Gas Power Cycles

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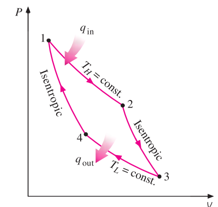
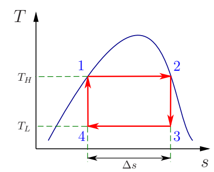
ME 203: Engineering Thermodynamics

The Carnot Gas Power Cycle



T222



T194

- $1 \to 2$: Reversible, isothermal expansion at T_H
- $2 \to 3$: Reversible, adiabatic expansion from T_H to T_L
- $3 \to 4$: Reversible, isothermal compression at T_L
- $4 \to 1$: Reversible, adiabatic compression from T_L to T_H

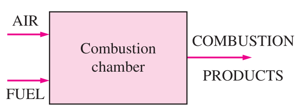
- $q_{in} = q_{12} = T_H(s_2 - s_1) = T_H \Delta s$
- $q_{out} = q_{34} = T_L(s_3 - s_4) = T_L \Delta s$
- $w_{net} = q_{net} = q_{in} - q_{out} = (T_H - T_L)\Delta s$
- $\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{(T_H - T_L)\Delta s}{T_H \Delta s} = 1 - \frac{T_L}{T_H}$

$\Longrightarrow$ $$\boxed{\eta_{th,Carnot} = 1 - \frac{T_L}{T_H}}$$

- $\eta_{th} \uparrow \Longleftarrow$: $T_H \uparrow$ AND/OR $T_L \downarrow$.
- In Boolean Logic: $\eta_{th} \uparrow = T_H \uparrow + T_L \downarrow$

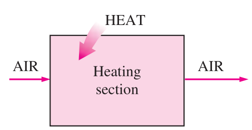
Air-Standard Cycle Assumptions

- The working fluid is air, which continuously circulates in a closed loop and always behaves as an ideal gas.
- All the processes that make up the cycle are internally reversible.
- The combustion process is replaced by a heat-addition process from an external source.



T223

(a) Actual



T224

(b) Ideal

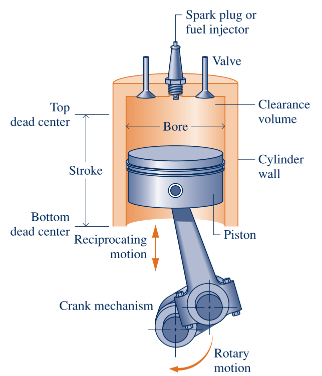
- The exhaust process is replaced by a heat-rejection process that restores the working fluid to its initial state.
- Air has constant specific heats determined at room temperature.

$\Longrightarrow$ A cycle for which the air-standard assumptions are applicable is frequently referred to as an air-standard cycle.

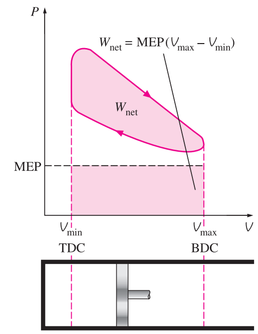
Review of Air Standard Gas Model

- $PV = mRT$
- $u(T_2) - u(T_1) = c_v(T_2 - T_1)$
- $h(T_2) - h(T_1) = c_p(T_2 - T_1)$
- $s(T_2, v_2) - s(T_1, v_1) = c_V \ln\left(\frac{T_2}{T_1}\right) + R \ln\left(\frac{v_2}{v_1}\right)$
- $s(T_2, P_2) - s(T_1, P_1) = c_P \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right)$
- $\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{(k-1)} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k}$
- Pv^k = constant

Overview of Reciprocating (R/C) Engines



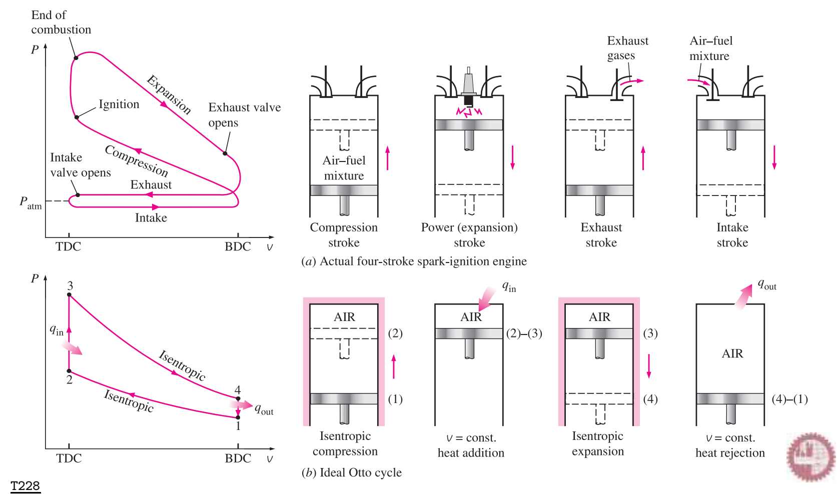
T625



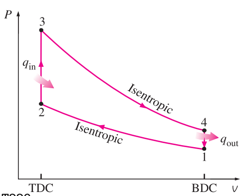
T227

- TDC ≡ Top Dead Centre, BDC ≡ Bottom Dead Centre
- Compression Ratio $\equiv r = \frac{V_{max}}{V_{min}} = \frac{V_{BDC}}{V_{TDC}}$
- Displacement Volume $\equiv V_d = \frac{\pi}{4} \times S \times B^2 = V_{max} - V_{min}$
- Mean Effective Pressure $\equiv MEP = \frac{W_{net}}{V_d}$

The Otto Cycle: Ideal Cycle for SI Engines



T228



T229

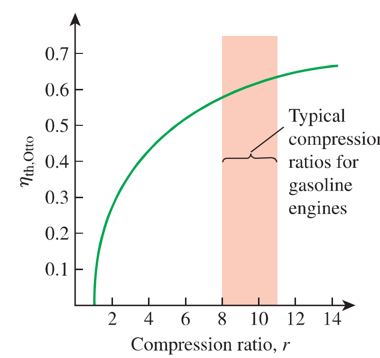
- $1 \longrightarrow 2$: Isentropic compression
- $2 \longrightarrow 3$: Reversible, Constant-volume heat addition
- $3 \longrightarrow 4$: Isentropic expansion
- $4 \longrightarrow 1$: Reversible, Constant-volume heat rejection

- Isentropic processes: $1 \longrightarrow 2$ & $3 \longrightarrow 4$. Also, $V_2 = V_3$ & $V_4 = V_1$

  $\longrightarrow \frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{k-1} = \left(\frac{V_3}{V_4}\right)^{k-1} = \frac{T_4}{T_3} \rightarrowtail \frac{T_1}{T_2} = r^{k-1}$ & $\frac{T_3}{T_2} = \frac{T_4}{T_1}$
- $q_{in} = u_3 - u_2 = c_v(T_3 - T_2)$: $q_{out} = u_4 - u_1 = c_v(T_4 - T_1)$
- $\eta_{th,Otto} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_2}{T_1}\frac{[T_3/T_2 - 1]}{[T_4/T_1 - 1]} = 1 - \frac{T_2}{T_1} = 1 - \frac{1}{r^{k-1}}$

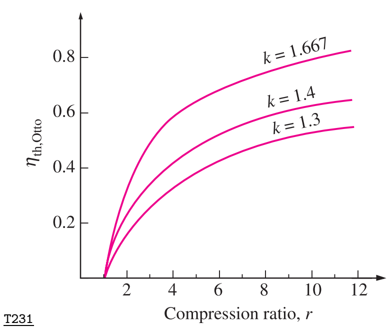
$$\eta_{th,Otto} = 1 - \frac{1}{r^{k-1}}$$

r = compression ratio,
k = ratio of specific heats, c_p/c_v



T230

Thermal efficiency of the ideal Otto cycle as a function of compression ratio (k = 1.4).



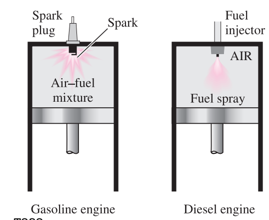
T231

The thermal efficiency of the Otto cycle increases with the specific heat ratio, k of the working fluid.

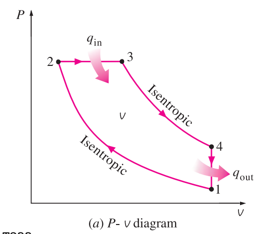
▷ Example: Otto cycle:
$P_1 = 0.1$ MPa, $T_1 = 300\ K$, $r = 10$, $q_{in} = 1800$ kJ/kg.

- $P_2/P_1 = r^k \longrightarrow P_2 = 2.511$ MPa
- $T_2/T_1 = r^{k-1} \longrightarrow T_2 = 753.6\ K$
- $v = RT/P \Rightarrow v_1 = 0.861\ \text{m}^3/\text{kg},\ v_2 = 0.0861\ \text{m}^3/\text{kg}$
- $c_p - c_v = R \rightsquigarrow c_v = \frac{R}{k-1} = 0.7175$ kJ/kgK
- $q_{in} = c_v(T_3 - T_2) \rightarrow T_3 = 3261.4\ K$
- $v_2 = v_3,\ v_4 = v_1$
- $T_4 = T_3 \left(\frac{v_3}{v_4}\right)^{k-1} = 1298.4\ K$
- $w_{net} = q_{in} - q_{out} = 1083.4$ kJ/kg
- $\eta_{th,Otto} = 1 - \frac{1}{r^{k-1}} = 0.602$ ◀
- $MEP = \frac{w_{net}}{v_1 - v_2} = 1.398$ MPa ◀

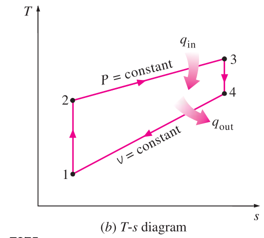
The Diesel Cycle: Ideal Cycle for CI Engines



T232



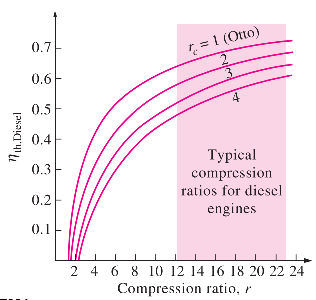
T233



T275

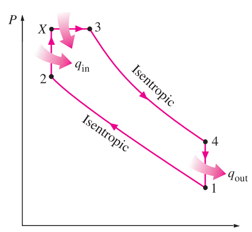
- Isentropic processes: $1 \rightarrow 2$ & $3 \rightarrow 4$.
- Cut-off ratio, $r_c = \frac{V_3}{V_2}$, and $V_4 = V_1$.
- $q_{in} = h_3 - h_2 = c_p(T_3 - T_2)$: $q_{out} = u_4 - u_1 = c_v(T_4 - T_1)$
- $\eta_{th,Diesel} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_2}{kT_1}\frac{[T_3/T_2 - 1]}{[T_4/T_1 - 1]} = 1 - \frac{1}{r^{k-1}}\left[\frac{r_c^k - 1}{k(r_c - 1)}\right]$

$$\eta_{th,Diesel} = 1 - \frac{1}{r^{k-1}}\left[\frac{r_c^k - 1}{k(r_c - 1)}\right]$$



T234

- For same r: $\eta_{th,Otto} > \eta_{th,Diesel}$.
- Diesel engines operate at much higher compression ratios, and thus are usually more efficient than SI-engines.



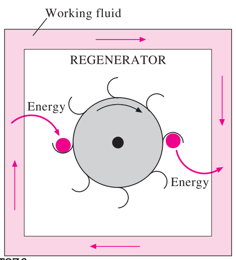
Dual Cycle:

- Two heat transfer processes, one at constant volume and one at constant pressure.

▷ Example: Diesel cycle:
$P_1 = 0.1$ MPa, $T_1 = 300\ K$, $r = 20$, $q_{in} = 1800$ kJ/kg.

- $P_2/P_1 = r^k \longrightarrow P_2 = 6.629$ MPa
- $T_2/T_1 = r^{k-1} \longrightarrow T_2 = 994.3\ K$
- $v = RT/P \Rightarrow v_1 = 0.861\ \text{m}^3/\text{kg},\ v_2 = 0.0430\ \text{m}^3/\text{kg}$
- $q_{in} = c_p(T_3 - T_2) \rightarrow T_3 = 2785.6\ K$
- $P_2 = P_3 \rightarrow v_3 = v_2\frac{T_3}{T_2},\ v_4 = v_1$
- $T_4 = T_3 \left(\frac{v_3}{v_4}\right)^{k-1} = 1270.0\ K$
- $w_{net} = q_{in} - q_{out} = 1104.5\ \text{m}^3/\text{kg}$
- $\eta_{th,Diesel} = \frac{w_{net}}{q_{in}} = 0.613$ ◀
- $r_c = v_3/v_2 = 2.80$
- $\eta_{th,Diesel} = 1 - \frac{1}{r^{k-1}}\left[\frac{r_c^k - 1}{k(r_c - 1)}\right] = 0.613$ ◀
- $MEP = \frac{w_{net}}{v_1 - v_2} = 1.355$ MPa ◀

Stirling & Ericsson Cycles



T276

- Stirling and Ericsson cycles involve an isothermal heat-addition at T_H and an isothermal heat-rejection at T_L. They differ from the Carnot cycle in that the two isentropic processes are replaced by two constant-volume regeneration processes in the *Stirling cycle* and by two constant-pressure regeneration processes in the *Ericsson cycle*.
- Both cycles utilize regeneration, a process during which heat is transferred to a thermal energy storage device (called a regenerator) during one part of the cycle and is transferred back to the working fluid during another part of the cycle.

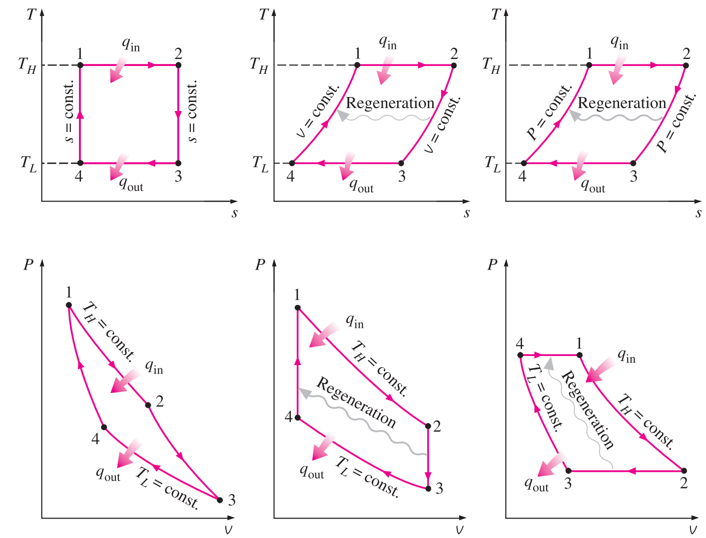
Stirling cycle is made up of four totally reversible processes:

1 → 2: Isothermal expansion (heat addition from the external source)

2 → 3: Isochoric regeneration (internal heat transfer from the working fluid to the regenerator)

3 → 4: Isothermal compression (heat rejection to the external sink)

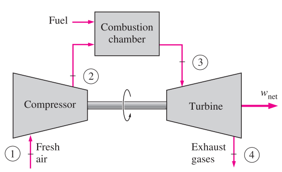
4 → 1: Isochoric regeneration (internal HT from regenerator back to fluid)



(a) Carnot cycle (b) Stirling cycle (c) Ericsson cycle

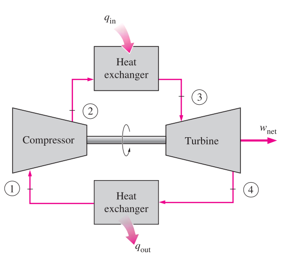
T236

Brayton Cycle: Ideal Cycle for Gas Turbines



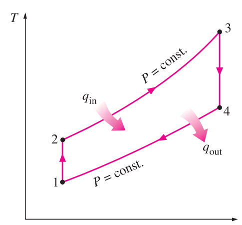
T237

An open-cycle gas-turbine

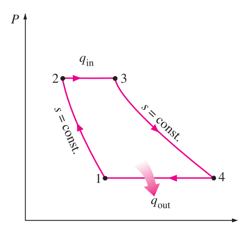


T238

A closed-cycle gas turbine



(a) T-s diagram



(b) P-v diagram

T239

- $q_{in} = h_3 - h_2 = c_p(T_3 - T_2)$
- $q_{out} = h_4 - h_1 = c_p(T_4 - T_1)$
- $r_p \equiv \frac{P_2}{P_1} \Rightarrow \frac{T_2}{T_1} = r_p^{(k-1)/k} = \frac{T_3}{T_4}$
- $\eta_{th,Brayton} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$

$$\Longrightarrow \boxed{\eta_{th,Brayton} = 1 - \frac{1}{r_p^{(k-1)/k}}}$$

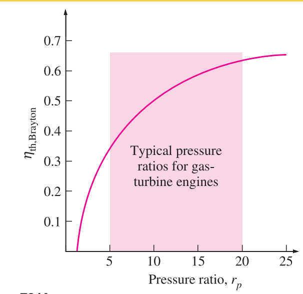
- $w_{net} = c_p[(T_3 - T_4) + (T_1 - T_2)]$

$\rightarrowtail \frac{w_{net}}{c_p} = T_3\left[1 - \frac{1}{r_p^{(k-1)/k}}\right] + T_1\left[1 - r_p^{(k-1)/k}\right]$

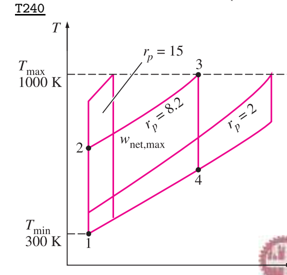
- For max. work: $\frac{\partial w_{net}}{\partial r_p} = 0$:

$$\Longrightarrow \boxed{r_p = \left(\frac{T_3}{T_1}\right)^{k/2(k-1)} : \text{for max. } w_{net}}$$

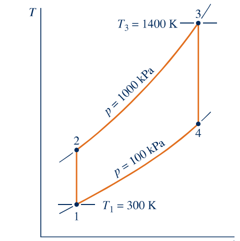
- If $T_3 = 1000\ K,\ T_1 = 300\ K \Rightarrow r_p = 8.2$.



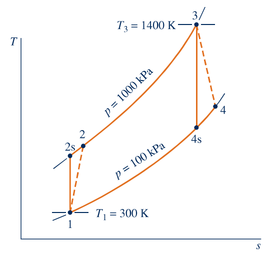
T240



T241



T626



T627

▹ [Moran 9.4, 9.6]: a) $\eta_{isen} = 1.0$, b) $\eta_{isen} = 0.8$

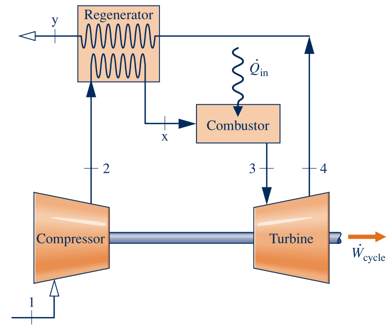
a) $r_p = 10,\ \eta_{isen} = 1.0$:

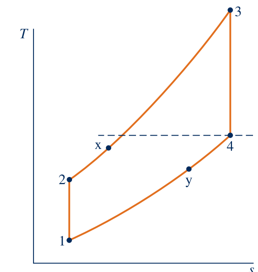
- $T_{2s} = 543.4\ K,\ \ T_{4s} = 717.7\ K$
- $w_{c,s} = 244.6$ kJ/kg, $w_{t,s} = 585.2$ kJ/kg
- $q_{in} = 760.2$ kJ/kg, $\eta_{th} = 0.448$ ◀

a) $r_p = 10,\ \eta_{isen} = 0.8$:

- $\eta_c = \frac{w_{c,s}}{w_{c,a}} \simeq \frac{T_{2s}-T_1}{T_2-T_1}\ :\ \eta_t = \frac{w_{t,a}}{w_{t,s}} \simeq \frac{T_3-T_4}{T_3-T_{4s}}$
- $T_{2a} = 604.3\ K,\ \ T_{4a} = 834.1\ K$
- $w_{c,a} = 305.7$ kJ/kg, $w_{t,a} = 468.1$ kJ/kg
- $q_{in} = 699.0$ kJ/kg, $\eta_{th} = 0.232$ ◀

Brayton Cycle with Regeneration

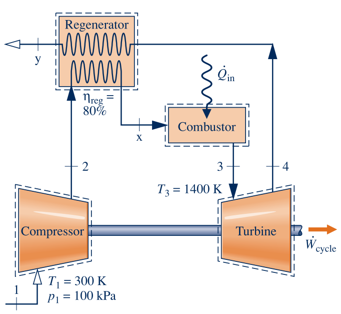


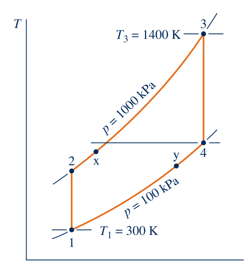


T628

- $q_{regen,act} = h_x - h_2 \quad : \quad q_{regen,max} = h_4 - h_2$
- Effectiveness, $\epsilon \equiv \frac{q_{regen,act}}{q_{regen,max}} = \frac{h_x - h_2}{h_4 - h_2} \simeq \frac{T_x - T_2}{T_4 - T_2}$
- $\eta_{th,regen} = 1 - \left(\frac{T_1}{T_3}\right) r_p^{(k-1)/k}$

▹ [Moran 9.7]:





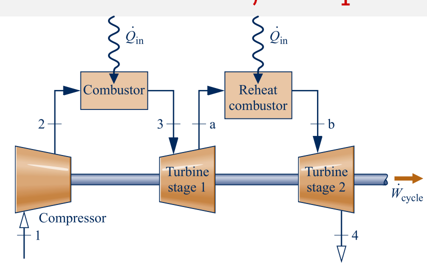
T629

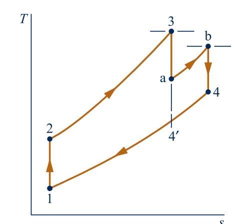
- $\epsilon \equiv \frac{q_{regen,act}}{q_{regen,max}} \simeq \frac{T_x - T_2}{T_4 - T_2} \rightsquigarrow T_x = \epsilon(T_4 - T_2) + T_2 = 745.5$ K
- $w_{net} = w_t + w_c = (h_3 - h_4) + (h_1 - h_2) = C_p[(T_3 - T_4) + (T_1 - T_2)]$

⇒ $w_{net} = 427.4$ kJ/kg

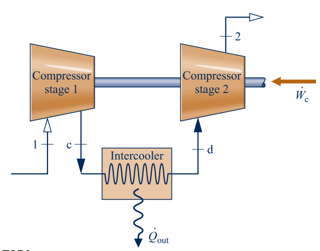
- $q_{in} = (h_3 - h_x) = C_p(T_3 - T_x) = 753.2$ kJ/kg
- $\eta = \frac{w_{net}}{q_{in}} = 56.7\%$

Turbines with Reheat, Compressors with Intercooling

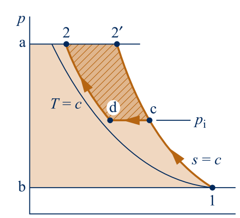




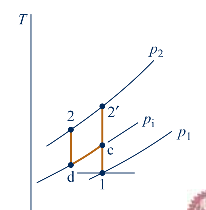
T246



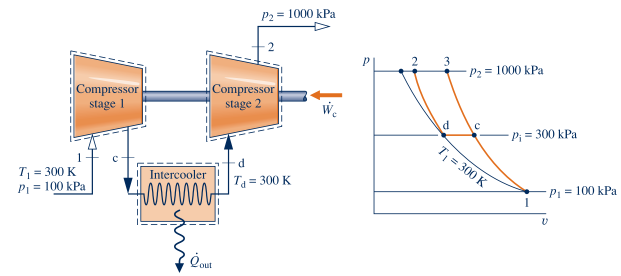
T250



T252



▷ [Moran 9.9]:

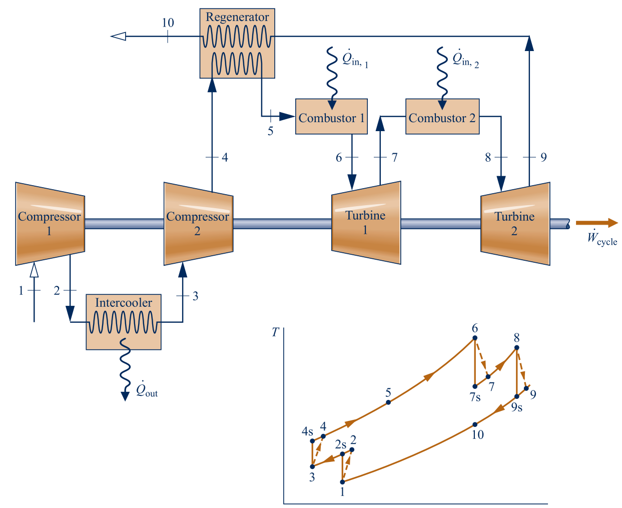


T631

- $h_1 = h(100\ kPa, 300\ K),\ \ s_1 = s(100\ kPa, 300\ K)$
- $h_c = h(300\ kPa, s_1),\ \ h_d = h(300\ kPa, 300\ K)$
- $w_c = w_{c1} + w_{c2} = (h_1 - h_c) + (h_d - h_2) =$ -234.9 kJ/kg◀

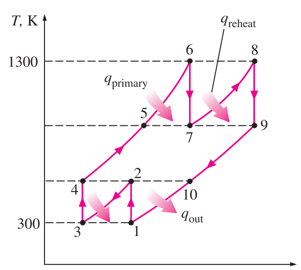
  If single stage compression is done:
- $h_2 = h(1000\ kPa, s_1)$
- $w_c = (h_1 - h_2) =$ -280.1 kJ/kg◀

Brayton Cycle with Intercooling, Reheating & Regeneration



T249

▷ [Cengel 9.8]: GT with reheating & intercooling: $r_p = 8,\ \eta_{isen} = 1.0,\ \epsilon = 1.0.$



T251

- In case of staging, for min. compressor work or for max. turbine work:

$$P_i = \sqrt{P_{min} P_{max}}$$

- $w_{turb} = (h_6 - h_7) + (h_8 - h_9)$
- $w_{comp} = (h_2 - h_1) + (h_4 - h_3)$
- $w_{net} = w_{turb} - w_{comp},\ \ bwr = \frac{w_{comp}}{w_{turb}}$

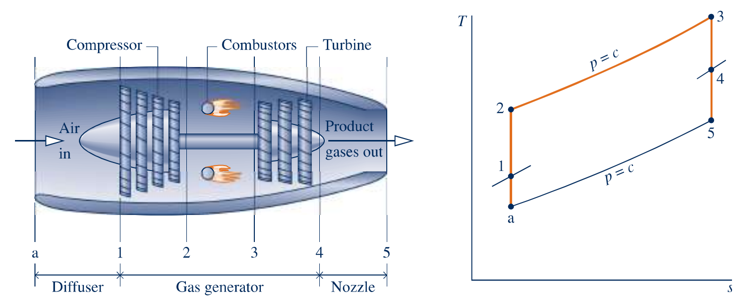
- Without regen: $w_{turb} = 685.28$ kJ/kg ◀ $w_{comp} = 208.29$ kJ/kg ◀
- $q_{in} = (h_6 - h_4) + (h_8 - h_7) = 1334.30$ kJ/kg ◀

⟹ $\eta_{th} = 0.358$ ◀ $bwr = 0.304$ ◀

- With regen: turbine and compressor works remains unchanged.
- $q_{in} = (h_6 - h_5) + (h_8 - h_7) = 685.28$ kJ/kg ◀

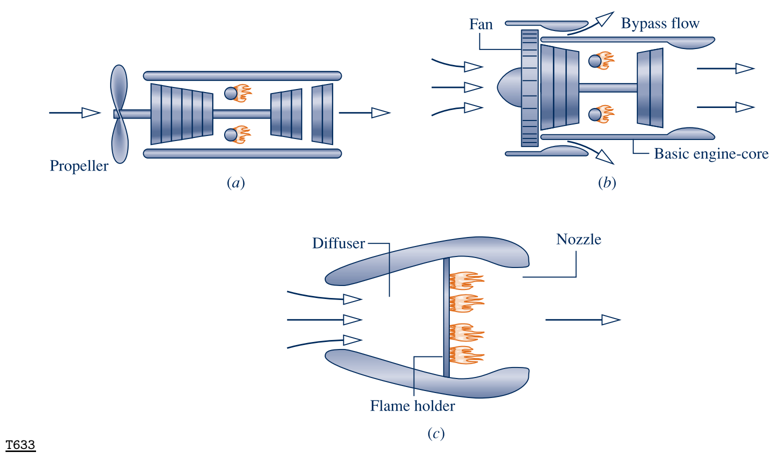
⟹ $\eta_{th} = 0.696$ ◀ $bwr = 0.304$ ◀

Jet Propulsion



T632

Turbojet engine schematic and accompanying ideal T-s diagram.



Other examples of aircraft engines. (a) Turboprop. (b) Turbofan. (c) Ramjet.