Massachusetts Institute of Technology
DEPARTMENT OF MECHANICAL ENGINEERING

2.611/612 SHIP POWER AND PROPULSION

Problem Set 6 Solutions 2006

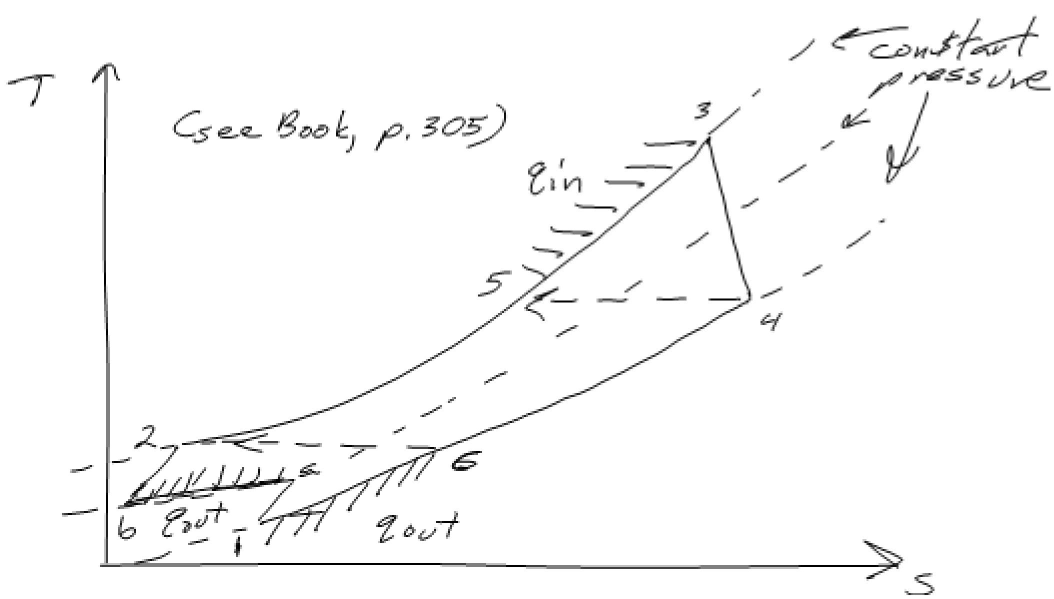
1. Describe the advantages and disadvantages of using a Gas Turbine vs. a Diesel Engine.

Advantages in general (not req'd for answer):
1) Fast Start-Up
2) Modular Construction
3) Easy Automation
4) High Reliability and Maintainabilty

Vs. Diesel
- low efficiency compared to diesel / higher fuel consumption than diesel
- requires higher fuel quality
- harder to repair underway
- higher power density than diesel so frees up space and weight

Ref:Woud, p. 137-138

2. Draw a T-S diagram for an intercooled regenerative Brayton Cycle. Label the points and explain, in words, each portion of the cycle. Mark on your diagram the area where heat is transferred into the system and where it leaves the system.



1 to a: Compressor raises pressure - work in

a - b: intercooler HX removes heat - qout

b-2: 2nd compressor raises pressure - work in

2-5: Fluid pre-heated in regenerator (internal flow)

5-3: Combustion - qin

3-4: Turbine - work out

4-6: Exhaust fluid enters regenerator. Loses heat to the fluid in stage 2-5. (internal)

6-1: In real cycle, heat is lost by exhausting the fluid. In closed cycle, heat is lost to a heat exchanger. - qout

3. Simple closed-cycle Brayton engine

Given:

$T_1 := 298.15K$

$p2\_over\_p1 := 11$

$\eta_c := 0.85$

$T_3 := 1698K$

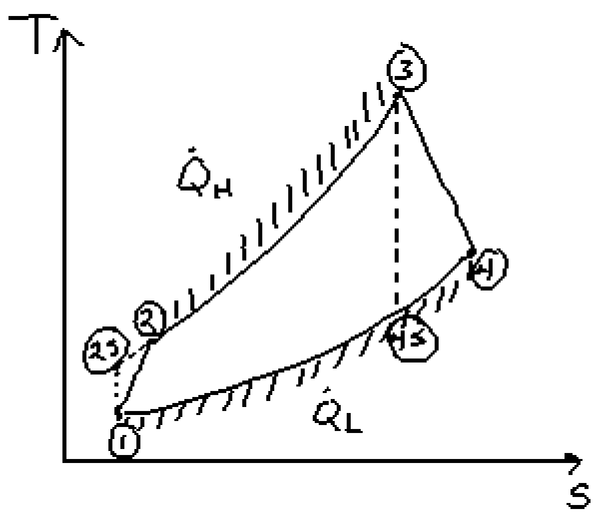
$\eta_t := 0.92$

$\Delta p\_over\_p := 0.06$

$c_{p\_air} := 1.00 \frac{kJ}{kg \cdot K}$

$\gamma_{air} := 1.4$

$m\_dot := 60 \cdot \frac{kg}{s}$



Compressor:

$$\frac{T_{2S}}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma - 1}{\gamma}} \quad = \quad p2\_over\_p1^{\frac{\gamma_{air} - 1}{\gamma_{air}}} = 1.984$$

and for the efficiency

$$\eta_c = \frac{T_1 \cdot \left(\frac{T_{2S}}{T_1} - 1\right)}{T_2 - T_1}$$

so rearrange to get:

$$T_2 = \frac{T_1 \cdot \left(\frac{T_{2S}}{T_1} - 1\right)}{\eta_c} + T_1$$

and using the result above

$$T_2 := \frac{T_1 \cdot \left(p2\_over\_p1^{\frac{\gamma_{air} - 1}{\gamma_{air}}} - 1\right)}{\eta_c} + T_1$$

$T_2 = 643.301K$

Turbine:

$$\frac{p_3}{p_4} = \frac{p_2}{p_1} \cdot \left(1 - \frac{\Delta p}{p}\right) \qquad = \qquad p2\_over\_p1 \cdot (1 - \Delta p\_over\_p) = 10.34$$

and by gas properties:

$$\frac{T_{4S}}{T_3} = \left(\frac{p_4}{p_3}\right)^{\frac{\gamma - 1}{\gamma}} \qquad = \qquad \left[\frac{1}{p2\_over\_p1 \cdot (1 - \Delta p\_over\_p)}\right]^{\frac{\gamma_{air} - 1}{\gamma_{air}}} = 0.513$$

$$T4S\_over\_T3 := \left[\frac{1}{p2\_over\_p1 \cdot (1 - \Delta p\_over\_p)}\right]^{\frac{\gamma_{air} - 1}{\gamma_{air}}}$$

and

$$\eta_t = \frac{T_3 - T_4}{T_3 \cdot \left(1 - \frac{T_{4S}}{T_3}\right)}$$

so rearrange and use the result above for p_3/p_4.

a

$$T_4 := T_3 - \eta_t \cdot T_3 \cdot (1 - T4S\_over\_T3) \qquad T_4 = 937.264K$$

Now that we have the temperatures, we can do the rest of the analyses. $m\_dot := 60 \frac{kg}{s}$

b). ratio of W_dot_compressor/W_dot_turbine

$$W\_dot\_compressor = m\_dot \cdot c_{p\_air} \cdot (h_1 - h_2) = m\_dot \cdot c_{p\_air} \cdot (T_2 - T)$$

$$W\_dot\_turbine = m\_dot \cdot c_{p\_air} \cdot (h_3 - h_4) = m\_dot \cdot c_{p\_air} \cdot (T_3 - T_4)$$

so:

$$\frac{W\_dot\_compressor}{W\_dot\_turbine} \qquad = \qquad \frac{T_2 - T_1}{T_3 - T_4} = 0.454$$

This is also called the "Back work" ratio.

$$Net\_power = W\_dot\_compressor + W\_dot\_turbine$$

c. Net power

$$= m\_dot \cdot c_{p\_air} \cdot (T_1 - T_2) + m\_dot \cdot c_{p\_air} \cdot (T_3 - T_4) = 2.494 \times 10^4 \, kW$$

d. Heater heat transfer rate

$$Q\_dot\_H = m\_dot \cdot c_{p\_air} \cdot (T_3 - T_2) = 6.328 \times 10^4 \, kW$$

e. Thermal efficiency

$$\eta_{th} = \frac{Net\_power}{Q\_dot\_H} = \frac{(T_1 - T_2) + (T_3 - T_4)}{T_3 - T_2} = 0.394$$

4. Regenerative closed-cycle Brayton engine

Given: All values from problem 3 + ...

$$\varepsilon := 0.9(\qquad T_5 := T_2 + .9 \cdot (T_4 - T_2) \qquad T_5 = 907.868K$$

$$q\_in := (T_3 - T_5) \cdot c_{p\_air} \qquad q\_in = 790.132 \frac{kJ}{kg} \qquad Q\_in := q\_in \cdot m\_dot$$

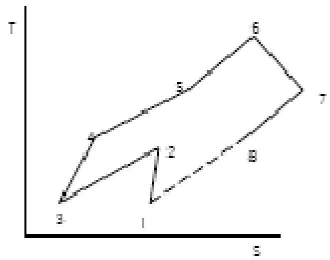
$$Net\_power := [(T_1 - T_2) + (T_3 - T_4)] \cdot c_{p\_air}$$

$$Q\_in = 4.741 \times 10^4 \, kW$$

$$\eta\_th := \frac{Net\_power}{q\_in}$$

$$\eta\_th = 0.526$$

5. Intercooled Recuperative Gas Turbine



$T_1 := 310 \cdot K$

$T_3 := T_1$

$P2\_over\_P1 := 5$

$P4\_over\_P3 := 5$

$T_6 := 1350 \cdot K$

$Pressure\_loss := .1$

$\eta_{pc} := .85$

$\eta_{pt} := .9$

$\eta_{comb} := .92$

$\varepsilon := .85$

$\gamma_a := 1.4$

$c_{pa} := 1.005 \cdot \frac{kJ}{kg \cdot K}$

$\gamma_p := 1.33$

$c_{pp} := 1.130 \cdot \frac{kJ}{kg \cdot K}$

$LHV := 43000 \frac{kJ}{kg}$

$T_\phi := 298.15 K$

$$T_2 := T_1 \cdot P2\_over\_P1^{\frac{\gamma_a - 1}{\gamma_a} \cdot \frac{1}{\eta_{pc}}}$$

$T_2 = 532.488 K$

$$T_4 := T_3 \cdot P4\_over\_P3^{\frac{\gamma_a - 1}{\gamma_a} \cdot \frac{1}{\eta_{pc}}}$$

$T_4 = 532.488 K$

$$P6\_over\_P7 := P2\_over\_P1 \cdot P4\_over\_P3 \cdot (1 - Pressure\_loss)$$

$P6\_over\_P7 = 22.5$

$$T_7 := T_6 \cdot P6\_over\_P7^{(-1) \cdot \left(\frac{\gamma_p - 1}{\gamma_p}\right) \cdot \eta_{pt}}$$

$T_7 = 673.566 K$

$$T_5 := T_4 + \varepsilon \cdot (T_7 - T_4)$$

$T_5 = 652.404 K$

a

$$fuel\_air\_ratio := \frac{c_{pp} \cdot (T_6 - T_\phi) - c_{pa} \cdot (T_5 - T_\phi)}{\eta_{comb} \cdot LHV - c_{pp} \cdot (T_6 - T_\phi)}$$

$fuel\_air\_ratio = 0.022$

b

$$specific\_power := (1 + fuel\_air\_ratio)\cdot c_{pp}\cdot(T_6 - T_7) - c_{pa}\cdot(T_2 - T_1) - c_{pa}\cdot(T_4 - T_3)$$

$$specific\_power = 333.755\frac{kW}{\frac{kg}{s}}$$

c.

$$sfc := \frac{fuel\_air\_ratio}{specific\_power}$$

$$sfc = 0.234\frac{kg}{kW\cdot hr}$$

$$P_{turb} := 20000\,kW$$

$$m\_dot_a := \frac{P_{turb}}{specific\_power} \qquad m\_dot_a = 59.924\frac{kg}{s}$$

d.

Assume ambient air conditions outside the ship

$$Press_{air} := 1\cdot bar \qquad T_{amb} := 298\cdot K$$

$$vel_{duct} := 25\cdot\frac{m}{s}$$

molar weight of air (assume .8 N2 and .2 O2):

$$MW_{air} := .8\cdot 28\frac{gm}{mol} + .2\cdot 32\cdot\frac{gm}{mol}$$

$$MW_{air} = 0.029\frac{kg}{mol}$$

Find air density using PV=nRT

$$\rho_{ambair} = \frac{n}{V}\cdot MW_{air} = \frac{P}{R\cdot T} \qquad Rcon := .08206\frac{L\cdot atm}{K\cdot mol}$$

$$n\_over\_V := \frac{Press_{air}}{Rcon\cdot T_{amb}} \qquad n\_over\_V = 40.359\frac{mol}{m^3}$$

$$\rho_{ambair} := n\_over\_V\cdot MW_{air} \qquad \rho_{ambair} = 1.162\frac{kg}{m^3}$$

$$Vflow := \frac{m\_dot_a}{\rho_{ambair}} \qquad Vflow = 51.555\frac{m^3}{s}$$

$$A_{duct} := \frac{Vflow}{vel_{duct}} \qquad A_{duct} = 2.062\,m^2$$

6.

$t_1 := 303K$ $\quad$ $p2\_over\_p1 := 5$ $\quad$ $p_1 := .1MPa$ $\quad$ $\Delta p\_over\_p := 0.06$

$\eta_c := 0.85$ $\quad$ $t_3 := 1373K$ $\quad$ $\eta_t := 0.92$ $\quad$ $c_{p\_air} := 1.00 \frac{kJ}{kg \cdot K}$ $\quad$ $\eta := .85$

$\gamma_{air} := 1.4$ $\quad$ $m\_dot := 60 \cdot \frac{kg}{s}$ $\quad$ $Power := 18000 kW$

$n_C := 1.5$ $\quad$ $n_T := 1.33$ $\quad$ $\beta := 220 \cdot \frac{kJ}{kg}$ $\quad$ $c_p := \frac{m^2 \cdot 1000}{K \cdot s^2}$

a) The temp after polytropic compression

$$t_2 := p2\_over\_p1^{\frac{n_C - 1}{n_C}} \cdot t_1 \qquad P_c := m\_dot \cdot c_p \cdot (t_2 - t_1) \qquad t_2 = 518.123K$$

$$P_c = 1.291 \times 10^4 kW$$

b) $t_3 = 1.373 \times 10^3 K$

$$t_4 := t_3 \cdot \left(\frac{1}{p2\_over\_p1}\right)^{.25} \qquad t_4 = 918.18K$$

$$P_e := m\_dot \cdot c_p \cdot (t_3 - t_4) \qquad P_e = 2.729 \times 10^4 kW$$

c)

$$t_5 := t_2 + \eta \cdot (t_4 - t_2) \qquad t_5 = 858.172K$$

$$Q\_rel := m\_dt \cdot c_p \cdot (t_3 - t_5) \qquad Q\_rel = 4.212 \times 10^4 kW$$

$$m\_fuel := \frac{Q\_rel}{43000 \frac{kJ}{kg}} \qquad m\_fuel = 0.98 \frac{kg}{s}$$

d) $P_B := P_e - P_c$ $\qquad$ $P_B = 1.438 \times 10^7 W$ $\qquad$ $\frac{P_B}{Q\_rel} = 0.341$

7.

$K_m := 5$ $\quad$ $K_e := 30$ $\quad$ $n := 3 \cdot \frac{1}{s}$

$I_m := 10 \cdot A$ $\quad$ $R_1 := 2 \cdot \Omega$

$U_m := 400 \cdot V$ $\qquad$ $\Phi_m = 4.222 Wb$

$$E := U_m - I_m \cdot R_1 \qquad E = 380 V \qquad \Phi_m := \frac{E}{K_e \cdot n}$$

$$\frac{E \cdot I_m}{n \cdot 2 \cdot \pi} = 201.596 N \cdot m$$

8. AC motor

a. $p := 6$ $f := 60 \cdot Hz$ $n_r = 1164$ rpm $R_r := .1 \cdot \Omega$ $X := .54 \Omega$

$n_s := 120 \cdot \frac{f}{p}$ $N_s = 1200$ rpm

b. $s_s := \frac{n_s - n_r}{n_s}$ $s_s = 0.03$

c. $Z_r := \left(\frac{R_r}{s} \right) + .54 \cdot i \cdot \Omega$ Z_r = 3.377 ohms at an angle of 9.2 degrees

d. $I_r = E/Z_r$ I_r = 44.4 amps at an angle of -9.2 degrees

e. Recalculate using same eqn. in step c above with new slip value

New rotor current = 18.7 amps, angle -3.9 deg.

f. $n_f = 1185$ rpm

Note: Think about the relationship between rotor current, rotor impedance and load.