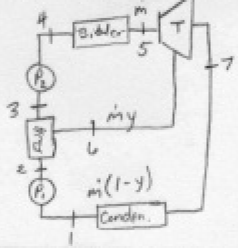
let $y = \frac{\dot{m}_6}{\dot{m}_3}$ $y \equiv$ % in feedwater heater (regenerator)

$r_{BW} = \frac{|w_P|}{w_T}$



Pump

${}_1q_2 = \Delta KE = \Delta PE = 0$

$\eta_P = 1 \Rightarrow s = ¢$ (h_1, v_1)

${}_1w_2 = -v_1(P_2 - P_3)$ ← incomp. liq.

${}_1w_2 = h_1 - h_2$ $w = \frac{w_s}{\eta}$

FWH

$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e$

let $y = \frac{\dot{m}_6}{\dot{m}_3}$

e.g. $\cancel{\dot{m}}(1-y)h_2 + \cancel{\dot{m}} y h_6 = \cancel{\dot{m}} h_3$

$q = w = \Delta KE = \Delta PE = 0$

Boiler

${}_4w_5 = \Delta KE = \Delta PE = 0$

${}_4q_5 = h_5 - h_4$

lookup s_5

Turbine

${}_5q_6 = \Delta KE = \Delta PE = 0$

$\eta_T = 1 \Rightarrow s = ¢$

$s_5 = s_6$

$s_6 = s_f + x_6 s_{fg}$

$h_6 = h_f + x_6 h_{fg}$

${}_5w_6 = h_6 - h_5$

$w = w_s \eta_T$

Condensor

${}_7w_1 = \Delta KE = \Delta PE = 0$

${}_7q_1 = h_1 - h_7$

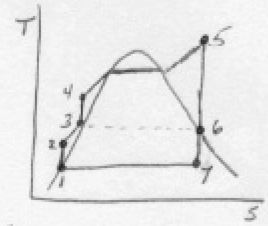
Reheater

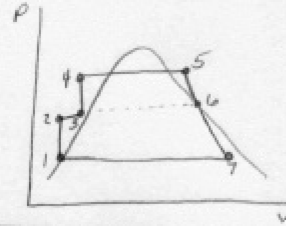
$w = \Delta KE = \Delta PE = 0$

$\eta_{th} = \frac{w_{net}}{q_{in}}$

assume SSSF

$\dot{W} = \dot{m}\, w_{net}$ (no FWH)



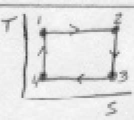


Ways to increase η_{th}	+	Δ
1. Reduce Condensor Press.	$\eta_{th}\uparrow$	$X\downarrow$ erodes turbine
2. Increase boiler temp.	$\eta_{th}\uparrow, X\uparrow$	
3. Increase boiler press.	$\eta_{th}\uparrow$	$X\downarrow$
4. Reduce condensor temp.	$\eta_{th}\uparrow$	$X\downarrow$
5. Increase turbine inlet temp.	$\eta_{th}\uparrow$	$X\downarrow$ % reheat

Deviations from ideal rankine cycle

1. pressure drop in piping
2. pressure drop in condensor, boiler
3. heat transfer from pipes
4. turbine, pump ⇒ $\eta_{th} \neq 1$

Carnot Cycle

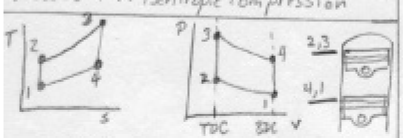


Process 1-2: isothermal expansion
$\Delta KE = \Delta PE = 0$, closed system
$T_1 = T_2$

Process 2-3: Isentropic expansion

Process 3-4: isothermal heat rejection

Process 4-1: isentropic compression



Otto Cycle (closed system)

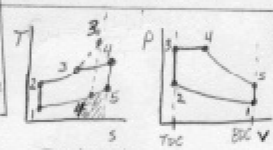
Process 1-2: Isentropic compression
$\Delta KE = \Delta PE = 0 = {}_1q_2$ $\frac{V_2}{V_1} = \frac{v_{r2}}{v_{r1}}$
${}_1w_2 = u_1 - u_2 = C_v(T_1 - T_2)$
$\frac{P_2}{P_1} = (r_v)^k$ ¦ $r_v \equiv \frac{V_1}{V_2}$ ¦ $\frac{T_2}{T_1} = (r_v)^{k-1}$

Process 2-3: $V = ¢$ heat addition
${}_2w_3 = 0 = \Delta KE = \Delta PE$
$\frac{P_3}{P_1} = r_v^{\,k}$ ¦ $\frac{P_3}{P_2} = \frac{T_3}{T_2}$

Process 3-4: $s = ¢$ expansion
${}_3q_4 = \Delta KE = \Delta PE = 0$
$\frac{T_4}{T_3} = \left(\frac{1}{r_v}\right)^{k-1}$

Process 4-1: $V = ¢$ heat rejection
$\Delta KE = \Delta PE = {}_4w_1 = 0$
$mep = \frac{w_{net}}{(V_1 - V_2)}$
$\dot{W} = \dot{m}\, w_{net}$ $\dot{W} = \omega T$
$\dot{m} = \frac{\rho_{in}(V_{PD})(R_s)}{n}$ $T = \frac{\dot{W}_{net}}{2\pi R_s}$
$V_{PD} = V_{BDC} - V_{TDC}$
R_s – rotational speed (RPs)
n – # strokes related to import of mass
$n = 2$ (4-stroke)
$n = 1$ (2-stroke)

$\eta_{th} = 1 - \frac{q_L}{q_H}$



Dual Cycle

Process 1-2: $s = ¢$ compression
$\frac{T_2}{T_1} = (r_v)^{k-1}$
$\frac{P_2}{P_1} = (r_v)^k$

Process 2-3: $V = ¢$ heat addition
$P_3 = P_2 \frac{T_3}{T_2}$

Process 3-4: $P = ¢$
${}_3q_4 = u_4 - u_3 + {}_3w_4$
${}_3w_4 = P(V_4 - V_3) = \int P\,dv$
${}_3q_4 = (u_4 + P_4 V_4) - (u_3 + P_3 V_3)$
${}_3q_4 = h_4 - h_3 \approx C_p(T_4 - T_3)$

Process 4-5: $s = ¢$ expansion
$\frac{V_4}{V_3} = \frac{T_4}{T_3}$
$\frac{V_5}{V_4} = \frac{r_v}{T_4/T_3}$
$T_5 = T_4 \left(\frac{V_4}{V_5}\right)^{k-1}$

Process 5-1: $V = ¢$ heat rejection
${}_5w_1 = \Delta KE = \Delta PE = 0$
${}_5q_1 = u_1 - u_5 = C_v(T_1 - T_5)$
$\eta_{th} = 1 - \frac{q_L}{q_H}$
$w_{net} = \eta_{th}(q_H)$
$mep = \frac{w_{net}}{V_1 - V_2}$

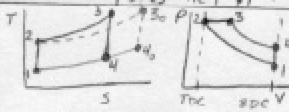
To use r_v & PR exponentiated terms, must be I.G, $C_p = ¢$, $s = ¢$

Dual cycle rejects more heat if r_v & q_H stay the same

Diesel/Otto comparison:
* If q_H same, $q_L \uparrow$, $\eta_{th} \downarrow$
* Can obtain same q_H by compression
* $r_v \uparrow$, $\eta_{th} \uparrow$ & in diesel compress air ∴ no auto-ignite.
* Can't compress Otto because of auto-ignite,
* mep for diesel < Otto because fuel must be at high P to ignite, so limited time for burn
* In otto, P can be lower

– Otto: mep better
$\eta_{th} < \eta_{th}$ of diesel at steady operating conditions

– Carnot Engines: highest η_{th}
size & dependability negate high η_{th}



Diesel Cycle

Process 1-2: $s = ¢$ compression
$\Delta KE = \Delta PE = {}_1q_2 = 0$
$\frac{T_2}{T_1} = (r_v)^{k-1}$
$\frac{P_2}{P_1} = (r_v)^k$

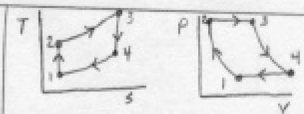
Process 2-3: $P = ¢$ heat addition
${}_2q_3 = u_3 - u_2 + {}_2w_3$
${}_2w_3 = \int P\,dv = P(V_3 - V_2)$
${}_2q_3 = (u_3 + PV_3) - (u_2 + PV_2)$
${}_2q_3 = h_3 - h_2$
$r_c \equiv \frac{V_3}{V_2}$ (fuel cutoff ratio)
$P_2 = \frac{RT_2}{V_2} = P_3 = \frac{RT_3}{V_3}$ ∴ $r_c = \frac{T_3}{T_2}$

Process 3-4: $s = ¢$ expansion
$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{k-1}$ don't calc. work
$\frac{P_4}{P_3} = \left(\frac{V_3}{V_4}\right)^k$
$\frac{V_4}{V_3} = \frac{r_v}{r_c}$

Process 4-1: $V = ¢$ heat rejection
${}_4q_1 = u_1 - u_4$
$\eta_{th} = 1 - \frac{q_L}{q_H}$
$\eta_{th} = 1 - \frac{1}{(r_v)^{k-1}}\left[\frac{r_c^{\,k} - 1}{k(r_c - 1)}\right]$
$w_{net} = \eta_{th} \cdot q_H$
$mep = \frac{w_{net}}{V_1 - V_2}$
$w_{net} \neq {}_1w_2 + {}_3w_4$ because there is ${}_2w_3$

Otto cycle: – good mep
– η_{th} reasonable
– must set P_{max}, T_{max} for dependability
– $\eta_{th} = 1 - \frac{1}{r_v{}^{k-1}}$ for ideal case
$r_v \uparrow$, $\eta_{th} \uparrow$, $T_{max} \uparrow$
– actual operation: knock if $r_v \uparrow$
– $V = ¢$ burn unobtainable so $q_H \downarrow$, $w_{net} \downarrow$
– expansion is cooled
– pumping losses occur
– open valve before BDC ∴ lose work

Diesel cycle:
– if r_v same, $(\eta_{th})_O > (\eta_{th})_{DC} > (\eta_{th})_D$
– Don't have to worry about auto-ignite ∴ $(r_v)_D > (r_v)_O$ ∴ $(\eta_{th})_D > (\eta_{th})_O$
– regulate power by amount of fuel (fuel doesn't burn @ low P)
∴ $(mep)_O > (mep)_D$



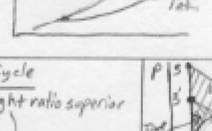
Brayton Cycle (turbine engine)

Process 1-2: ${}_1q_2 = \Delta PE = 0$
${}_1q_2 + h_1 + \frac{V_1^2}{2} + g\cancel{z_1} = h_2 + \frac{V_2^2}{2} + g\cancel{z_2} + {}_1w_2$
isentropic compression (stagnation)
∴ $\cancel{q_2}^{0} + h_{t1} = h_{t2} + {}_1w_2$
cold air I.G.
∴ ${}_1w_2 = C_p(T_{t1} - T_{t2})$
$C_p T_{t1} = C_p T_1 + \frac{V_1^2}{2}$
$PR_c = \frac{P_{t2}}{P_{t1}}$ ¦ $\frac{P_{t2}}{P_{t1}} = \frac{P_{r2}}{P_{r1}}$
$\left(\frac{P_{t2}}{P_{t1}}\right)^{\frac{k-1}{k}} = \frac{T_{t2}}{T_{t1}}$ ¦ $P_{r2} = P_{r1}(PR_c)$

Process 2-3: $P = ¢$ heat addition, SSSF
$\Delta PE = {}_2w_3 = 0$
${}_2w_3 = -\int v\,dP$ ∴ ${}_2w_3 = 0$
${}_2q_3 = \int T\,ds$
${}_2q_3 = h_{t3} - h_{t2} = C_p(T_{t3} - T_{t2})$

Process 3-4: isentropic compression
${}_3q_4 = \Delta PE = 0$
${}_3w_4 = C_p(T_{t3} - T_{t4})$
$s = ¢$, $k = ¢$, I.G.
$PR_c = \frac{P_{r3}}{P_{r4}}$ ¦ $T_{t4} = T_{t3}\left(\frac{1}{PR_c}\right)^{\frac{k-1}{k}}$
$r_{BW} = \frac{w_c}{w_T}$

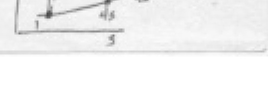
Process 4-1: $P = ¢ = P_{atm}$ heat rejection
${}_4w_1 = \Delta PE = 0$
${}_4q_1 = h_{t4} - h_{t1} = C_p(T_{t4} - T_{t1})$
$\eta_{th} = 1 - \frac{T_{t1}\left(\frac{T_{t4}}{T_{t1}} - 1\right)}{T_{t2}\left(\frac{T_{t3}}{T_{t2}} - 1\right)} = 1 - \frac{1}{(PR_c)^{\frac{k-1}{k}}}$



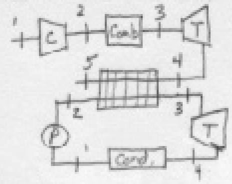
// ∴ don't see effects of T_{max}

Brayton Cycle

power to weight ratio superior
$(\eta_{th})_B < (\eta_{th})_D$
$\eta_{th} = 1 - \frac{1}{(PR)^{\frac{k-1}{k}}}$ (Ideal only)
if $PR_c \uparrow$, $\eta_{th} \uparrow$ (limited PR_c)
if $T_{max} \uparrow$, $\eta_{th} \uparrow$
sees T_{max} all times ∴ limited
$r_{bw} \uparrow$
can add regeneration cycle if $T_{TE} > T_{C1}$



Co-Generation cycle



Comp. T_e must be $<$ Turb. T_e

Process 1-2: Comp. (G.T.)

$$w_{cs} = (h_{t2s} - h_{t1})$$

$$w_c = \frac{w_{cs}}{\eta_c} = h_{t2} - h_{t1}$$

Process 2-3: $P=\text{¢}$ comb. (G.T.)

$$_2q_3 = h_{t3} - h_{t2}$$

Process 3-4: expansion (G.T.)

$$P_{r4s} = P_{r3}\left(\frac{1}{PR_c}\right)$$

$$w_{Ts} = h_{t4s} - h_{t3}$$

$$w_T = w_{Ts} \cdot \eta_{th} = h_{t4} - h_{t3}$$

Process 1-2: Pump (R)

$$w_{ps} = v_f (P_2 - P_1)$$

$$w_p = \frac{w_{ps}}{\eta_p} = h_2 - h_1$$

Process 2-3: heat exchanger

$$_2w_3 = {_2q_3} = \Delta KE = \Delta PE = 0$$

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e$$

$$\dot{m}_{st}(h_3 - h_2) = \dot{m}_G (h_{t4} - h_{t5})$$

Process 3-4: Turbine (R)

$w_{Ts} = h_3 - h_{4s}$, $s_3 = s_{4s} \Rightarrow x_4$

$$h_{4s} = h_f + x_4 h_{fg}$$

$$w_T = w_{Ts} \cdot \eta_T$$

$$\dot{W} = \dot{m}_G (w_{net})_{GT} + \dot{m}_{st}(w_{net})_R$$

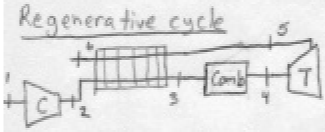
$$\frac{\dot{m}_{st}}{\dot{m}_G} = \frac{h_{t4} - h_{t5}}{h_3 - h_2}$$

$$\dot{W} = \dot{m}_G (w_{net})_{GT} + \left(\frac{\dot{m}_{st}}{\dot{m}_G}\right)(w_{net})_R$$

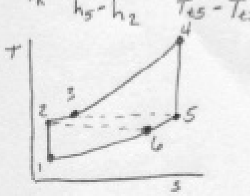
$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_H}$$

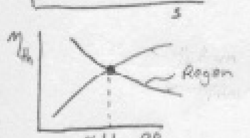
$$\dot{Q}_H = \dot{m}_{GT} ({_2q_3})_{GT}$$

Regenerative cycle



$$\eta_R = \frac{h_3 - h_2}{h_5 - h_2} = \frac{T_{t3} - T_{t2}}{T_{t5} - T_{t2}} \text{ if } c_p = \text{¢}$$





Jet Propulsion

Diffuser: $w = q = 0$

$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2} = h_{t2}$$

$$c_p T_1 + \frac{V_1^2}{2} = c_p T_2 + \frac{V_2^2}{2}$$

$$\dot{m}_1 = \dot{m}_2 \quad \text{solve for } V_2$$

$$\rho_1 A_1 V_1 = \rho_2 A_2 V_2$$

$$P_1 = \rho R T$$

$$A_1 = \frac{\dot{m}}{\rho_1 V_1}$$

$$\frac{P_2}{P_{t2}} = \left(\frac{T_2}{T_{t2}}\right)^{\frac{k-1}{k}}$$

$$T_{t2} = T_2 + \frac{V_2^2}{2c_p}$$

Compressor $q=0$ $s=\text{¢}$

$$w_{cs} = h_{t3} - h_{t2}$$

$$T_{t3} = T_{t2} \cdot (PR)_c^{\frac{k-1}{k}}$$

Combustor $w=0$ $P=\text{¢}$

$$P_{t3} = P_{t4}$$

$$q = h_{t4} - h_{t3}$$

Turbine $q=0$ $s=\text{¢}$

$$w = h_{t4} - h_{t5}$$

$$\frac{P_{t5}}{P_{t4}} = \left(\frac{T_{t5}}{T_{t4}}\right)^{\frac{k-1}{k}}$$

Nozzle

$$P_6 = P_1$$

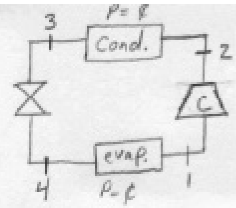
$$\frac{T_6}{T_{t5}} = \left(\frac{P_6}{P_{t5}}\right)^{\frac{k-1}{k}}$$

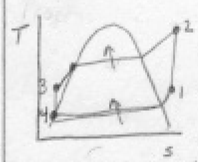
$$c_p T_{6s} + \frac{(V_{6s})^2}{2} = c_p T_{t5}$$

$$V_6 = \sqrt{\eta_N \cdot (V_{6s})^2}$$

$$\text{Thrust} = \dot{m}(V_6 - V_1)$$

$$\eta_{PR} = \frac{(\text{thrust})\, V_1}{q_H \cdot \dot{m}} \leftarrow \text{vel.}$$





Process 1-2 $s=\text{¢}$ comp.

$$\dot{W} = \dot{m}(h_1 - h_{2s})/\eta_c$$

Process 3-4 $s=\text{¢}$

$$_3w_4 = {_3q_4} = 0$$

$$\therefore h_3 = h_4$$

$$h_3 = h_f @ T_3$$

$$\dot{Q}_L = \dot{m}(h_1 - h_4)$$

$$\beta = \frac{\dot{Q}_L}{\dot{W}_{in}}$$

$$y_i = \frac{n_i}{n_m}\left(\frac{\text{kmol}_i}{\text{kmol}_m}\right)$$

mol. weight

$$m_i = M_i y_i \left({}^{kg}/_{kmol}\right)$$

$$M_m = \sum M_i y_i$$

$$mf_i = \frac{m_i}{m_m}$$

$$y_i = \frac{P_i}{P_m}$$

$$M_m = \sum m_i y_i$$

$$\left(n_i = \frac{m_i}{M_i}\right)$$

$$\bar{C}_p = C_p M$$

$$\bar{C}_p = \sum y_i \bar{C}_{pi}$$

$$PV_m = M_m R_m T_m$$

$$R_m = \frac{\bar{R}}{m_m}$$

$$\dot{m} = \frac{\dot{V}}{v}$$

Given (kg) m

$$n_i = \frac{m_i}{M_i}$$

$$y_i = \frac{n_i}{n_m}$$

Compression Ratios

$$\frac{T_2}{T_1} = (r_v)^{k-1}$$ I.G., $c_p = ¢$ compression

$$\frac{P_2}{P_1} = (r_v)^{k}$$

$$\frac{T_2}{T_1} = \left(\frac{1}{r_v}\right)^{k-1}$$ I.G. expansion

Pressure Ratios

$$\frac{T_2}{T_1} = \left(\frac{1}{PR_c}\right)^{\frac{k-1}{k}}$$

$$\frac{P_2}{P_1} = \frac{1}{PR_c}$$

$$PR \equiv \frac{P_1}{P_2}$$

$$v_1 = \frac{\forall_1}{m}$$

$$C_p T_{t2} = C_p T_1 + \frac{V_1^2}{2}$$

$$1\ kJ = 1000\ kg\ m^2/s^2$$

$$\rho = \frac{1}{v}$$

$$C_p - C_v = R$$

$$\frac{C_p}{C_v} = k$$

Heat Pump

$$\alpha = \frac{q_h}{w_{net}} = \frac{q_h}{q_h - q_L}$$ heat

$$\beta = \frac{q_L}{w_{net}} = \frac{q_L}{q_h - q_L}$$ AC

$$\alpha - \beta = 1$$

$$w_{net} = q_h - q_L$$

$211\ kJ/min = 1$ ton

Throttling

$T = ¢$

$h = ¢$

not reversible

$$Q + \sum m_i \left[u_i + \frac{V_i^2}{2} + g z_i\right] = W + \sum m_e \left[u_e + \frac{V_e^2}{2} + g z_e\right] \quad \boxed{\text{closed system}}$$

$$W = \int P\,dv + \frac{V_e^2 - V_i^2}{2} + g(z_e - z_i) \quad \boxed{\text{closed system reversible}}$$

$$Q + \sum m_i \left[h_i + \frac{V_i^2}{2} + g z_i\right] = W + \sum m_e \left[h_e + \frac{V_e^2}{2} + g z_e\right] \quad \boxed{\text{steady flow}}$$

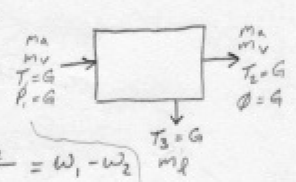
$$W = -\int v\,dP - \frac{V_e^2 - V_i^2}{2} - g(z_e - z_i) \quad \boxed{\text{reversible steady flow}}$$

$$Q = \int T\,ds \quad \boxed{\text{reversible}}$$

$$\dot m_{v_1} = \dot m_{v_2} + \dot m_{v_3}$$

$$\dot m_{a_1} = \dot m_{a_2} + \dot m_{a_3}$$

$$\dot m_\ell = \dot m_{v_1} - \dot m_{v_2}$$



$$\frac{\dot m_\ell}{\dot m_a} = \frac{\dot m_{v_1}}{\dot m_{a_1}} - \frac{\dot m_{v_2}}{\dot m_{a_1}} = \omega_1 - \omega_2$$

$$Q + m_a h_{a_1} + m_{v_1} h_{g_1} = m_a h_{a_2} + m_{v_2} h_{g_2} + m_\ell h_{f_3}$$

$$\frac{Q}{m_a} + h_{a_1} + \omega_1 h_{g_1} = h_{a_2} + \omega_2 h_{g_2} + (\omega_1 - \omega_2) h_{f_3}$$

$$\phi_1 = \frac{P_{v_1}}{P_g @ T_1}$$

$$P_{v_1} = \phi_1\ P_g @ T$$

$$\omega_1 = 0.622 \left(\frac{P_{v_1}}{P_{m_1} - P_{v_1}}\right)$$

$$P_{v_2} = \phi_2\ P_g @ T_2$$

$$\omega_2 = 0.622 \left(\frac{P_{v_2}}{P_{m_2} - P_{v_2}}\right)$$

$$\dot\forall = V \cdot A$$

$$\dot m = \rho \dot\forall$$

$$v = \frac{1}{\rho}$$

$$r_{bw} = \frac{W_c}{W_T}$$

$$T_3 = T_2 + \frac{{}_2q_3}{C_v}$$