Review for Exam II **10.213** **04/03/02**
Spring 2002 YT

Study Guide

I advise you to also go through the study guide for the first quiz to remind you of fundamental concepts.

Energy Balance on Open Systems

1) What is the most general form of the energy balance (1^{st} Law) for open system? What terms do we usually neglect because they are not significant?
2) How is shaft work different from the work W?
3) Make sure you are comfortable with the sign conventions. When are Q and Ws positive?
4) If a question asks you about "heat released during heating", does it want value for ΔH, ΔU, Ws, or Q?

2^{nd} Law

5) The formulation of the 2^{nd} Law is: ___________________________________
6) In a sense, the 2^{nd} Law is not a balance. It's an inequality that places a limit on the behavior of the universe. When does the inequality become an equality? At the limit when the process is _________________, we have an equation (rather than just an inequality).
7) What is ΔS for an adiabatic reversible case?
8) How would you calculate ΔS of an ideal gas that goes from some T_1, P_1 to some T_2, P_2?
9) How would you calculate the above for a real gas if there no data (chart,table) are available?
10) In determining the possibility of a device, what three equations must be satisfied?

Equipment analysis

11) What characterizes a throttle valve? It is an equipment used to expand a fluid from ____ pressure to ______ pressure. For a throttle valve, ___________ = 0.
12) In a heat exchanger / condenser / evaporator / boiler, we usually assume that there is no change in _________________.
13) If a turbine is reversible, then ___________ = 0. This allows us to calculate the work produced by the turbine, which is equal to the change in __________________.
14) For an irreversible turbine of a given efficiency, how would you calculate the work produced?
15) A pump is different from a compressor mainly because it is used for _______________ instead for gases. The work of a pump is calculated as ________________________________ because we have assumed that liquids are usually incompressible (V does not change much with P).

Power cycle / Heat engine

16) Describe a Carnot engine. Draw the process on a T-S diagram.
17) What is the definition of efficiency for a power cycle?
18) What is the efficiency of a Carnot engine? What's so special about Carnot efficiency?
19) A Rankine cycle is a real, practical engine. What are the components of a Rankine cycle. Draw the process.
20) Draw the Rankine cycle process on a T-S diagram. Draw it also on a P-H diagram.
21) Should the boiler be operated at the higher temperature or lower? What about the condenser?
22) What is the main purpose of the turbine and the pump?

Refrigeration cycle

23) What is the definition of coefficient of performance (COP) for a refrigeration system?
24) What is the COP of a Carnot refrigerator? The Carnot COP is the ________est possible COP for a refrigeration running between some given T_H and some given T_C.
25) What are the components of a practical refrigeration system? In an industrial refrigerator, work is usually *obtained* using an ______________, whereas in household refrigerators / AC, no work is obtained because the cheaper ______________________ is used instead.
26) Draw the refrigeration process on a T-S diagram. Draw it also on a P-H diagram.
27) Should the evaporator be operated at the higher temperature or lower? What about the condenser?
28) When we say "the refrigerator is doing some cooling", we usually mean that it takes away heat from the surrounding and uses it to ______________________ the refrigerant. How do you calculate the cooling that is done by a refrigeration? Which equipment in the cycle is doing the cooling?
29) What is the main purpose of the turbine and the pump?

<u>A general approach to problems</u>

Think about the following when starting on a problem:

1) Is this familiar? Can I jump into the problem using something I saw before?
   (An example would be if the problem is on a reversible turbine).

2) What is the system that I am choosing? The whole process, one equipment, part of an equipment?
3) Do I need to break up the problems into several parts (e.g. for a power cycle)?
4) What is it that I want to find out? What information is given in the problem?

5) Is my system open or closed?
6) If it's an open system, do I need to write material balance on the system?
7) What are the changes that are happening? Work, heat, shaft work: are these terms given as a number or can I calculate it somehow? Is pressure constant? Is temperature constant? Is *total* volume constant? Is *molar* volume constant? Is it adiabatic? Is $\Delta H = 0$? Is $\Delta S = 0$?

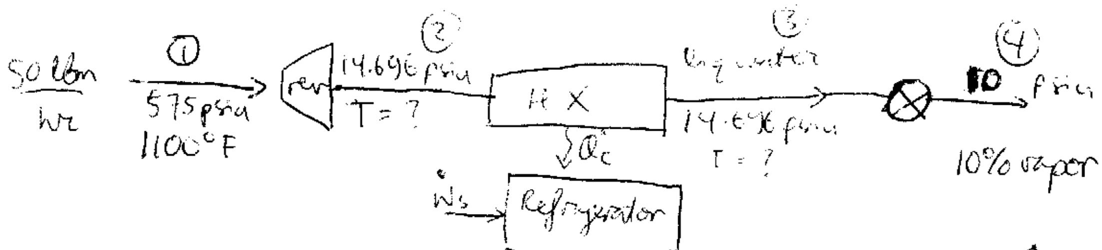
8) How do I get P, T, V, H, U and S (whatever is applicable)?
   a) Am I dealing with an ideal gas?
   b) If it's a real gas, are there data at the back of the book (steam, tetrafluoroethane,etc)?
   c) If it's real and there are no data, am I given an equation of state to use (vdW, Redlich Kwong, etc)?
   d) If it's real, there are no data, and no EOS is specified, then I must use generalized correlation. How do I calculate P, T, or V, or ΔH and ΔS for this?

Of course, there are some special problems that cannot be solved this way (e.g. Problem 17 in Pset E) and require some thinking outside this scheme.

1)

50 lbm/hr of steam at 575 psia and 1100°F passes through a reversible turbine from which it exits at atmospheric pressure (=14.696 psia). It then goes to a heat exchanger where it is condensed and further cooled down to some temperature, all at constant pressure. The cooling is done using a refrigeration unit running on tetrafluoroethane (data on Figure G.2.). The cooled water is then throttled to 10 psia where 10% of the stream is now vapor.

If the refrigeration cycle has a coefficient of performance of 1.5, what is its power requirement (in Btu/hr)? Assume that liquid water has a constant Cp of 1 Btu/lbm°F for temperature range of interest.



Asked: $\dot{W}_s = ?$ $\quad COP = \dfrac{|\dot{Q}_c|}{|\dot{W}_s|} \Rightarrow |\dot{W}_s| = \dfrac{|\dot{Q}_c|}{COP}$ ✓ ?

1st law around HX: $\dot{m}\Delta H_{HX} = \dot{Q}_c + \cancel{\dot{W}_s}$ $\quad \Delta H_{HX} = H_3 - H_2$? ✓ ?

Turbine: $T_1 = 1100°F \quad P_1 = 575\ psia \Rightarrow S_1 = 1.7568\ Btu/lbm;\ H_1 = 1572.6\ Btu/lbm$ (steam table)

Reversible: $S_2 = S_1 = 1.7568\ Btu/lbmR$

Looking up in steam table: $P_2 = 14.696\ psia$, $S_2 = 1.7568\ Btu/lbmR$ $\Rightarrow$ / $H_2 = 1150.5\ Btu/lbm$ / (in fact, saturated vap)

Valve: $\Delta H = 0 \Rightarrow H_3 = H_4 = x \cdot H_{sat\,vap}$ (at 10 psia) $+ (1-x) H_{sat\,liq}$ (at 10 psia)

/ $H_3 = (0.1 \cdot 1143.3 + 0.9 \cdot 161.26)\ Btu/lbm = 259.5\ Btu/lbm$ /

Back to HX: $\Delta H_{HX} = H_3 - H_2 = (259.5 - 1150.5)\ Btu/lbm = -891.0\ Btu/lbm$

$\dot{Q}_c = \dot{m}\Delta H = (50\ lbm/hr)(-891.0\ Btu/lbm) = -44{,}550\ Btu/hr$

$|\dot{W}_s| = \dfrac{|\dot{Q}_c|}{COP} = \dfrac{44{,}550\ Btu/hr}{1.5} = \boxed{29{,}700\ Btu/hr}$

2)

Some gas Z_2 flows through an adiabatic and reversible turbine. It enters at some T_1 and P_1. It produces a shaft work of W (J/mol). Cp can be assumed to be constant.

a) What are the outlet T_2 and P_2 if the gas is ideal? (Express answer in terms of W, T_1, P_1, Cp, and R).
b) Determine T_2 and P_2 if the gas is not ideal but has a relatively constant compressibility factor of 1.2 for the range of temperature and pressure considered?
c) Set up the problem for the case where the gas is in fact well described by generalized correlation?

For adiabatic reversible turbine: $\Delta S = 0 \qquad \Delta H = W_s \cancel{+Q}^{=0}$

a) Ideal gas: $\cancel{W_s} = \Delta H = \int_{T_1}^{T_2} C_p dT = C_p(T_2 - T_1)$ (const C_p)

$$W = C_p(T_2 - T_1) \Rightarrow \boxed{T_2 = \frac{W}{C_p} + T_1}$$

$$0 = \Delta S = \int_{T_1}^{T_2} \frac{C_p}{T} dT - \int_{P_1}^{P_2} \frac{R}{P} dP = C_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right)$$

Rearranging: $P_2 = P_1 \exp\left[\frac{C_p}{R} \ln\left(\frac{T_2}{T_1}\right)\right] = \boxed{P_1 \exp\left[\frac{C_p}{R} \ln\left(\frac{W}{C_p T_1} + 1\right)\right] = P_2}$

b) $\Delta H = \int_{T_1}^{T_2} C_p dT + \int_{P_1}^{P_2} \left[V - T\left(\frac{\partial V}{\partial T}\right)_P\right] dP$ (eq 6.20 in book; also done in lecture)

$\to ?$

$\left(\frac{\partial V}{\partial T}\right)_P = ? \qquad Z = 1.1 \Rightarrow \frac{PV}{RT} = 1.2 \Rightarrow V = \frac{1.2RT}{P} \Rightarrow \left(\frac{\partial V}{\partial T}\right)_P = \frac{1.2R}{P}$

$$\left[V - T\left(\frac{\partial V}{\partial T}\right)_P\right] = \frac{1.2RT}{P} - T\frac{1.2R}{P} = 0$$

$\Delta H = \int_{T_1}^{T_2} C_p dT + 0 = C_p(T_2 - T_1) = W \Rightarrow \boxed{T_2 = \frac{W}{C_p} + T_1}$ same as ideal gas

$$0 = \Delta S = \int_{T_1}^{T_2} \frac{C_p}{T} dT - \int_{P_1}^{P_2} \left(\frac{\partial V}{\partial T}\right)_P dP = C_p \ln\left(\frac{T_2}{T_1}\right) - \int_{P_1}^{P_2} \frac{1.2R}{P} dP$$

$$0 = C_p \ln\left(\frac{T_2}{T_1}\right) - 1.2 R \ln\left(\frac{P_2}{P_1}\right)$$

Rearranging: $P_2 = P_1 \exp\left[\frac{C_p}{1.2R} \ln\left(\frac{T_1}{T_2}\right)\right] = \boxed{P_1 \exp\left[\frac{C_p}{1.2R} \ln\left(\frac{W}{C_p T_1} + 1\right)\right] = P_2}$

c) generalized correl. setup

$\Delta H = W = \Delta H^{ig} + \Delta H^R$

$\Delta H^{ig} = C_p(T_2 - T_1)$

H_1^R & H_2^R from chart or table

$f(T_1, P_1)$ $f(T_2, P_2)$

✓ ✓ ? ?

$\Delta S = 0 = \Delta S^{ig} + \Delta S^R$

$\Delta S^{ig} = C_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right)$

S_1^R & S_2^R from chart or table

$f(T_1, P_1)$ ✓✓ $f(T_2, P_2)$

2 equations, 2 unknowns $\Big]$ → can solve

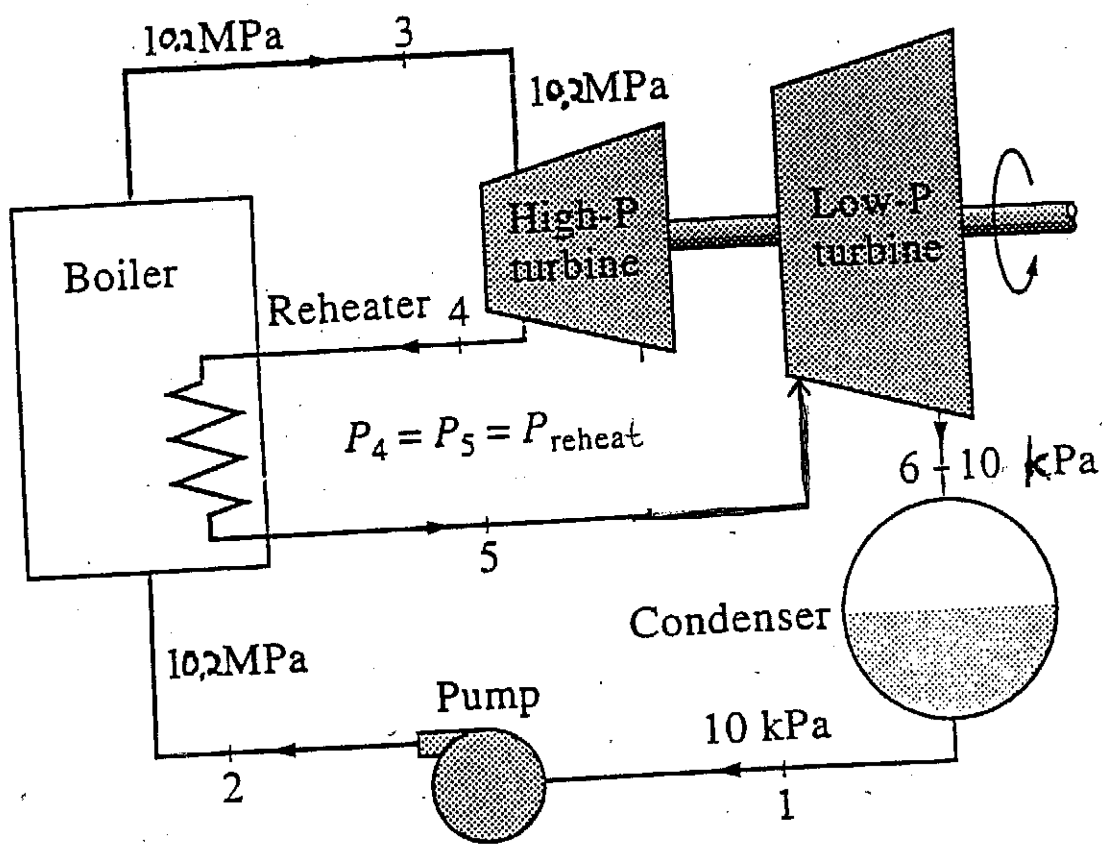
Consider a steam power plant that operates on the ideal reheat Rankine cycle pictured below (i.e, the turbines and compressors operate isentropically). The steam enters the high-pressure turbine at 10.2 MPa and is condensed in the condenser at a pressure of 10 kPa. Streams leaving the boiler exit at 550 °C. The moisture content of the steam at the exit of the low-pressure turbine is not to exceed 10.4 %.

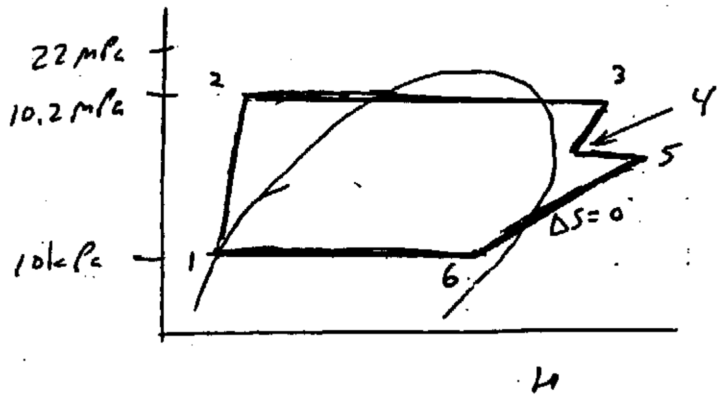
a) Plot the cycle on a T-S diagram and a log P-H diagram labelling the positions of 1 to 6 as in the figure. In drawing the liquid-vapor envelope, sketch the cycle in relation to the critical point for steam. (6 points)

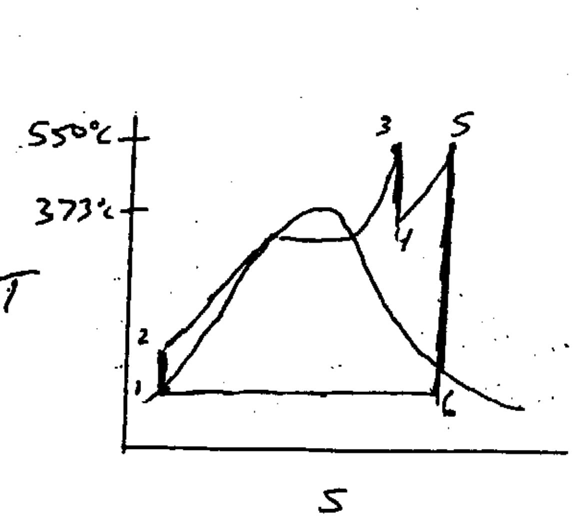
b) Determine the pressure at which the steam should be reheated. (8 points)

c) Determine the thermal efficiency of the process. (8 points)

d) Suggest three ways to improve the thermal efficiency of the cycle and note a practical problem associated with each one. (3 points)







b) To determine the pressure for streams 4 and 5, note that $P_4 = P_5$ (given in problem and boilers are constant pressure) and $S_5 = S_6$ (isentropic process).
For Position 6, P = 10 kPa and x = 1 - 0.104 = 0.896. From page 676, $S^l = 0.6493$ kJ/kg-K and $S^v = 8.1511$ kJ/kg-K. Thus, $S_6 = [(0.104)(0.6493)+(0.896)(8.1511)]$ kJ/kg-K = 7.3709 kJ/kg-K. As $S_5 = S_6$, $S_5 = 7.3709$ kJ/kg-K.
As $T_5 = 550$ °C, find P where $S_5 = 7.3709$ kJ/kg-K. From steam tables (page 692) for these two conditions, $P_5 = 3.0$ MPa.

c) Thermal efficiency = (desired outpu t)/(required input)
Desired output is from turbines - pump = $(H_5 - H_6) + (H_3 - H_4) - (H_2 - H_1)$

H_5 at 550 °C and P of 3.0 MPa = 3568.1 kJ/kg (page 692)
H_6 at 10 kPa and quality of 0.896 = (0.104)(191.832)+(0.896)(2584.8) = 2335.9 kJ/kg
H_3 at 550 °C and P of 10.2 MPa = 3497.8 kJ/kg (page 705)
H_4 at 350 °C and P of 3.0 MPa = 3117.5 kJ/kg
[Note: $T_4 = 350$ °C determined using $S_4 = S_3$ (S3 = 6.7454 kJ/kg-K) and P = 3.0 MPa (page 690)]
H_1 for sat liquid at 10 kPa = 191.832 kJ/kg (page 676)
H_2 for liq at 10.2 MPa = $H_1 + V(P_2 - P_1)$ (get V from page 669 for T = 60 °C))
= 191.8 kJ/kg + 0.001017 m^3/g)([10200-10]kPa)(1 kJ/1 kPa-m^3)
= 191.8 kJ/kg + 10.4 kJ/kg = 202.2 kJ/kg

Desired output = [(3568.1 - 2335.9) + (3497.8 - 3117.5) - (202.2 - 191.8)]kJ/kg = 1602.1 kJ/kg
Required input = boilers = $(H_3 - H_2) + (H_5 - H_4)$
Required input = [(3497.8 - 202.2) + (3568.1 - 3117.5)}kJ/kg = 3746.2 kJ/kg
Thermal efficiency = (desired outpu t)/(required input) = (1602.1 kJ/kg)/(3746.2 kJ/kg) = 0.43

d)

Increase 10.2 MPa to a higher pressure	Hard to handle high pressures (more expensive equipment)
Raise temperature leaving boiler	Need to construct equipment from expensive alloys to handle the temperature/corrosion problems
Lower exhaust P of low P turbine	Need bigger equipment (i.e., greater cost)