Massachusetts Institute of Technology
DEPARTMENT OF MECHANICAL ENGINEERING
Center for Ocean Engineering

2.611 SHIP POWER and PROPULSION

Problem Set #4 Basic Thermodynamic Cycles, Due: October 31, 2006

1. First Law refresher-

a) Write the generic first law thermodynamic equation for a single inlet and single exit flow.

$$\frac{d}{dt}U = Q_{dot} - W_{dot} + m_{in\_dot}\left[h_{in} + g\cdot z_{in} + \frac{\left(V^2\right)_{in}}{2}\right] - m_{out\_dot}\left[h_{out} + g\cdot z_{out} + \frac{\left(V^2\right)_{out}}{2}\right]$$

b) What does this equation not take into account?

The influence of chemical reactions is not included in this calculation.

c) Discuss the adiabatic process, the polytropic process and what it means for a process to be reversible.

AP - A process in which no heat is transferred across the assigned boundary

PP – A process in which during which expansion and compression can be related to ideal gas properties. More specifically, pressure and volume can be related by $PV^n=C$

RP – A reversible process is one that can be reversed without leaving any trace on its surroundings. This is possible only if the net heat and net work exchange between the system and he surroundings is zero for the combined process

2. Air at 10º C and 80kPa enters the diffuser of a jet engine steadily with a velocity of 200 m/s. The inlet area of the diffuser is 0.5 m^2. The air leaves the diffuser with a velocity that is very small compared with the inlet velocity. (Assume the diffuser is the system, flow is steady and air is an ideal gas (R=.287 (kPA*m^3)/(kg*K), enthalpy @ 283 Kelvin ~ 283 kJ/kg)

Determine:

a) The mass flow rate of the air
b) The temperature of the air leaving the diffuser.

$t1 := 283 \cdot K$ $P1 := .080 \cdot MPa$ $velocity\_in := 200 \cdot \frac{m}{s}$ $Area := .5 \cdot m^2$ $R := .287 \cdot \frac{1000 \cdot Pa \cdot m^3}{kg \cdot K}$

$kJ := 1000J$

To determine the mass flow rate, find specific volume of the air using the ideal gas relationship

$Volume\_spec := R \cdot \frac{t1}{P1}$ $Volume\_spec = 1.015 \frac{m^3}{kg}$ $m\_dot := \frac{velocity\_in \cdot (Area)}{Volume\_spec}$

$m\_dot = 98.497 \frac{kg}{s}$

The flow is steady and Energy in = Energy out

$h\_in := 283.14 \frac{kJ}{kg}$ $velocity\_out := 0$

$h\_out = 303.14$

$h\_out := h\_in \cdot \frac{velocity\_in^2}{2}$

$t2 := 303.14K$

3. Consider the tank system below. Tank A has a volume of 100ft^3 and initially contains R134a at a pressure of 100 kPa and a temperature of 313 Kelvin. The compressor evacuates tank A and charges tank B. Tank B is initially evacuated and is of such volume that the final pressure of the R134a in tank B is 800 kPa. Temperature remains constant. Determine the work done by the compressor.

$VA := 100 \cdot ft^3$ $PA := .1MPa$ $TA := 313 \cdot K$ $PB := .8 \cdot MPa$ $TB := 313 \cdot K$

$h\_A := 287.66 \frac{kJ}{kg}$ $vA := .25076 \frac{m^3}{kg}$ $TA = 39.85°C$

$T\_o := TA$

$u\_A := h\_A - PA \cdot vA$

$u\_A = 262.584 \frac{kJ}{kg}$ $s\_A := 1.141 \cdot \left(\frac{kJ}{kg \cdot K}\right)$

$u\_B := 252.13 \frac{kJ}{kg}$ $s\_B := .9374 \left(\frac{kJ}{kg \cdot K}\right)$

$Work\_r := (u\_A - u\_B) - T\_o \cdot (s\_A - s\_B)$ $Work\_r = -5.327 \times 10^4 \frac{1}{kg} joule$

$mass := \frac{VA}{vA}$ $mass = 11.292kg$ $Work\_rev := Work\_r \cdot mass$

$Work\_rev = -6.016 \times 10^5 J$

Negative indicates work was added to the system

4. Steam enters an adiabatic turbine at 8 MPa and 500C with a mass flow rate of 3kg/s and leaves at 30 kPa. The isentropic efficiency of the turbine is .9. Neglecting kinetic energy, determine:

a) Temperature at the turbine exit
b) Power output

Define state 1 and 2

$m1 := 3 \cdot \frac{kg}{s}$

$v1 := .0417 \cdot \frac{m^3}{kg}$ $h1 := 3398.3 \frac{kJ}{kg}$ $s1 := 6.724 \frac{kJ}{kg}$ $Pi := 8 \cdot MPa$ $T1 := 773.15 K$

$P2 := .030 \cdot MPa$

s1 = s2 for an adiabitic process. Using the tables provided, saturated vapor temperature is 342.25 K

$T2 := 342.25 K$

Now state 2 is defined in the saturated region.

$hf := 289.23 \frac{kJ}{kg}$

$sf := .9439 \frac{kJ}{kg}$ $sfg := 6.8337 \cdot \frac{kJ}{kg}$

$hfg := 2336.1 \cdot \frac{kJ}{kg}$

$hg := 2625.5 \frac{kJ}{kg}$

$\frac{(s1 - sf)}{sfg} = 0.846$

.846 represents the quality of the sat vapor. Use this to determine the enthalpy at state 2.

$h2 := hf + .846 \cdot hfg$ $h2 = 2.266 \times 10^3 \frac{kJ}{kg}$

$h\_actual := [.9 \cdot (h1 - h2) - h1]$

$h\_actual = -2.379 \times 10^3 \frac{kJ}{kg}$

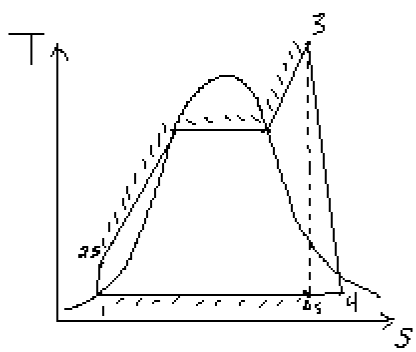
$Work := m1 \cdot (h1 + h\_actual)$

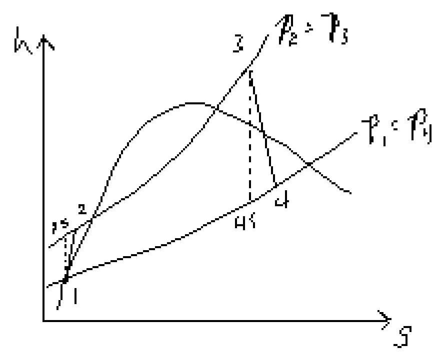
$\boxed{Work = 3.058 \times 10^3 \frac{1}{s} kJ}$

5. A marine steam plant operates as a simple Rankine cycle with a turbine inlet temperature and pressure of 600 °C and 4 MPa. The condenser operates at a pressure of 20kPa. Assume that the turbine isentropic efficiency is 80% and the pump isentropic efficiency is 90%.

a. Sketch the cycle on T-s and h-s diagrams.
b. Determine the steam quality at exit from the turbine.
c. Determine the specific enthalpy change across each component.
d. Determine the net power of the cycle with a mass flow rate of 3 kg/s.
e. Determine the thermal efficiency of the Rankine cycle.

a). T-s and h-s diagrams





b). Steam quality

$p_1 := 0.02\text{MPa}$ $\quad p_3 := 4\text{MPa}$ $\quad T_3 := 873.15\text{K}$ $\quad \eta_t := 0.8$ $\quad \eta_p := 0.9$

$p_4 := p_1$ $\quad p_2 := p_3$ $\quad T_1 := 333.21\text{K}$ $\quad v_1 := .001017\frac{\text{m}^3}{\text{kg}}$

From the steam tables:

$h_3 := 3674.4\frac{\text{kJ}}{\text{kg}}$ $\quad h_1 := 251.42\frac{\text{kJ}}{\text{kg}}$ $\quad h_{4f} := 251.42\frac{\text{kJ}}{\text{kg}}$ $\quad s_{4f} := 0.83202\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$

$s_3 := 7.3688\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$ $\quad s_1 := 0.83202\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$ $\quad h_{4g} := 2609.7\frac{\text{kJ}}{\text{kg}}$ $\quad s_{4g} := 7.9072\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$

$s_{4S} := s_3$ $\quad s_{2S} := s_1$ $\quad h_{4fg} := h_{4g} - h_{4f}$

$h_{4fg} = 2.358\times 10^3\frac{\text{kJ}}{\text{kg}}$ $\quad s_{4fg} := s_{4g} - s_{4f}$ $\quad s_{4fg} = 7.075\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$

The quality of steam at 4S is:

$$X_{4S} := \frac{s_{4S} - s_{4f}}{s_{4fg}} \qquad X_{4S} = 0.924$$

Thus, the enthalpy at 4S can be calculated:

$$h_{4S} := h_{4f} + X_{4S}\cdot h_{4fg} \qquad h_{4S} = 2430.242\frac{\text{kJ}}{\text{kg}}$$

The efficiency of the turbine is $\eta_t = \frac{h_3 - h_4}{h_3 - h_{4S}} = 0.78$ (Given) so solve for h_4:

$$h_4 := h_3 - \eta_t\cdot\left(h_3 - h_{4S}\right) \qquad h_4 = 2679.074\frac{\text{kJ}}{\text{kg}}$$

Now, the quality of the steam at 4 can be determined.

$$X_4 := \frac{h_4 - h_{4f}}{h_{4fg}} \qquad X_4 = 1.029$$

c). Determine Δh across each component. We only need to solve for h_2 to complete this. I used a slightly different pump calc. I gave credit for either method.

$$h_{2S} := h_1 + v1 \cdot (p_2 - p_1)$$

$$h_2 := h_1 + \frac{h_{2S} - h_1}{\eta_p} \qquad h_2 = 435.827 \frac{kJ}{kg}$$

$$h_{2S} = 417.386 \frac{kJ}{kg}$$

Δh results:

turbine: $h_3 - h_4 = 995.326 \frac{kJ}{kg}$

pump: $h_2 - h_1 = 184.407 \frac{kJ}{kg}$

steam generator: $h_3 - h_2 = 3238.573 \frac{kJ}{kg}$

condenser: $h_4 - h_1 = 2427.654 \frac{kJ}{kg}$

d). Net power. $m\_dot := 3 \frac{kg}{s}$

$$Power = m\_dot \cdot (w\_dot_t + w\_dot_p) = m\_dot \cdot (\Delta h_t - \Delta h_p)$$

$$Power := m\_dot \cdot [(h_3 - h_4) - (h_2 - h_1)] \qquad Power = 2432.759 kW$$

e). Efficiency of thermal cycle.

$$\eta_{th\_real} := \frac{m\_dot \cdot [(h_3 - h_4) - (h_2 - h_1)]}{m\_dot \cdot (h_3 - h_2)} \qquad \eta_{th\_real} = 0.25$$