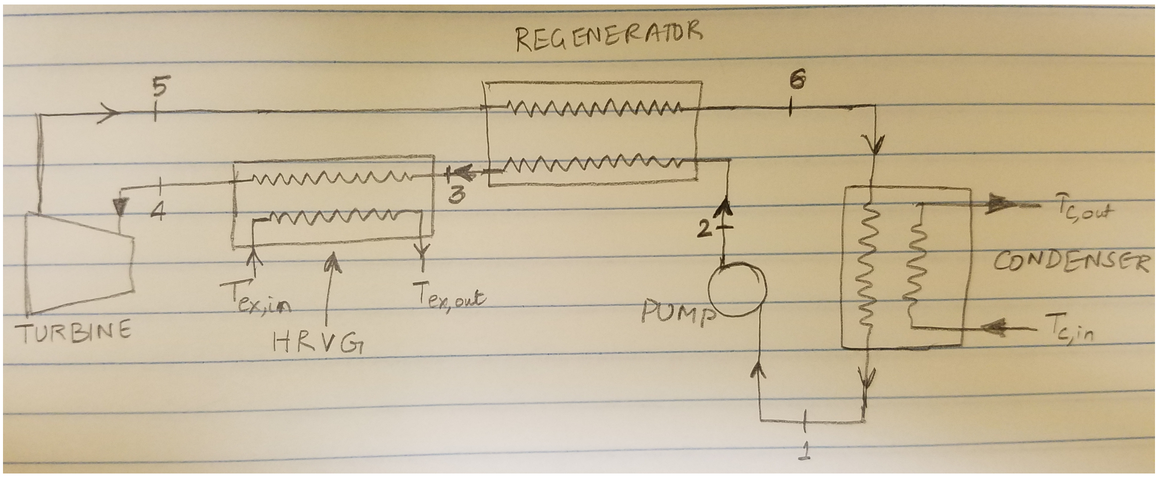

Figure 1: Layout of a simple S-CO_2 Rankine cycle. HVRG stands for *heat recovery vapor generator*.

previous step). Assume that the high pressure of the steam cycle is 20 MPa. No feedwater heaters are used for the steam Rankine cycle.

Problem 3: Exhaust gas at 538 ^{o}C and a mass flow rate of 69.8 kg/s is available as a waste heat source. The outlet temperature of the exhaust gas is 77 ^{o}C. The ambient is at 288 K. Assuming that the turbine and pump have isentropic efficiencies of 0.8 and 0.85 respectively, find the maximum power that can be generated by the simple S-CO_2 operating between 6.6 MPa and 23 MPa. The efficiency of the regenerator is 0.9. The minimum temperature difference between the exhaust gas stream and the working fluid (in the HRSG) should be 30 K and that in the regenerator should be 10 K. The variable under your control is the mass flow rate of the working fluid. Find the mass flow rate(s) that satisfy the two temperature difference criteria. Plot the net power output vs mass flow rate of the working fluid. Assume that properties of the exhaust gas coincide with that of air. Use CoolProp to solve this problem.

References

[1] Thomas Conboy, Steven Wright, James Pasch, Darryn Fleming, Gary Rochau, and Robert Fuller. Performance characteristics of an operating supercritical co2 brayton cycle. *Journal of Engineering for Gas Turbines and Power*, 134(11):111703, 2012.