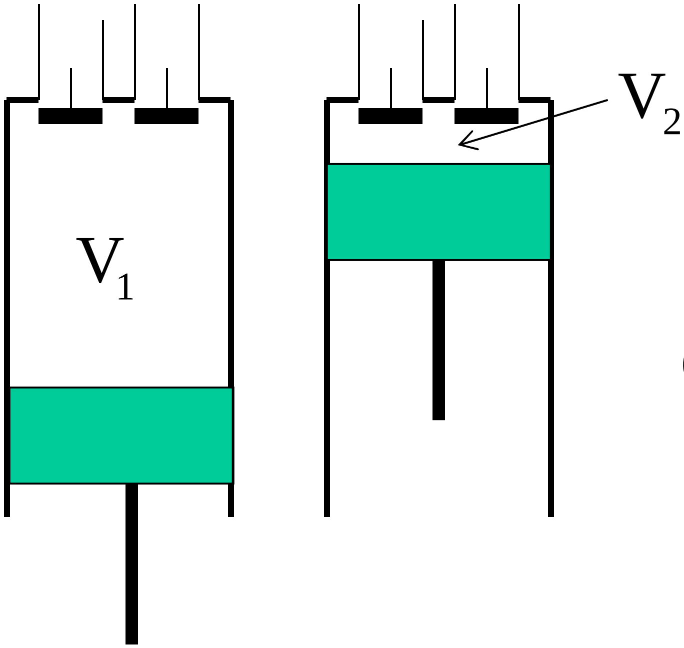
Internal Combustion Engines

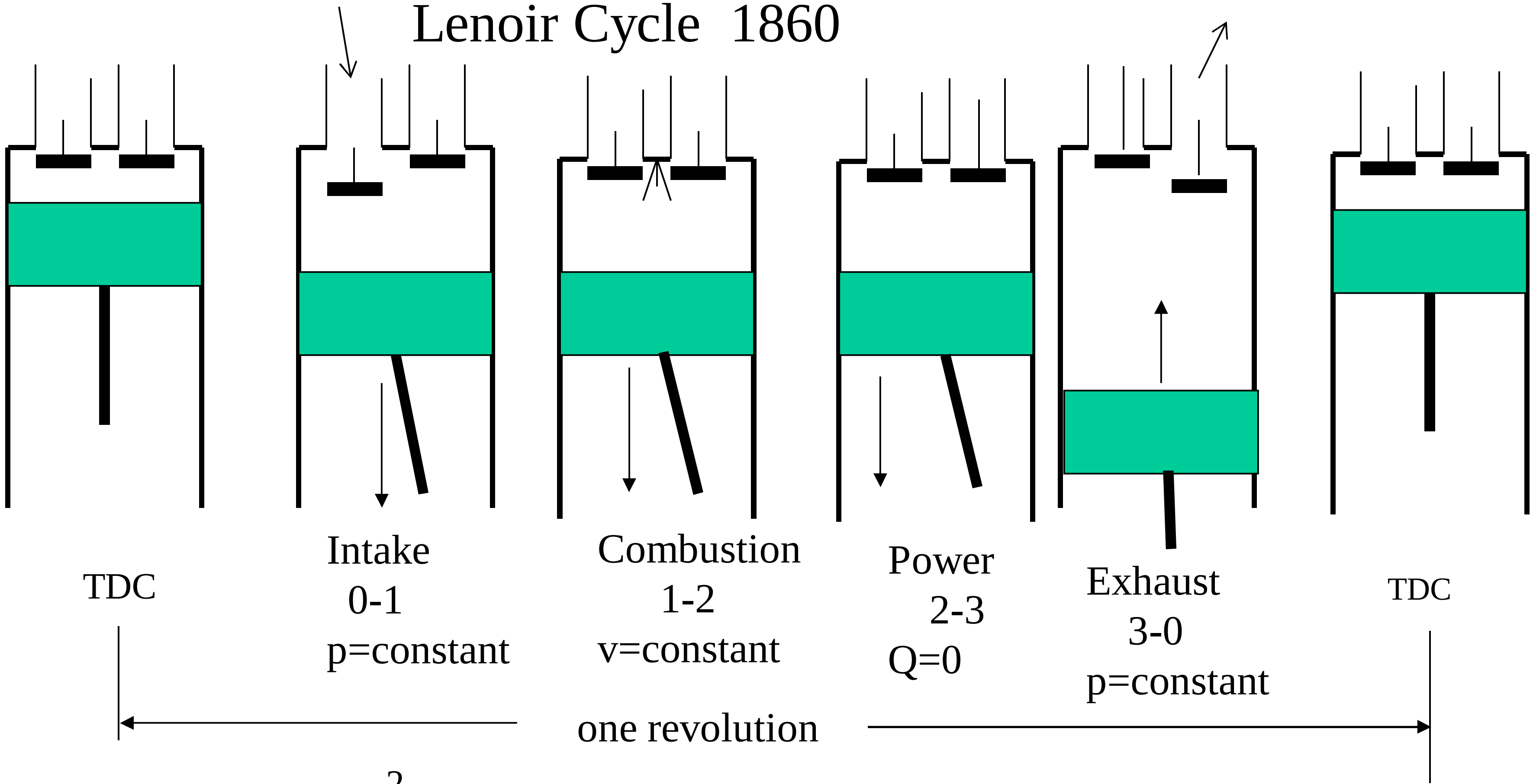


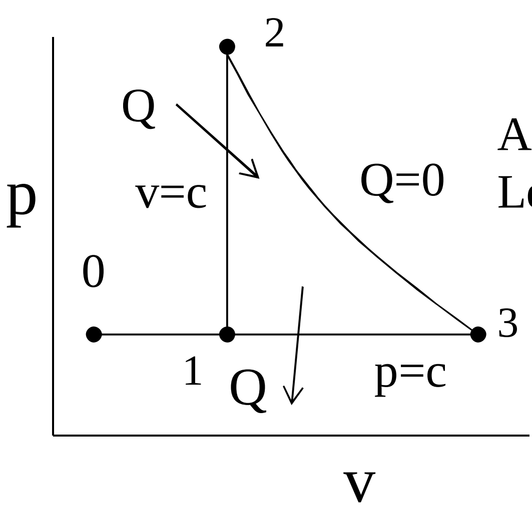
Bottom Dead Center BDC

Top Dead Center TDC

Compression Ratio, $r_c = \dfrac{V_1}{V_2}$

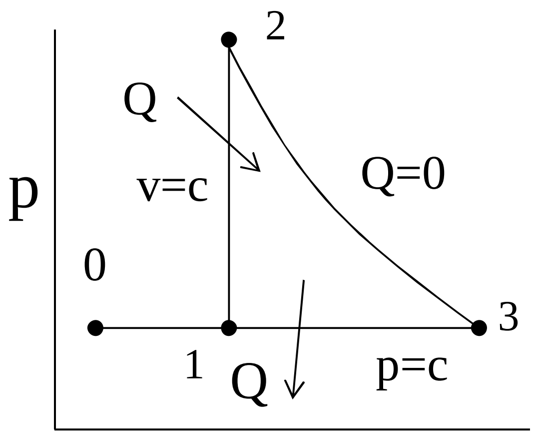
Lenoir Cycle 1860





Air Standard
Lenoir Cycle

Air Standard Lenoir Cycle



Closed Thermodynamic System – quantity of mass

$q = qpu + w$

$2-3$ Combustion Process

$v = \text{constant} \Rightarrow w = 0$

$q = u_2 - u_1$

$2-3$ Expansion Process, Power Stroke

$q = 0$, adiabtic process

$$\frac{T_3}{T_2} = \left(\frac{p_3}{p_2}\right)^{\frac{k}{k-1}} = \left(\frac{v_2}{v_1}\right)^{k-1}$$

$w = -(u_2 - u_3)$

$3-1$ Exhaust Process

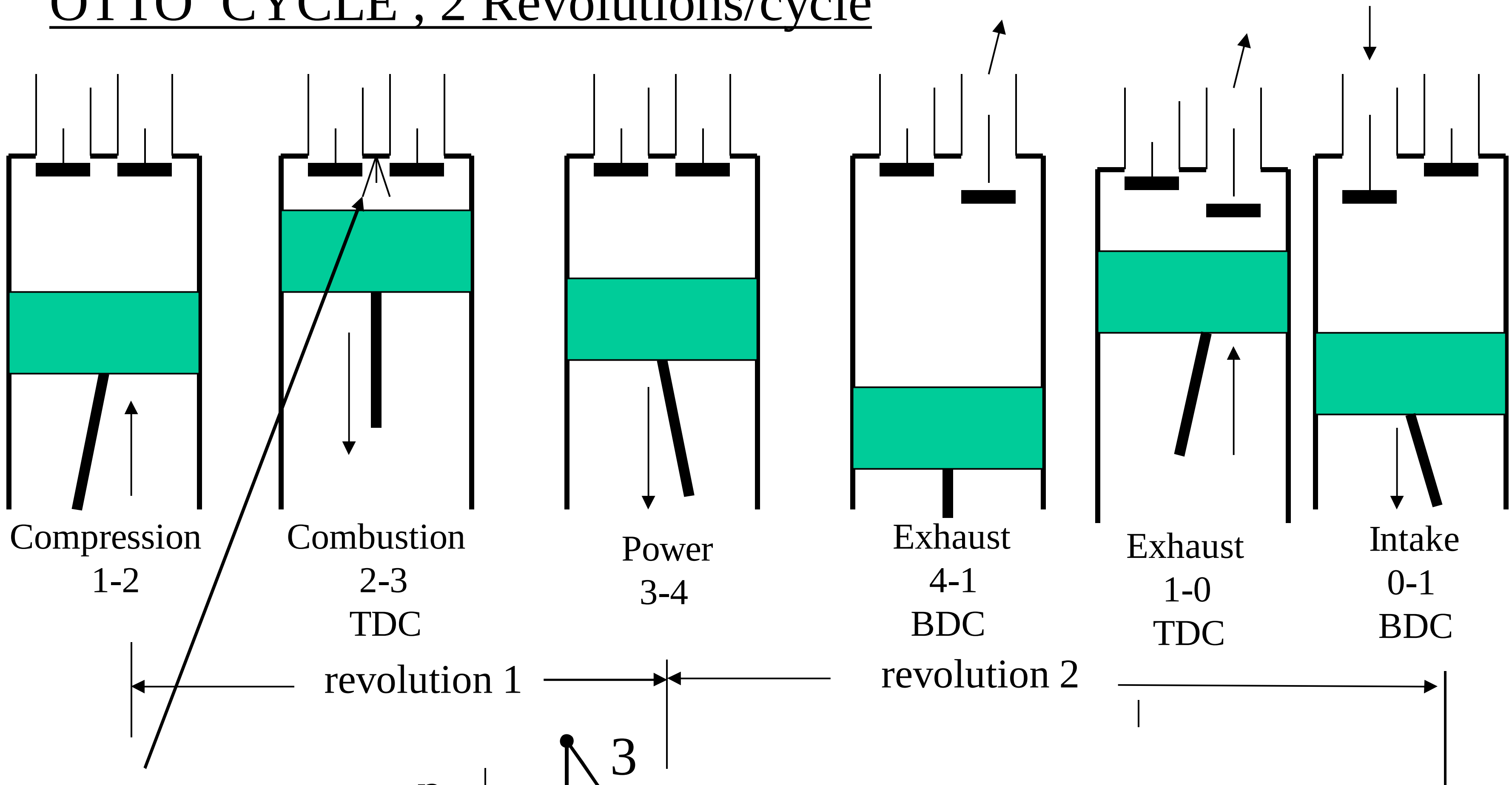
$p = c$

$q = qpu + w$

$q = (u_1 - u_3) + p_3(v_1 - v_3) = h_1 - h_3$

$w = q_{31} - (u_3 - u_1)$

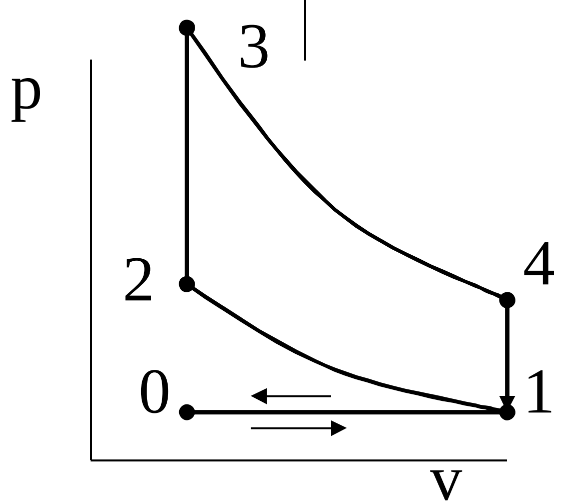
OTTO CYCLE , 2 Revolutions/cycle



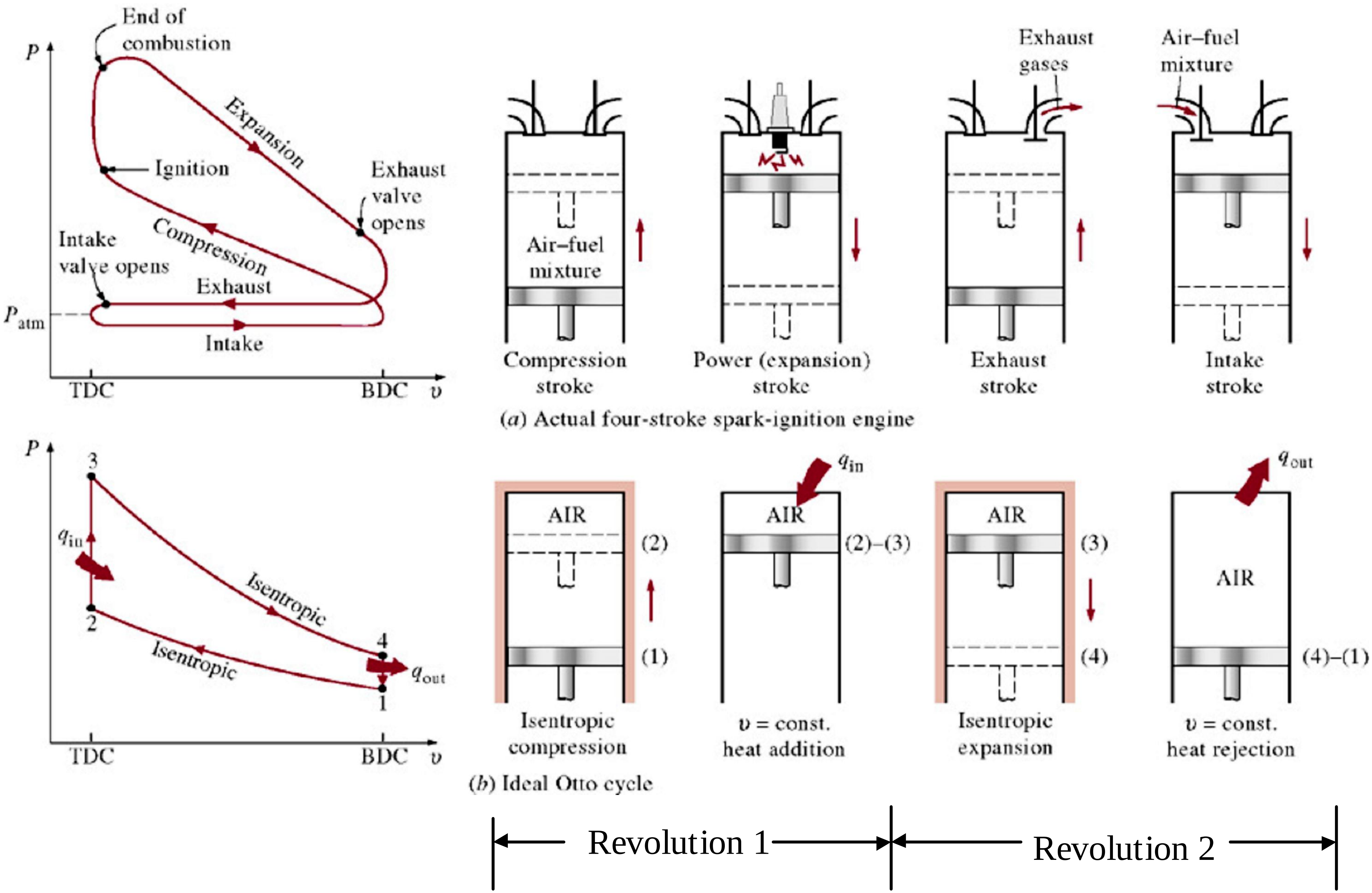
OTTO CYCLE

spark ignition, SI

fuel injection + SI

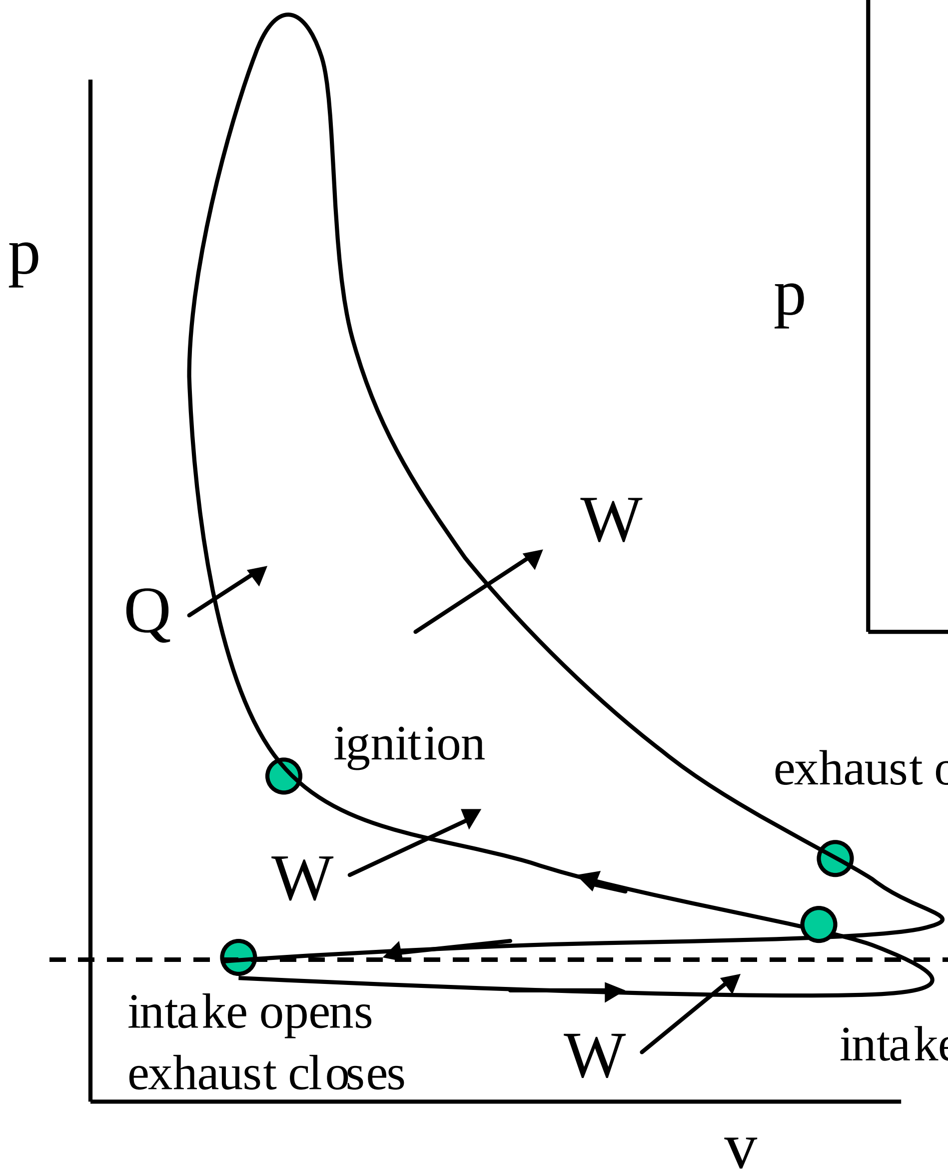


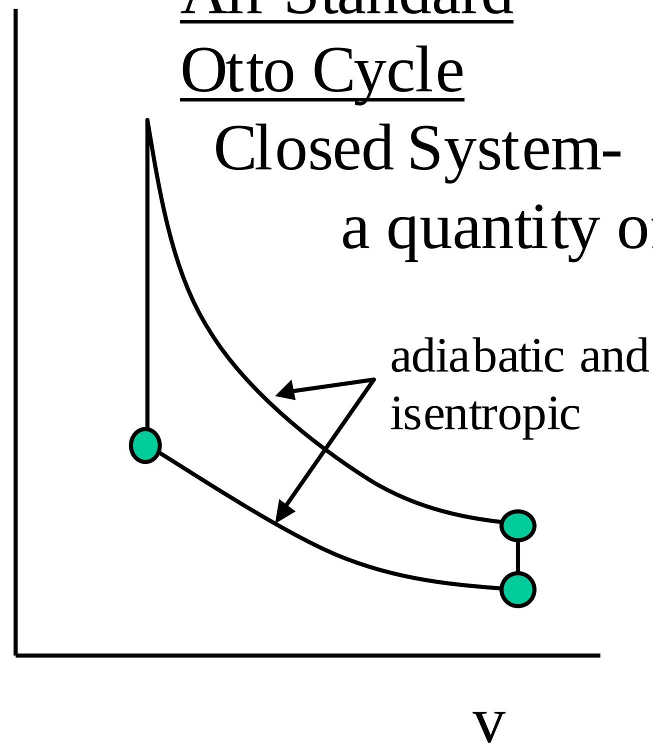
4 CYCLE, 2 REVOLUTIONS



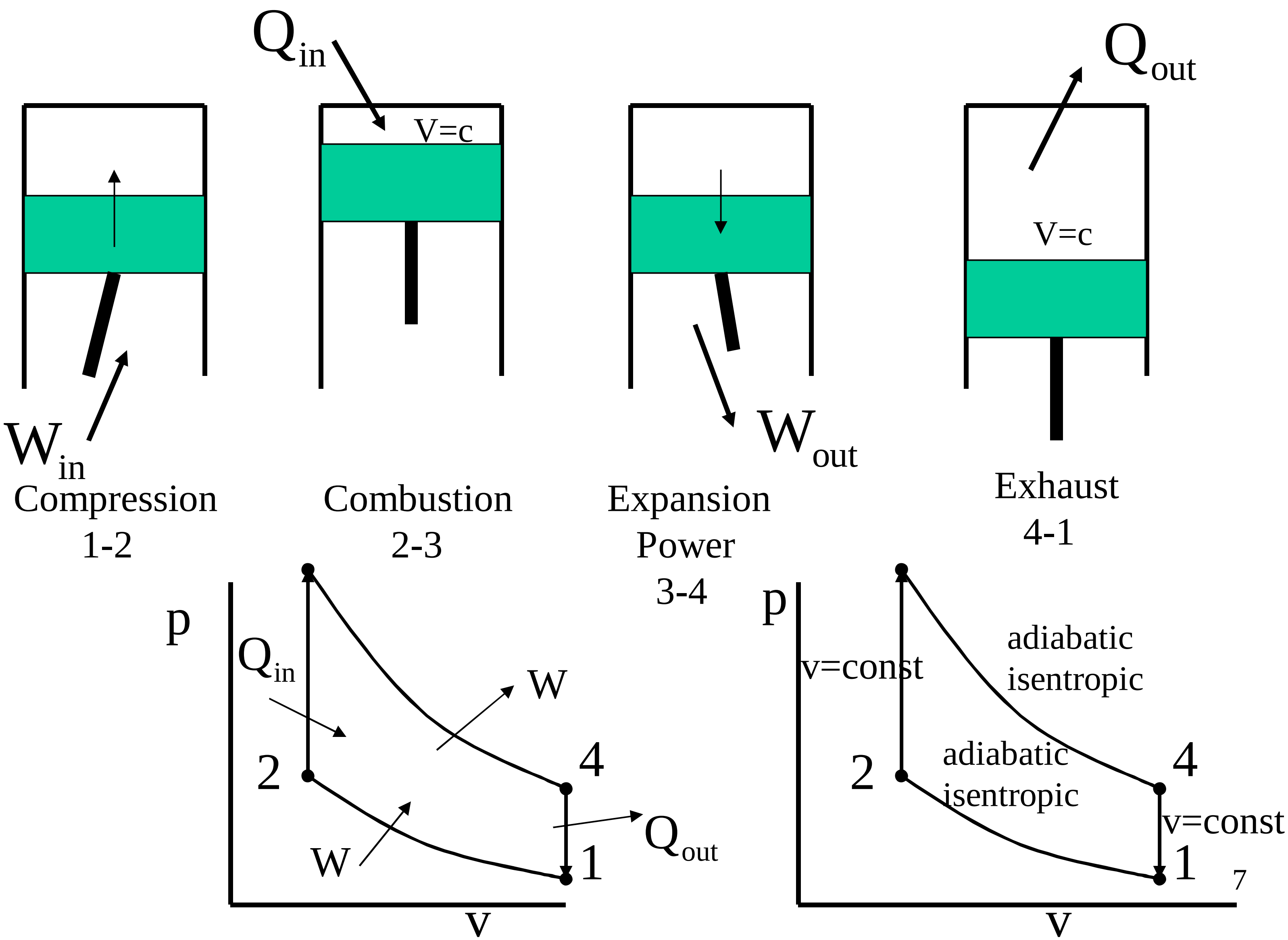
<u>Air Standard</u>
<u>Otto Cycle</u>

Closed System-
a quantity of mass



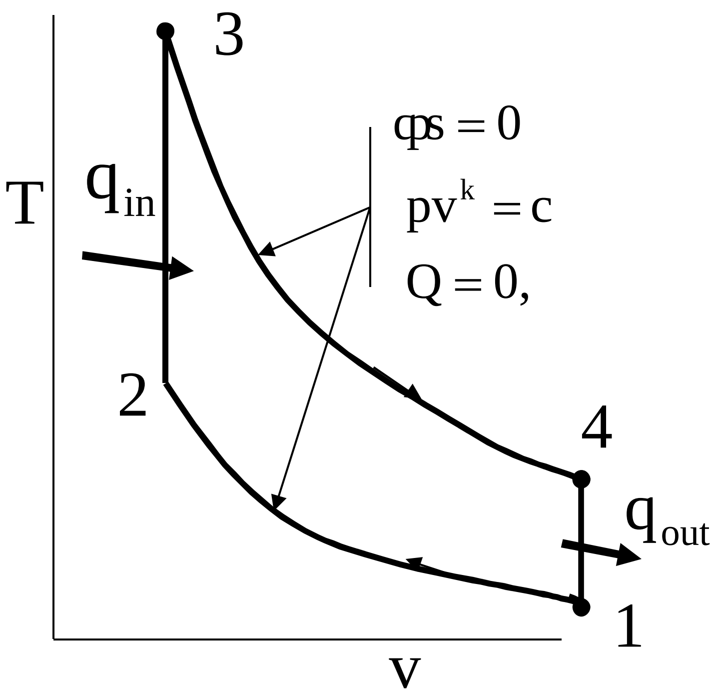


AIR STANDARD OTTO CYCLE, 2 Revolutions/cycle



ñCOLDò

Air Standard Otto Cycle



CLOSED SYSTEM

$$q = \varphi u + w$$

"COLD"$\Rightarrow$

constant $c_{p,}$ c_v at T_1.

Compression $\mathbf{1 \rightarrow 2}$, $\varphi s = 0,\ pv^k = c,\ q = 0,\quad w = \varphi u$

$$p_1 v_1^{\ k} = p_2 v_2^{\ k}$$

$$T_2 = T_1 \left(\frac{v_1}{v_2}\right)^{k-1}$$

$$w_{2-1} = \varphi u = u_{2-} u_1 = c_v (T_2 - T_1)$$

Combustion $\mathbf{2 \rightarrow 3}$, $v = c,\ w = \int pdv = 0,\ q = \varphi U$

$$q_{2-3} = \varphi u = u_3 - u_2 = c_v (T_3 - T_2)$$

Expansion $\mathbf{3 \rightarrow 4}$, $\varphi s = 0,\ pv^k = c, q = 0,\quad w = \varphi U$

$$T_4 = T_3 \left(\frac{v_3}{v_4}\right)^{k-1}$$

$$w_{3-4} = \varphi u = u_3 - u_4 = c_v (T_3 - T_4)$$

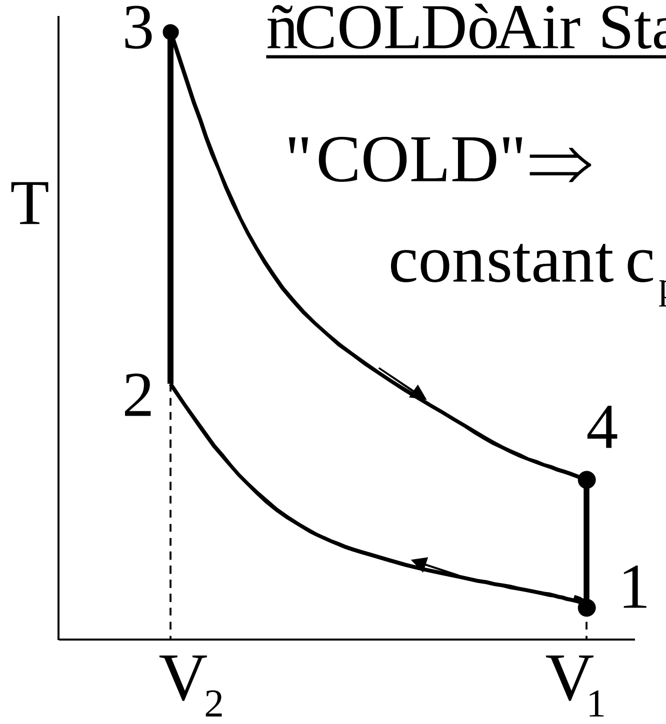
Exhaust $\mathbf{4} \rightarrow 1$, $v = c,\ w = \int pdv = 0,\qquad q = \varphi U$

$$q_{4-1} = \varphi u = u_4 - u_1 = c_v (T_4 - T_1)$$

Cycle

$$d_{cycle} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{q_{4\text{-}1}}{q_{3\text{-}2}} = 1 - \frac{c_v (T_4 - T_1)}{c_v (T_3 - T_2)}$$

ñCOLDòAir Standard Otto Cycle



$$\text{"COLD"} \Rightarrow$$

$$\text{constant } c_{p,}\ c_v \text{ at } T_1$$

CLOSED SYSTEM, $Q = \varphi U + W$

Compression $1 \rightarrow 2$, $\varphi s = 0$, $Q = 0$, $W = \varphi U$

Combustion $2 \rightarrow 3$, $v = c$, $W = \int p\,dv = 0$, $Q = \varphi U$

Expansion $3 \rightarrow 4$, $\varphi s = 0$, $Q = 0$, $W = \varphi U$

Exhause $2 \rightarrow 3$, $v = c$, $W = \int p\,dv = 0$, $Q = \varphi U$

$$\Delta s_{2\rightarrow 3} = \varphi s_{4\rightarrow 1}$$

$$c_v \ln\left(\frac{T_3}{T_2}\right) - R\ln\cancelto{1.0}{\left(\frac{v_3}{v_2}\right)} = c_v \ln\left(\frac{T_4}{T_1}\right) - R\ln\cancelto{1.0}{\left(\frac{v_4}{v_1}\right)}$$

$$\frac{T_3}{T_2} = \frac{T_4}{T_1}$$

$$\frac{T_1}{T_2} - = \left(\frac{v_2}{v_1}\right)^{k-1}$$

$$\eta = 1 - \frac{1}{\left(\frac{v_1}{v_2}\right)^{k-1}} = 1 - \frac{1}{\left(\begin{matrix}\text{compression}\\ \text{ratio}\end{matrix}\right)^{k-1}} = 1 - \frac{1}{(r)^{k-1}}$$

$$w_{net} = p_{mean} \times (V_2 - V_1)$$

Mean Effective Pressure **(mep)** $= \dfrac{\mathbf{w_{net}}}{(\mathbf{V_1} - \mathbf{V_2})}$

Compression Ratio $= r_c = \dfrac{V_1}{V_2} = \dfrac{v_1}{v_2}$

$$\eta = 1 - \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

$$\eta = 1 - \frac{u_4 - u_1}{u_3 - u_2} = 1 - \frac{c_v(T_4 - T_1)}{c_v(T_3 - T_2)}$$

$$\eta = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{T_1}{T_2}\frac{\left(\frac{T_4}{T_1} - 1\right)}{\left(\frac{T_3}{T_2} - 1\right)}$$

What is the thermal efficiency of a COLD air standard Otto cycle operating between 2800 F and 100 F with a compression ratio of 6?

Closed System

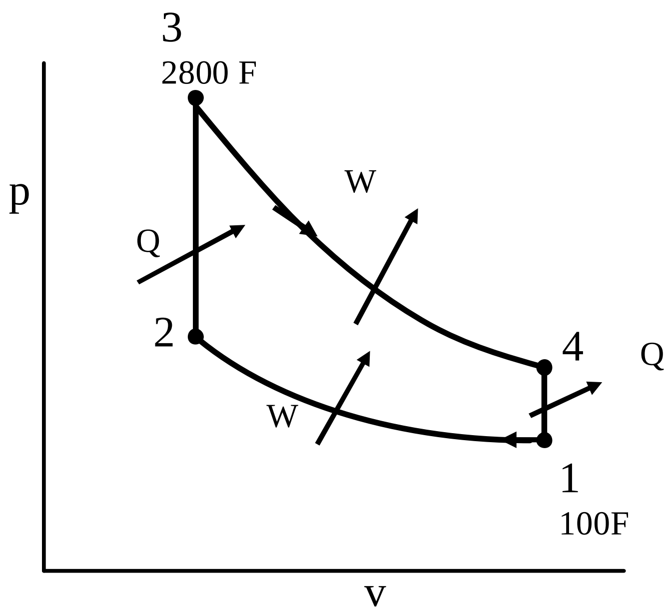
$Q = \varphi U + W$

Compression $1 \rightarrow 2, \varphi s = 0, q = 0, \quad w = \varphi u$

Combustion $2 \rightarrow 3, v = c, w = \int pdv = 0, \; q = \varphi u$

Expansion $3 \rightarrow 4, \varphi s = 0, q = 0, \quad w = \varphi u$

Exhaust $2 \rightarrow 3, v = c, w = \int pdv = 0, \quad q = \varphi U$



$$T_2 = T_1\left(\frac{v_1}{v_2}\right)^{k-1} = 559.7 \times 6^{.4} = 1146^{o}\,R$$

$$w_{2-1} = u_{2-}u_1 = c_v\left(T_2 - T_1\right)$$

$$w_{2-1} = .171 \times \left(1146 - 559.7\right) = 100.3\text{BTU/lb}$$

$$q_{2-3} = u_3 - u_1$$

$$q_{2-3} = .171 \times \left(3259.7 - 1146\right) = 361.4\text{BTU/lb}$$

$$T_4 = T_3\left(\frac{v_3}{v_4}\right)^{k-1} = 3259.7\left(\frac{1}{6}\right)^{.4} = 1591.9^{o}\,R$$

$$w_{3-4} = u_3 - u_4$$

$$w_{3-4} = .171\left(3259.7 - 1591.9\right) = 285.2\text{BTU/lb}$$

$$q_{4-3} = u_4 - u_3$$

$$q_{4-3} = .171\left(1591.9 - 559.7\right) = 176.5\text{BTU/lb}$$

$$d_{cycle} = \left(\frac{w_{net}}{q_{in}}\right) = \left(\frac{285.2 - 100.3}{361.4}\right) = 51.1\%$$

$$d_{cycle} = 1 - \frac{1}{\left(\frac{v_1}{v_2}\right)^{k-1}} = 1 - \frac{1}{6^{1.4-1}} = 51.1\%$$

AIR TABLE - Tables A-22, A-22E

specific heats are integrated as variables of T- page 113, 230

1) Table base $0^{o}\,F,\ 0^{o}\,C$

2) Isentropic Process,

$$pv^{k} = \text{constant}$$

$$\frac{p_1}{p_2} = \frac{(p_r)_1}{(p_r)_2}$$

$$\frac{v_1}{v_2} = \frac{(v_r)_1}{(v_r)_2}$$

3) Enthalpy

$$h = \int c_p(T)\,dT$$

4) Internal Energy

$$u = \int c_v(T)\,dT$$

5) Entropy - ideal gas

$$s_2 - s_1 = c_v \ln\left(\frac{T_2}{T_1}\right) + R\ln\left(\frac{v_2}{v_1}\right)$$

$$s_2 - s_1 = c_p \ln\left(\frac{T_2}{T_1}\right) - R\ln\left(\frac{p_2}{p_1}\right)$$

Entropy - Using Table A – 22 and Table A 22E,

$$s = \int c_v(T)\frac{dT}{T} + R\ln(\text{volume ratio})$$

$$s = \int c_p(T)\frac{dT}{T} - R\ln(\text{pressure ratio})$$

$$s_2 - s_1 = s^0(T_2) - s^0(T_1) + R\ln\left(\frac{v_2}{v_1}\right)$$

$$s_2 - s_1 = s^0(T_2) - s^0(T_1) - R\ln\left(\frac{p_2}{p_1}\right)$$

9.1

$@\,300^{o}\,\mathrm{K}, \quad v_{r1} = 621.2, \quad u_1 = 214.07$

$$v_1 = \frac{RT}{p} = \frac{.286\times 300}{100} = .858\ m_3/kg$$

$$\frac{v_{r2}}{v_{r1}} = \frac{v_2}{v_1},\ v_{r2} = v_{r1}\left(\frac{v_2}{v_1}\right) = 621.2/8.5 = 73.08$$

T	v_r	u
	75.5	496.62
	73.08	503.06 kJ/g $= u_3$
	72.56	504.45

$$\text{interpolation ratio} = \frac{73.08-72.56}{75.5-72{,}56} = \frac{.52}{2.94} = .1769$$

$Q_{in} = u_3 - u_2 = 1400\ kJ/kg$

$u_3 = 1400 - 503.6 = 1903.06\ kJ/kg$

Interpolate Table A − 22 near $u_3 = 1903.6\ kJ/kg$

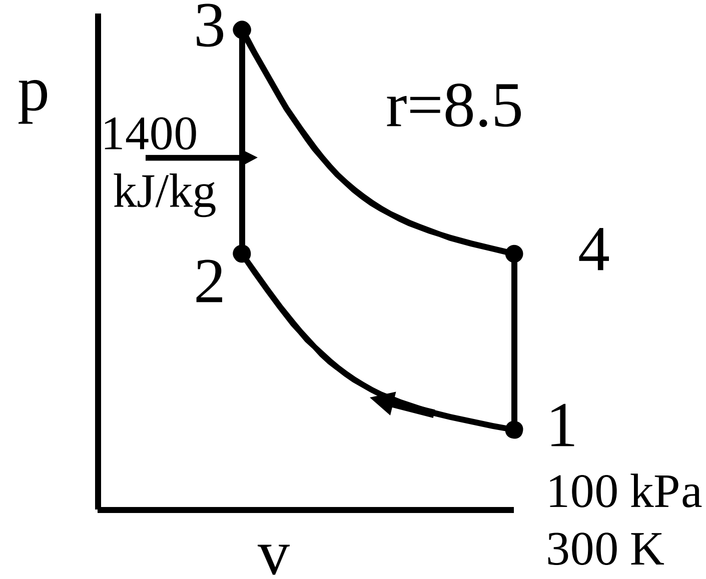
$v_{r3} = 1.9176$

$$v_{r4} = v_{r3}\left(\frac{v_4}{v_3}\right) = 1.9176\times 8.5 = 16.3$$

Interpolate Table A − 22 near $v_{r4} = 16.3$

$u_4 = 888.32\ kJ/kg$

$Q_{out} = (u_3 - u_4) = (888.32 - 214.07) = 674.25\,kJ/kg$



a) $W = Q_{in} - Q_{out} = 1400 - 674.25$

$W = 725.75\,kJ/kg$

b) $$\eta = 1 - \left(\frac{Q_{out}}{Q_{in}}\right) = 1 - \frac{725.75}{1400} = 51.8\,\%$$

c) $$mep = \frac{W}{V_1 - V_2} = \frac{W}{v_1\left(1 - \frac{v_2}{v_1}\right)}$$

$$mep == \frac{725.75}{.858\times\left(1 - \frac{1}{8.5}\right)} = 958.7\ psi$$

The initial temperature and pressure of air inan ideal Cold Otto cycle having a compression ratio of10, is 60 F and 14.7 psia respectively. Heat isadded in the constant volume process at a rateof 800 BTU/lbm. Consider air to be an idea gas.

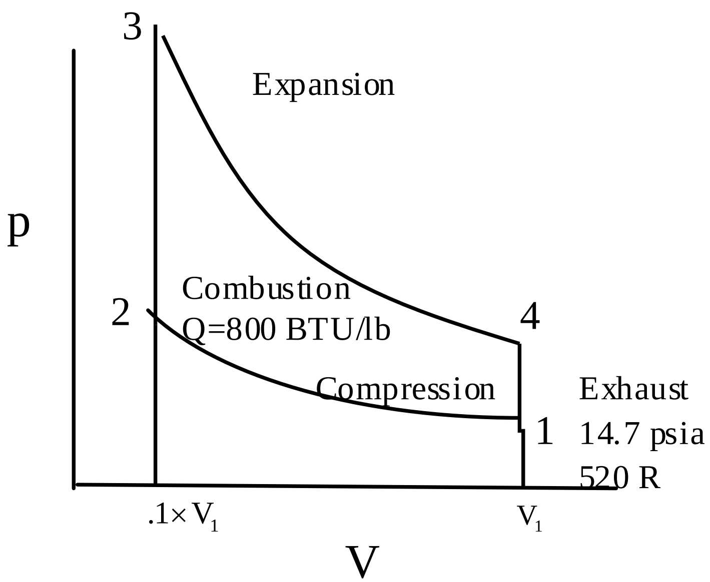
Calculate: a) The change in internal energy per pound of air during the compression process.

b) The maximum temperature and pressure of the cycle

$k = 1.4$

$c_v = .171\,BTU/lb - R$

$c_p = .24\,BTU/lbm - R$



Process 1-2

isentropic, adiabatic with $pv^k = \text{constant}$

$$T_2 = T_1 \times \left(\frac{V_1}{V_2}\right)^{k-1} = 520 \times 10^{.4} = 1305^o$$

a)

$$qU = c_v(T_2 - T_1) = .17 \times (1305 - 520) = 134.2\,BTU/lb$$

b)

$$\text{Combustion Heat}, Q = c_v(T_3 - T_2)$$

$$800 = .17 \times (T_3 - 1305)$$

$$T_3 = 5893^o R$$

Since $V_2 = V_3$, from the ideal gas law $Pv = mRT$,

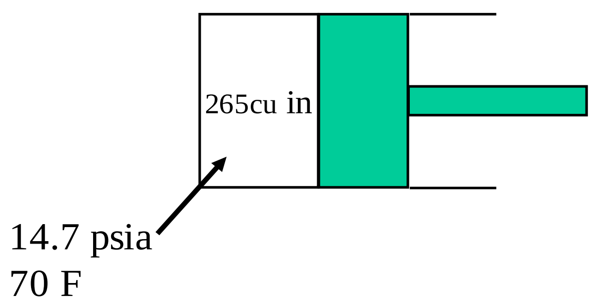
$$p_3 = p_2\left(\frac{T_3}{T_2}\right)$$

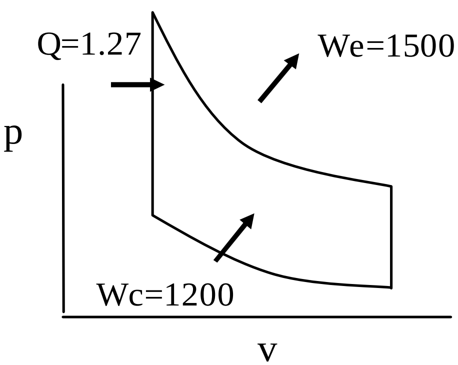
Since 1–2 is isentropic and adiabatic,

$$p_2 = p_1\left(\frac{V_1}{V_2}\right)^k = 14.7 \times 10^{1.4} = 367\,psia$$

$$p_3 = 367 \times \left(\frac{5983}{1305}\right) = 1685\,psia$$

A 265 cubic in V8 gasoline engine runs at 4600 rpm. Compression work is 1200 ft-lb, expansion work is 1500 ft-lb and heat input is 1.27 BTU per piston per cycle. The atmosphere is 14.7 psia and 70 F. The air fuel ratio is 20:1. The heating value of gasoline is 18,900 BTU/lb. Find a) indicated HP b) thermal efficiency c) gasoline consumption per hr d) specific fuel consumption.





a)

$$HP = \frac{(1500 - 1200)\ \text{BTU/power stroke/cylinder} \times 8\ \text{cylinders} \times 4600\ \text{rpm}}{550\ \text{ft} - \text{lb/HP} \times 2\ \text{rev/ power stroke} \times 60\ \text{sec/min}}$$

$$HP = 167.3\ \text{HP}$$

b)

$$\eta = \frac{w_{net}}{q_{in}} = \frac{(1500 - 1200)}{1.277 \times 778} = 30.4\%$$

c)

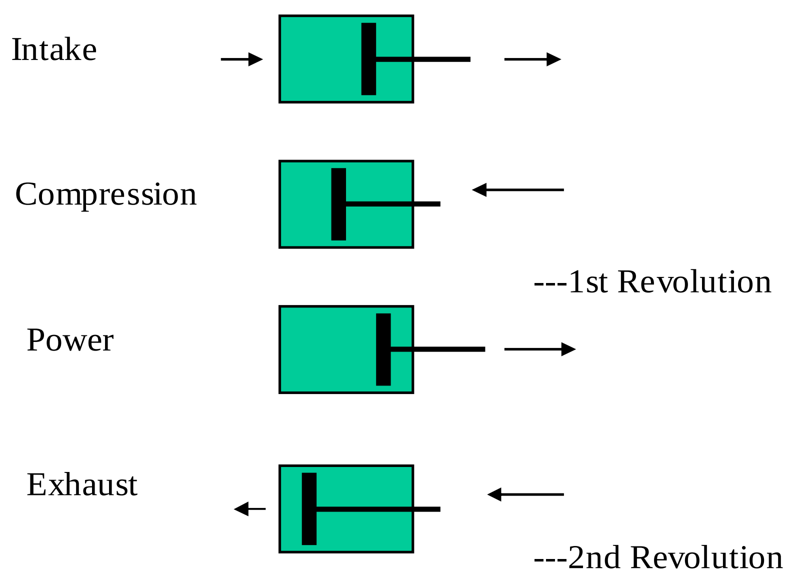
$$\text{Fuel} = \frac{1.27\ \text{BTU/power stroke/cylinder} \times 8\ \text{cylinders} \times 4600 \times 60}{18{,}900 \times 2\ \text{rev/power stroke}}$$

$$\text{Fuel} = 74.18\text{lb/hr}$$

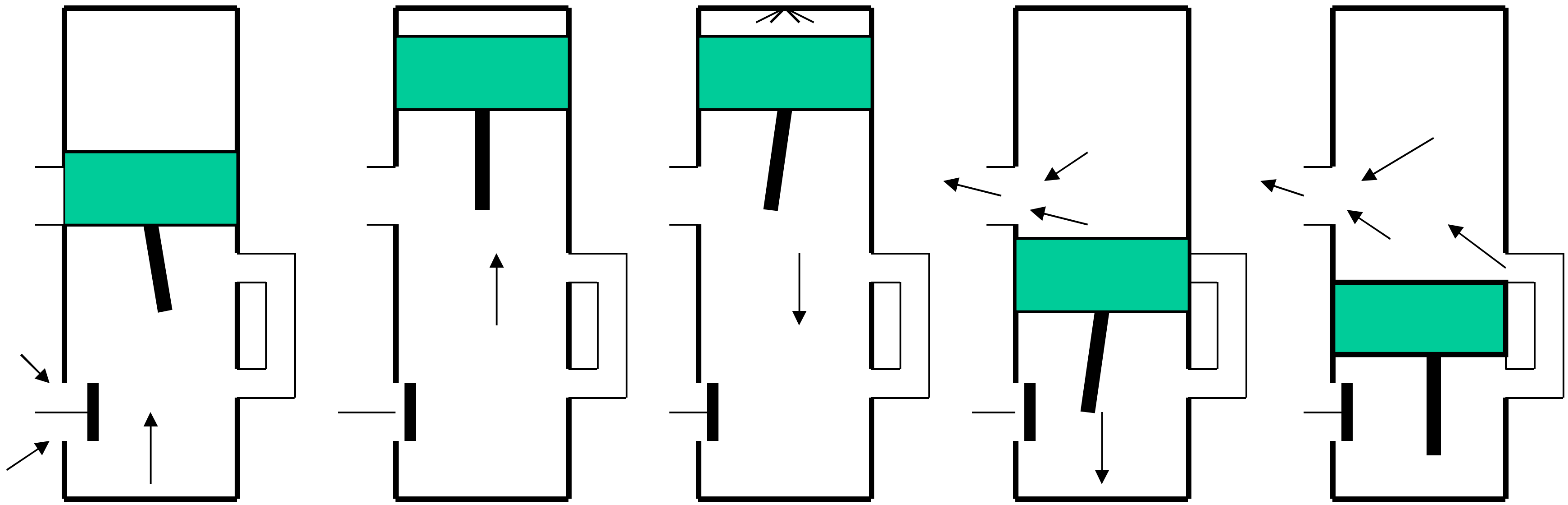
d)

$$\text{Specific Fuel Consumption} = \frac{74.18\ \text{lb/hr}}{167.3\ \text{HP}}$$

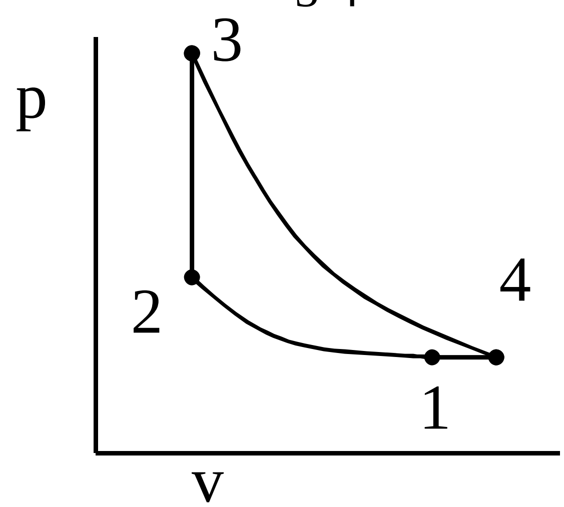
$$\text{Specific Fuel Consumption} = .44\text{lb fuel/HP hr}$$



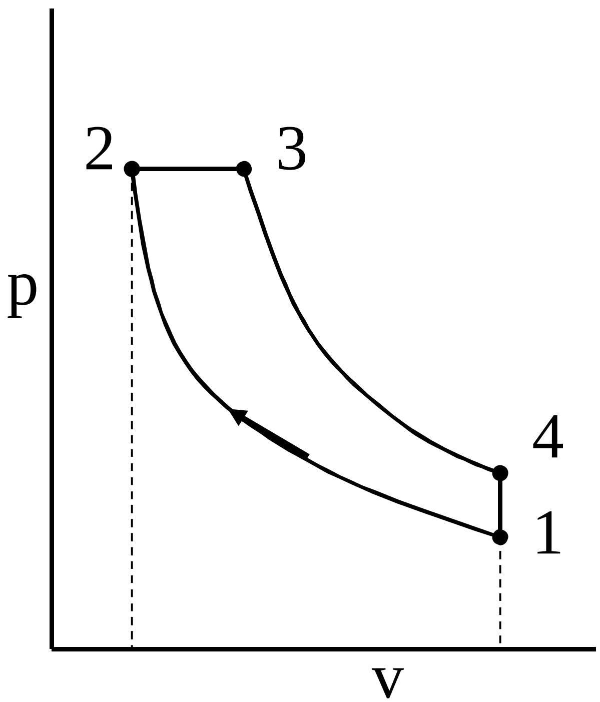
2 CYCLE, 1 Revolution/cycle



Compression 1-2 | Ignition 2-3 | Power 3-4 | Exhaus 4-1 | Intake 1



Diesel Cycle



Compression - isentropic, Q=0
Combustion -constant pressure
Expansion - isentropic, Q=0
Exhaust - constant volume

Closed system

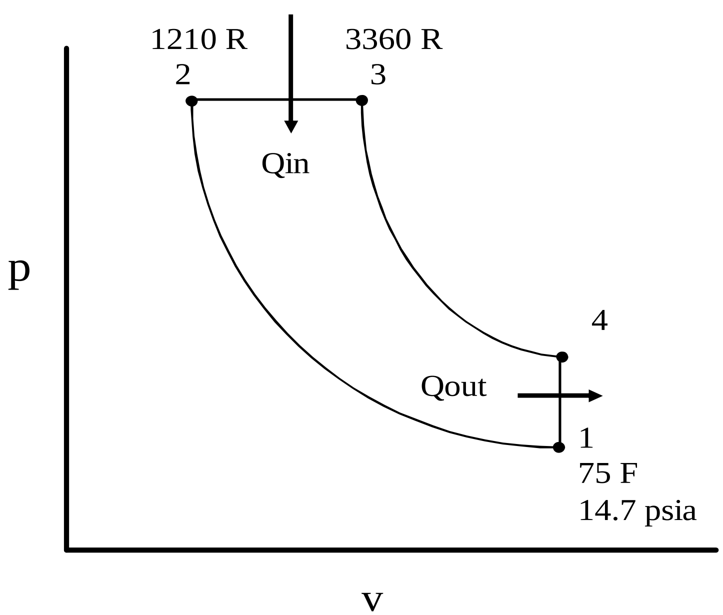
$$W_{1\to 2} = \varphi U$$
$$Q_{2\to 3} = \varphi H$$
$$Q_{4\to 1} = \varphi U$$

Compression ratio, $r = \dfrac{V_1}{V_2}$

Cut off ratio, $r_c = \dfrac{V_3}{V_2}$

$$d_{cycle} = 1 - \frac{1}{(r)^{k-1}}\left(\frac{r_c^k - 1}{k(r_c - 1)}\right)$$

What is the thermal efficiency of a COLD air standard diesel cycle operating on 14.7 psia air at 75 F? The temperature of the air before and after heat addition are 750 F and 2900 F respectively.



$$v_1 = \frac{RT_1}{p_1} = \frac{53.35 \times 535}{14.2 \times 144} = 13.94\ \text{ft}^3/\text{lb}$$

$$v_2 = v_1\left(\frac{T_1}{T_2}\right)^{\frac{1}{k-1}} = 13.94\left(\frac{535}{1210}\right)^{2.5} = 1.812\ \text{ft}^3/\text{lb}$$

$$v_3 = v_2\left(\frac{T_2}{T_1}\right) = 1.812\left(\frac{3360}{1210}\right) = 5.032\ \text{ft}^3/\text{lb}$$

$$T_4 = T_3\left(\frac{v_3}{v_4}\right)^{k-1} = 3360\left(\frac{5.032}{13.94}\right)^{.4} = 2235^{o}\,R$$

$$q_{in} = c_p\left(T_3 - T_2\right) = .241\left(3360 - 1210\right)$$

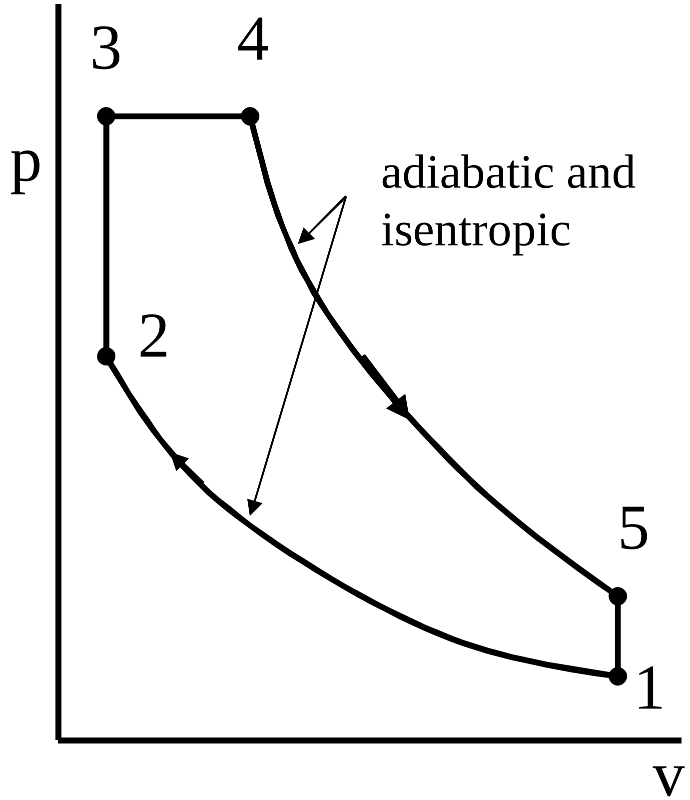
$$q_{in} = 518.15\ \text{BTU/lb}$$

$$q_{out} = c_v\left(T_4 - T_1\right) = .171\left(2235 - 535\right) =$$

$$q_{out} = 290.7\ \text{BTU/lb}$$

$$d_{cycle} = \frac{q_{in} - q_{out}}{q_{in}} = \frac{518.15 - 290.7}{518.15} = 43.9\%$$

AIR STANDARD DUAL CYCLE



$$\text{Cut off ratio, } r_c = \frac{V_4}{V_3}$$

$$\text{Compression ratio, } r = \frac{V_2}{V_1}$$

Closed System

$-$ quantity of mass

$$q = \Delta u + w$$

$$w_{p=\text{constant}} = p(\Delta v)$$

$$q_{p=\text{constant}} = \Delta h$$

$$w_{1\to2} = u_2 - u_1 \qquad q_{1\to2} = 0$$

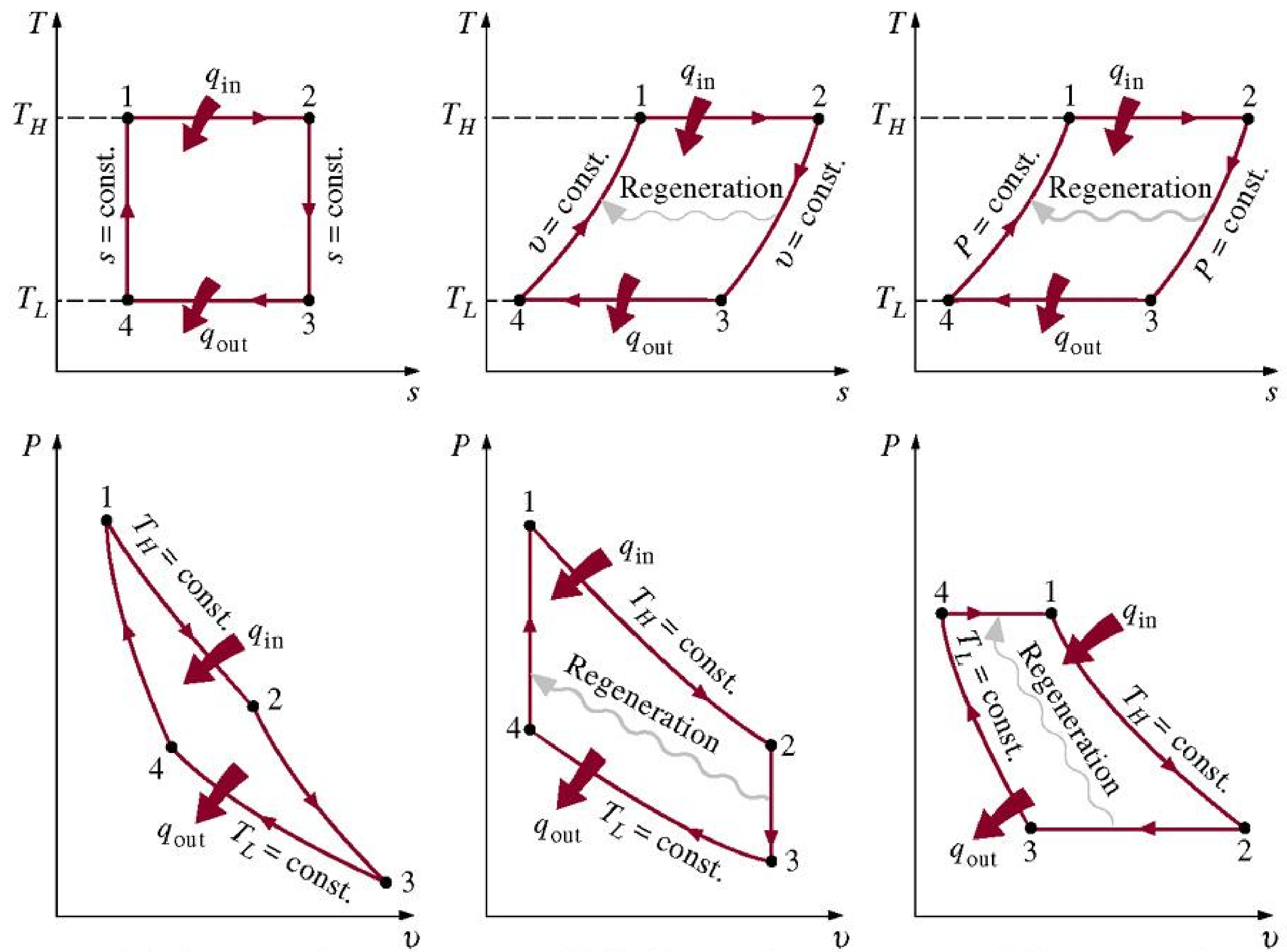
$$w_{2\to3} = u_2 - u_3 \qquad q_{3\to4} = u_3 - u_2$$

$$w_{3\to4} = p(v_4 - v_3) \qquad q_{3\to4} = h_3 - h_4$$

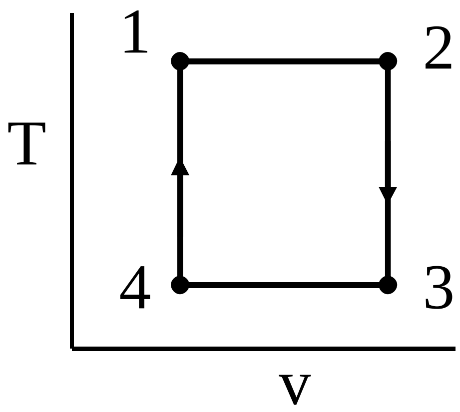
$$w_{4\to5} = u_4 - u_5 \qquad q_{4\to5} = 0$$

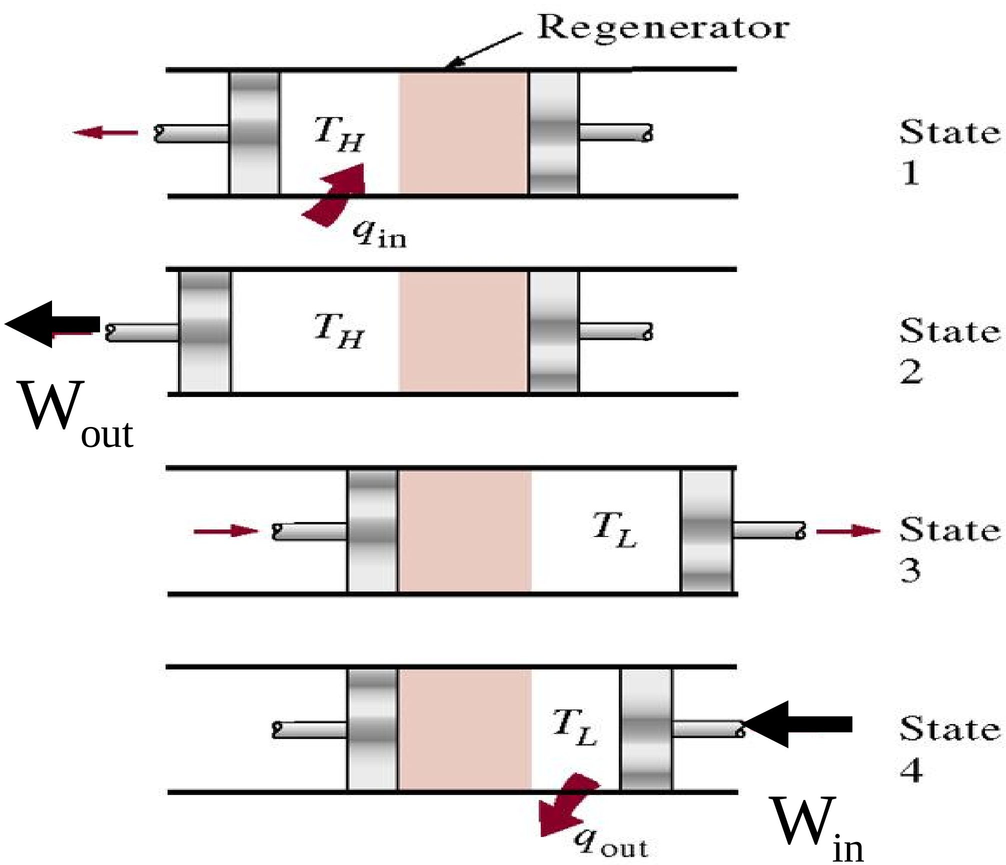
$$w_{5\to1} = 0 \qquad q_{5\to1} = u_5 - u_1$$

Stirling and Erickson Cycles



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





Stirling Cycle, Closed System

Process $1 \rightarrow 2$

q_{in} at conatant T_H, v increases

$$w_{out} = RT_1 \ln\left(\frac{v_2}{v_1}\right)$$

Process $2 \rightarrow 3$

$v = \text{constant}$

$$q_{regenerator} = \varphi u$$

Process $3 \rightarrow 4$

q_{out} at conatant T_H, v decreases

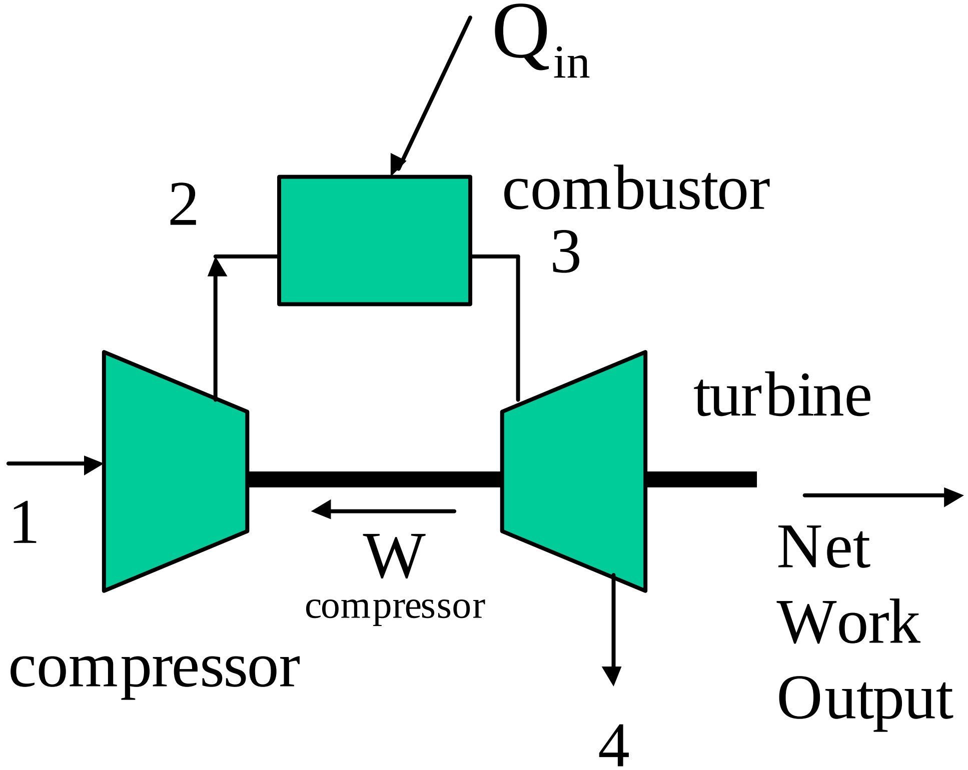
$$w_{in} = R\,T_3 \ln\left(\frac{v_4}{v_3}\right)$$

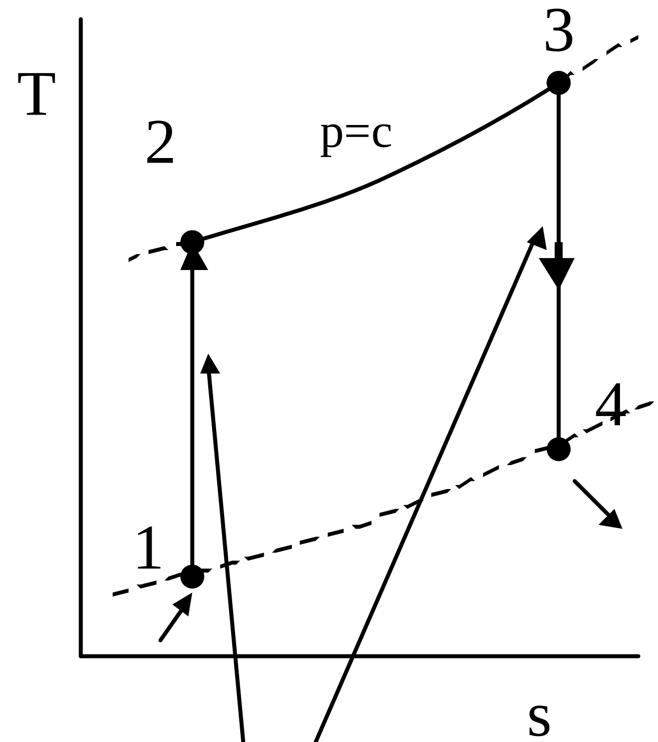
Process $4 \rightarrow 1$

$v = \text{constant}$

$$q_{regenerator} = \varphi u$$

Simple Brayton, Gas Turbine, Cycle





$\Delta s = 0$, isentropic

$Q = 0$, adiabatic

$pv^k = \text{constant}$

reversible

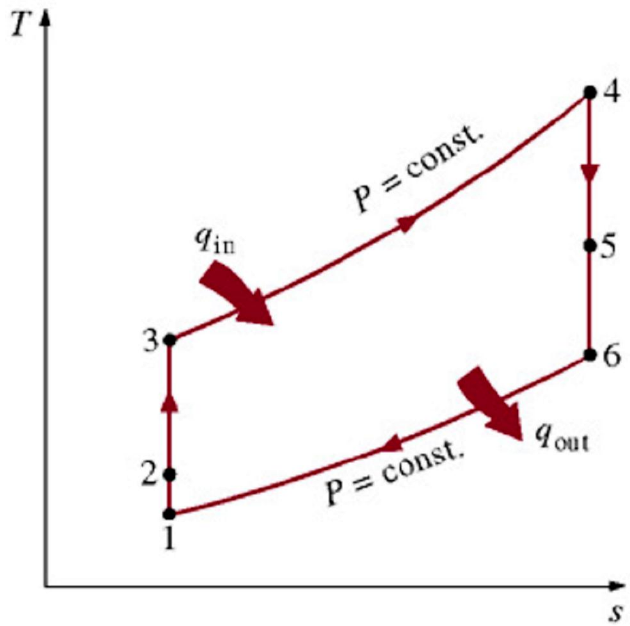
Compressor, Combustion, and Turbine are

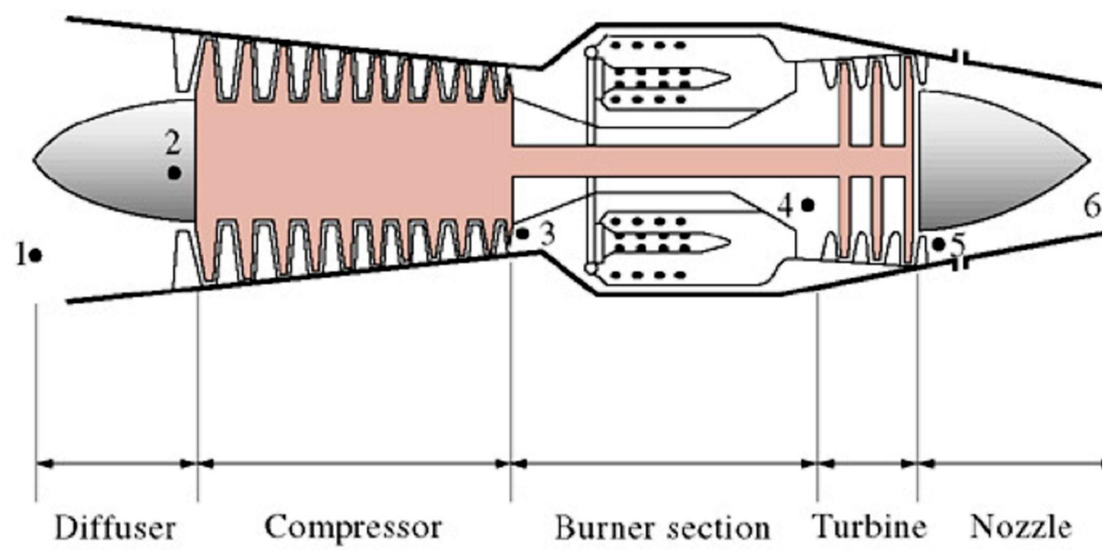
Open Thermodyanic Systems

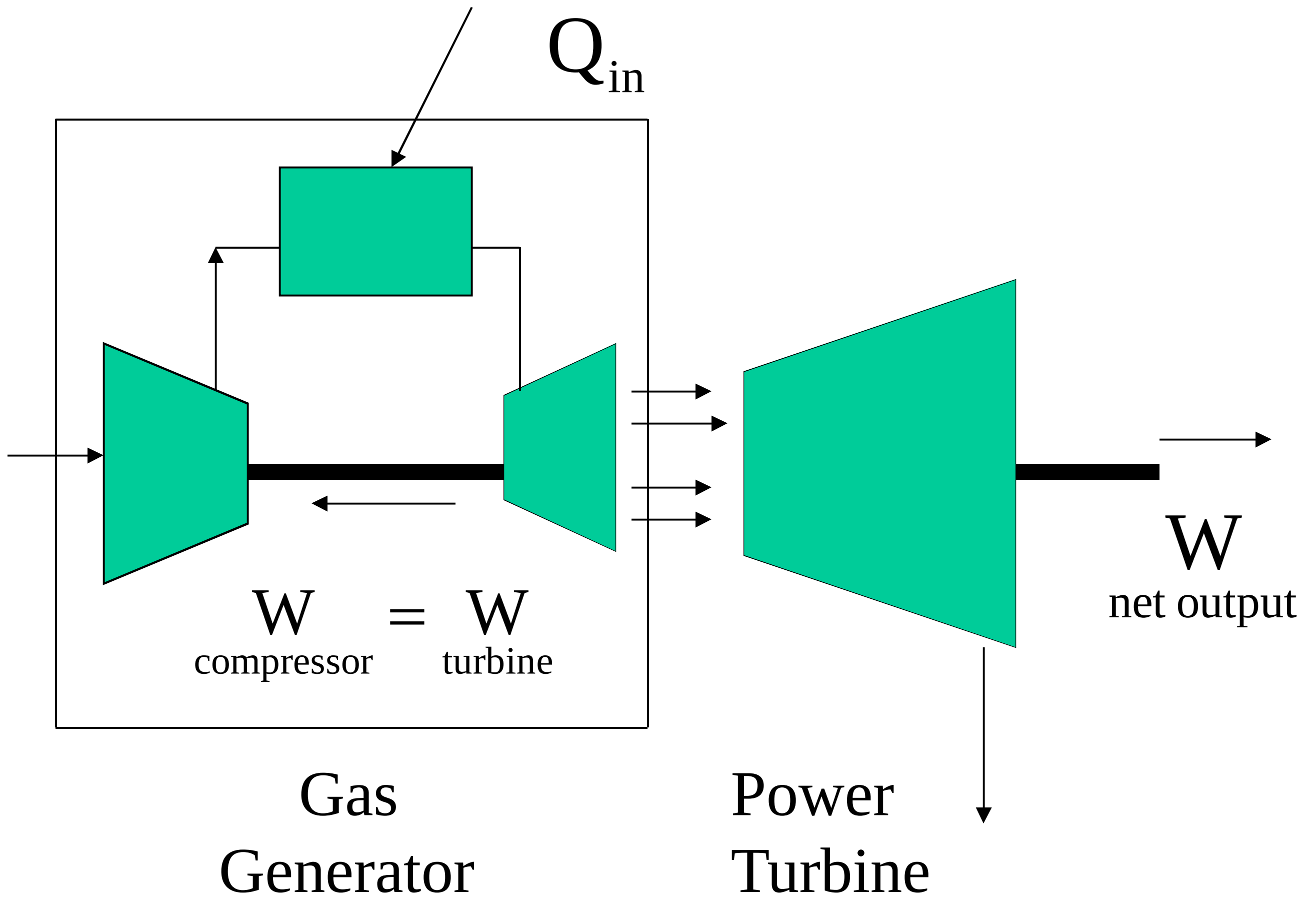
Steady Flow Energy Equation Form of First Law

$$Q = \Delta(h + KE) + W_{net}$$

Propulsion Gas Turbine

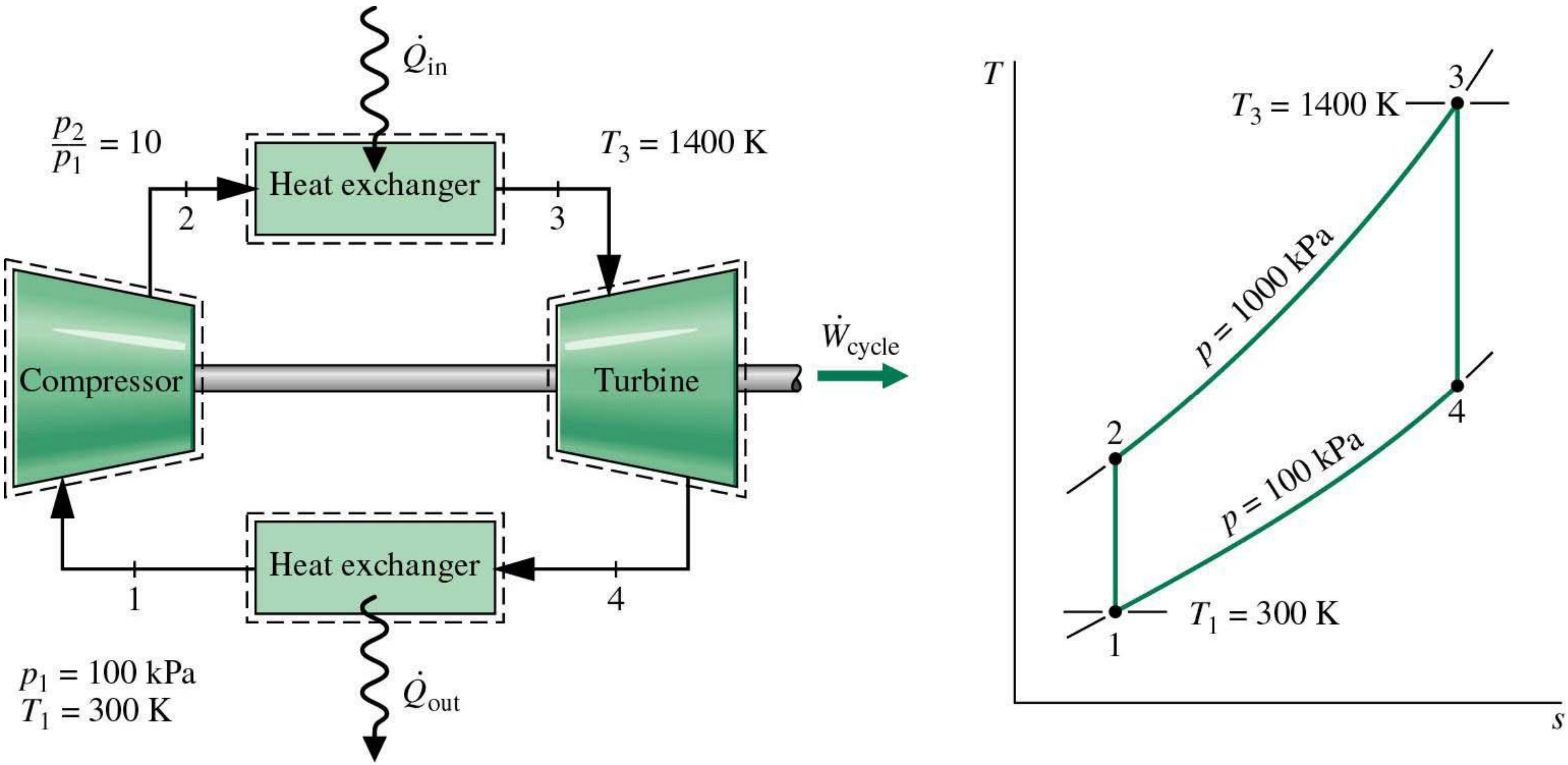






Aero-derivative Gas Turbine

Figure 9.4 Air Standard Brayton Cycle



Brayton Cycle with Real Compression and Expansion

Turbine Efficiency

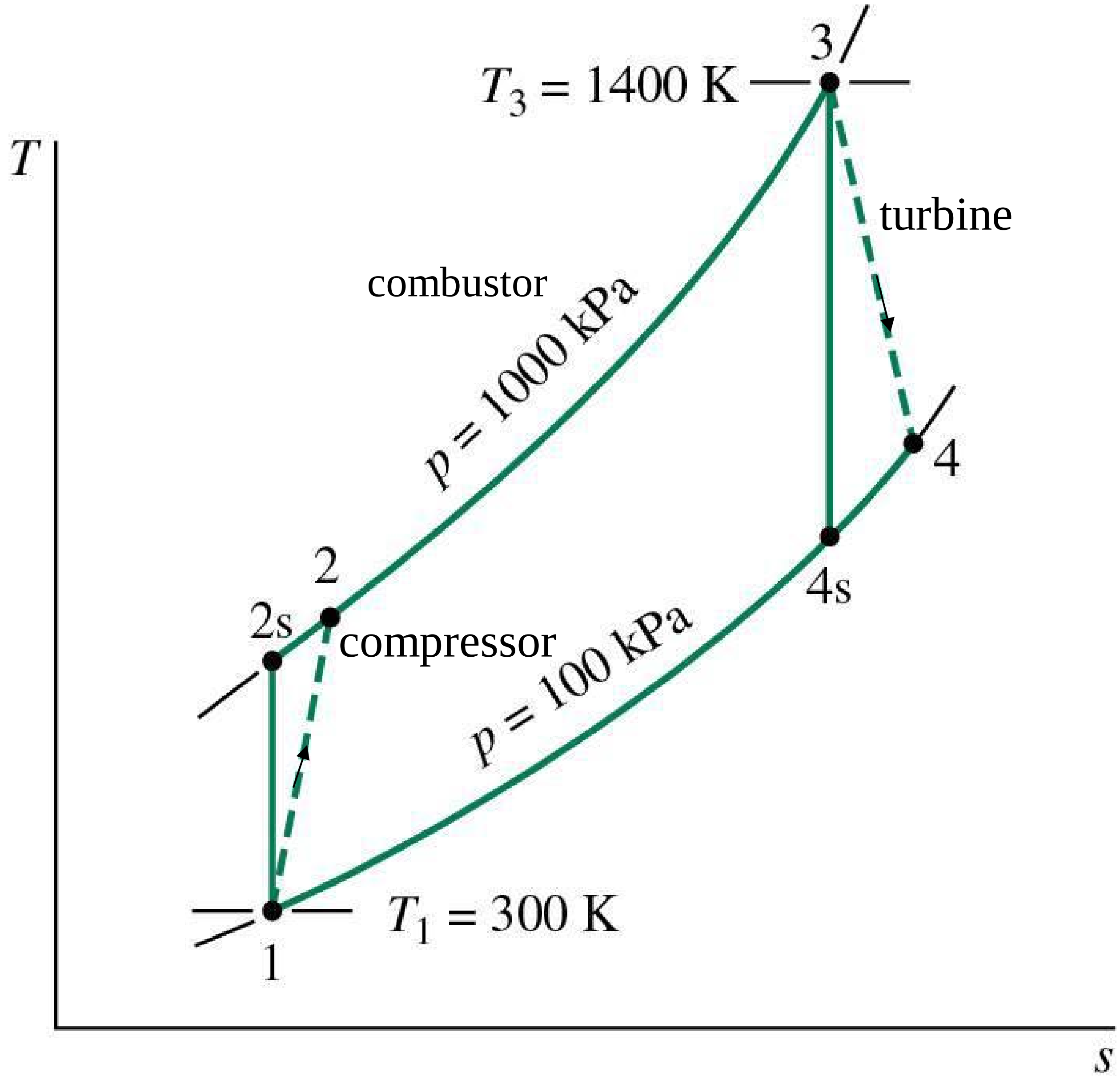
$$d_t = \frac{\text{actual work}}{\text{isentropic work}}$$

$$d_t = \frac{h_3 - h_4}{h_3 - h_{4s}}$$

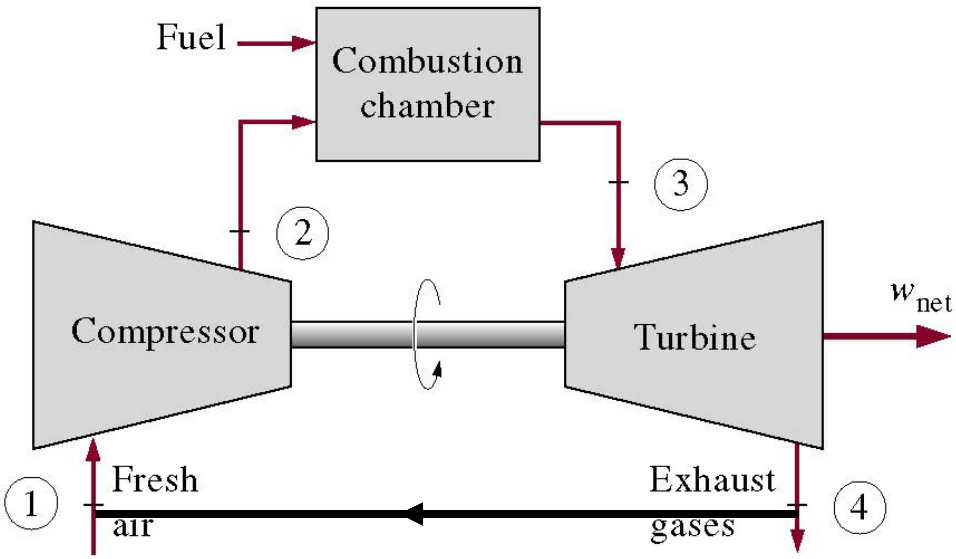
Compressor Efficiency

$$d_c = \frac{\text{isentropic work}}{\text{actual work}}$$

$$d_c = \frac{h_{2s} - h_1}{h_2 - h_1}$$

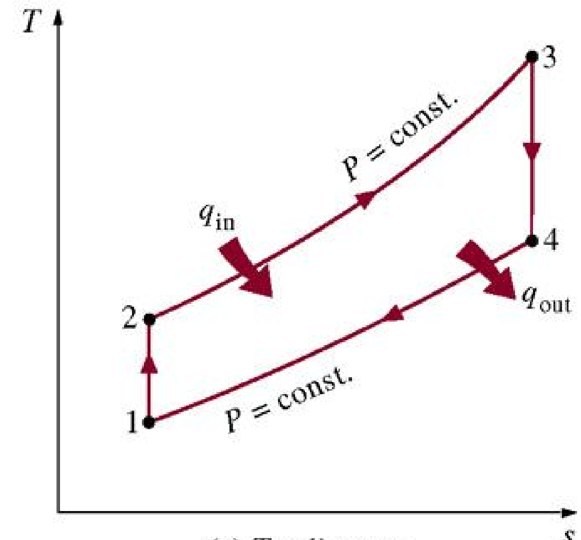


Brayton Air Standard Cycle

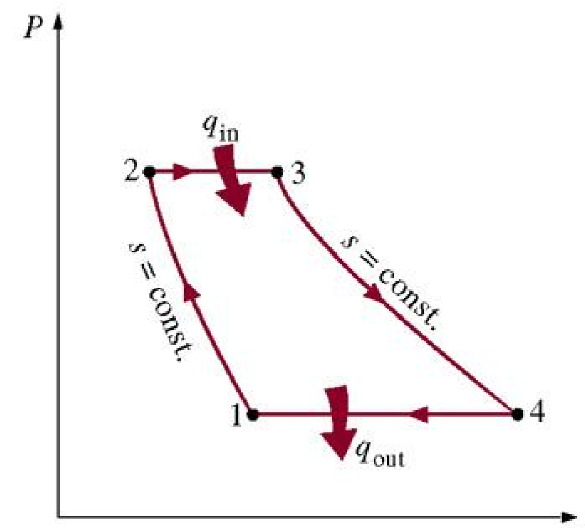


Air Standard Process

Actual Process



(a) *T*-*s* diagram



(b) *P*-υ diagram

Steady Flow, Open System - region in space

Steady Flow Energy Equation

$$Q = m \times \Delta\left(u + pv + \frac{V^2}{2} + gh\right) + W_{shaft}$$

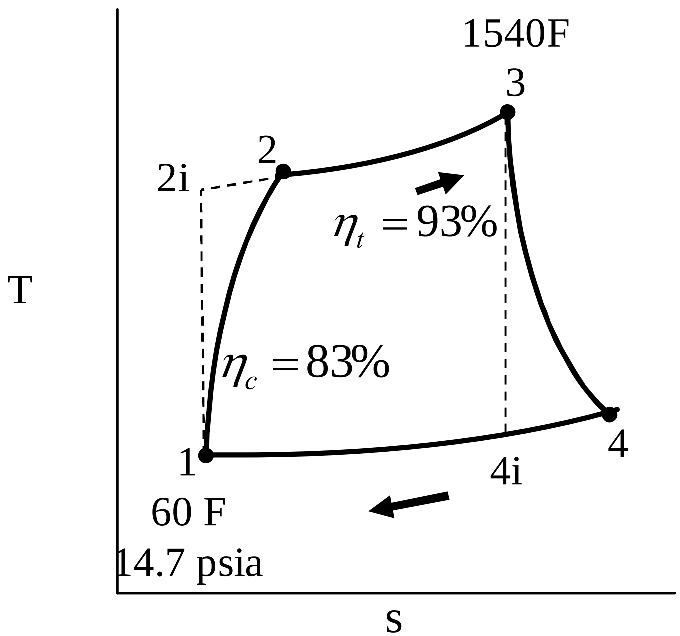
Compression Process, $Q = 0,\ W = m(h_2 - h_1)$

Combustion Process, $W = 0,\ Q = m(h_3 - h_2)$

Expansion Process, $Q = 0,\ W = m(h_3 - h_4)$

Exhause Process, $W = 0,\ Q = m(h_4 - h_1)$

In an air COLD standard gas turbine, 60 F and 14.7 psia air is compressed through a pressure ratio of 10. Air enters at 1540 F and expands to14.7 psia. If the isentropic efficiency of the compressor and turbine are 83% and 93% respectively. What is the thermal efficiency of the cycle?



$$\text{Check}: \sum w = \sum q$$

$$213.59 - 139.92 = 215.26 - 142.33$$

$$73.67 = 72.93$$

$$T_{2i} = T_1\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = (460+60)\times 10^{.2857} = 1003.9^{o}R$$

$$d_{compressor} = \frac{W_{ideal}}{W_{actual}} = \frac{h_{2is} - h_1}{h_2 - h_1} = \frac{c_p(T_{2is} - T_1)}{c_p(T_2 - T_1)} = .83$$

$$T_2 = T_1 + \frac{T_{2is} - T_1}{.83} = 520 + \frac{1003.9 - 520}{.83} = 1103.01^{o}R$$

$$q_{2-3} = h_3 - h_2 = c_p(T_3 - T_2)$$

$$q_{2-3} = .241(2000 - 1103.01) = 215.26\text{BTU/lb}$$

$$w_{1-2} = h_2 - h_1$$

$$w_{1-2} = c_p(T_2 - T_1) = .241(1103.01 - 520) = 139.92\text{BTU/lb}$$

$$T_{4i} = T_3\left(\frac{p_4}{p_3}\right)^{\frac{k-1}{k}} = 2000\times\left(\frac{1}{10}\right)^{.2857} = 1035.9^{o}R$$

$$d_{turbine} = \frac{w_{actual}}{w_{ideal}} = \frac{h_3 - h_4}{h_3 - h_{4i}} = \frac{c_p(T_3 - T_4)}{c_p(T_3 - T_{4i})} = \frac{1959.7 - T_4}{1959.7 - 1029.5} = .93$$

$$T_4 = T_3 - .92\times(T_3 - T_{4is}) = 2000 - .93\times(2000 - 1035.9) = 1113.03^{o}R$$

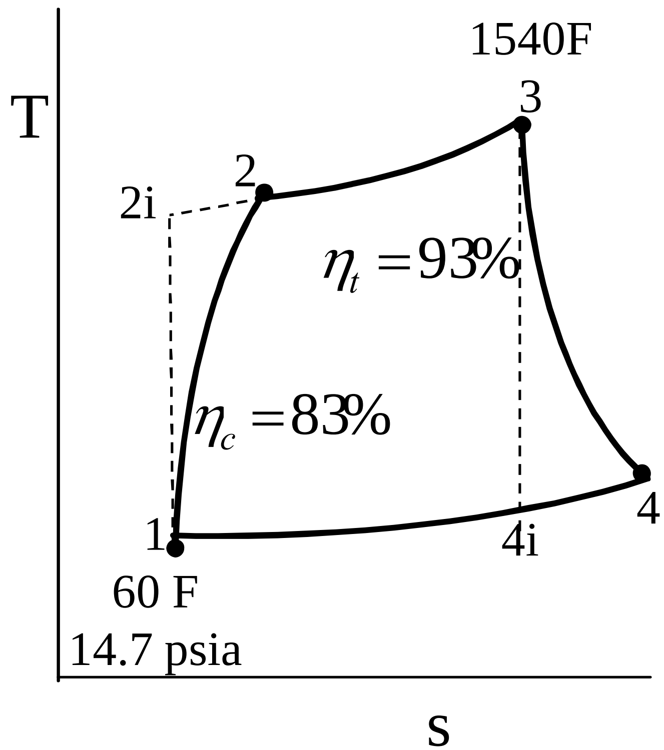
$$w_{3-4} = h_3 - h_4 = .241(2000 - 1110.03) = 213.59\text{BTU/lb}$$

$$q_{4-1} = h_4 - h_1 = .241(T_4 - T_1) = .241(1113.03 - 520.) = 142.33\text{BTU/lb}$$

$$d_{cycle} = 1 - \frac{h_4 - h_1}{h_3 - h_2} = 1 - \frac{1113.03 - 520}{2000 - 1103.01} = 33.9\%$$

$$d_{cycle} = \frac{w_{net}}{q_{in}} = \frac{215.26 - 139.92}{215.26} = 33.9\%$$

In an air standard gas turbine, 60 F and 14.7 psia air is compressed through a pressure ratio of 10. Air enters at 1540 F and expands to 14.7 psia. If the isentropic efficiency of the compressor and turbine are 83% and 93% respectively.What is the thermal efficiency of the cycle?



$$\text{at } 520^o\,\text{R}, \quad p_{r1} = 1.2147, \; h_1 = 124.27\,\text{BTU/lb}$$

T	p_r	h
980	10.61	236.02
998	12.147	240.48
1000	12.30	240.98
ratio	$\frac{.17}{1.69} = .1006$	

$$p_{r2is} = p_{r1}\left(\frac{p_{2is}}{p_1}\right) = 1.2147 \times 10 = 12.147$$

$$h_{2is} = 240.48\,\text{BTU/lb}$$

$$d_{compressor} = \frac{W_{ideal}}{W_{actual}} = \frac{h_{2is} - h_1}{h_2 - h_1} = .83$$

$$h_2 = h_1 + \frac{h_{2is} - h_1}{.83} = 124.27 + \frac{240.48 - 124.27}{.83}$$

$$h_2 = 264.28\,\text{BTU/lb}$$

$$\text{At } 2000^o\,\text{R}, \quad p_{r3} = 174., \quad h_3 = 504.71$$

$$p_{r4is} = p_{r3}\left(\frac{p_{4is}}{p_1}\right) = 174. \times 1/10 = 17.4$$

$$\text{by interpolation at } \; p_{r4is} = 1.74, \; h_{4is} = 265.99\,\text{BTU/lb}$$

$$d_{turbine} = \frac{W_{actual}}{W_{ideal}} = \frac{h_3 - h_4}{h_3 - h_{4i}} = .93$$

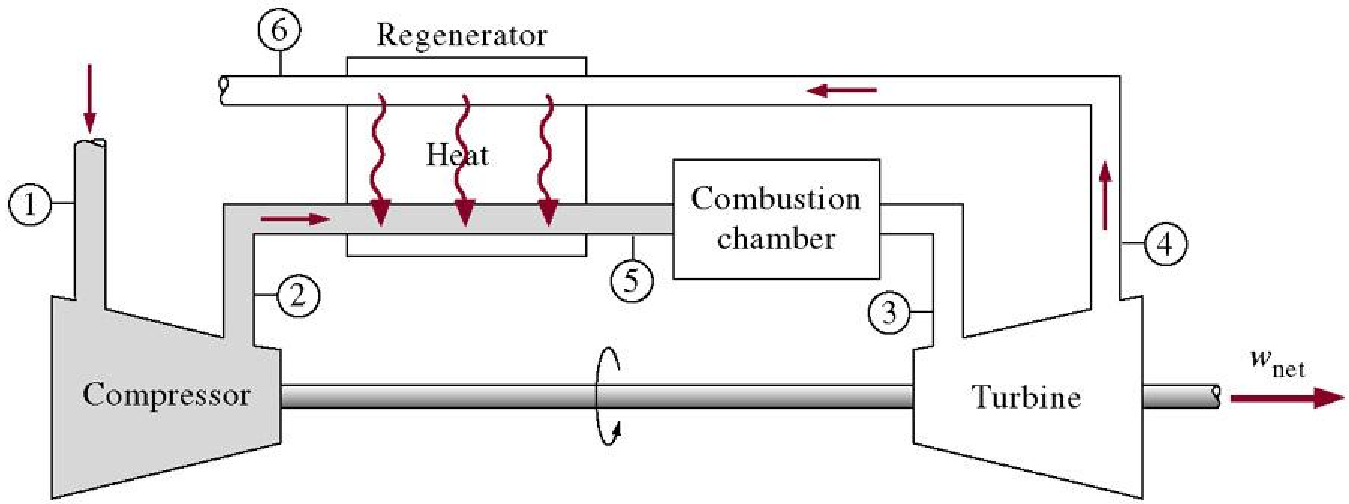
$$h_4 = h_3 - .92 \times \left(h_3 - h_{4is}\right) = 282.7\,\text{BTU/lb}$$

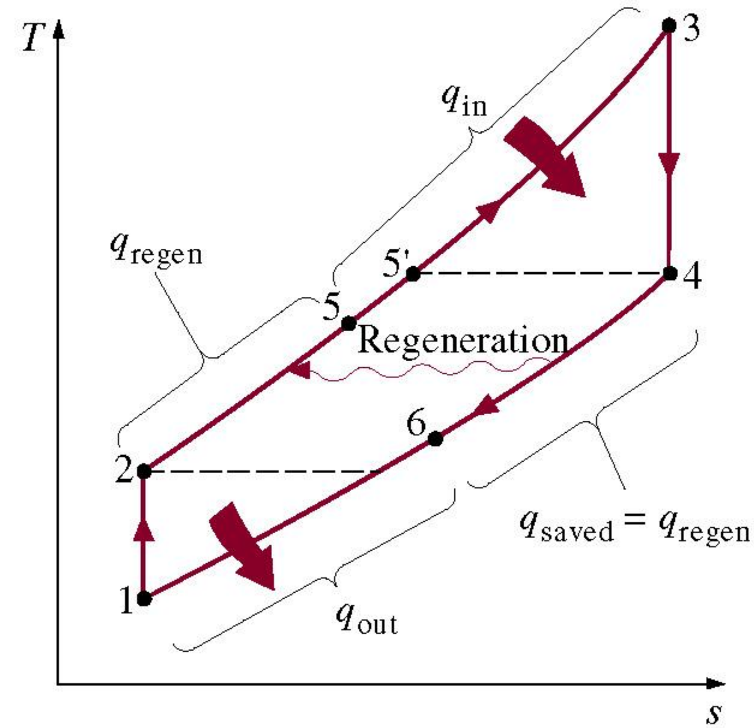
$$q_{in} = h_3 - h_2 = 504.7 - 264.28 = 240.42\,\text{BTU/lb}$$

$$q_{out} = h_4 - h_1 = 282.7 - 124.27 = 155.43\,\text{BTU/lb}$$

$$d = 1 - \frac{Q_{in}}{Q_{out}} = 1 - \frac{155.43}{240.42} = 35.3\%$$

Regenerated Brayton Cycle

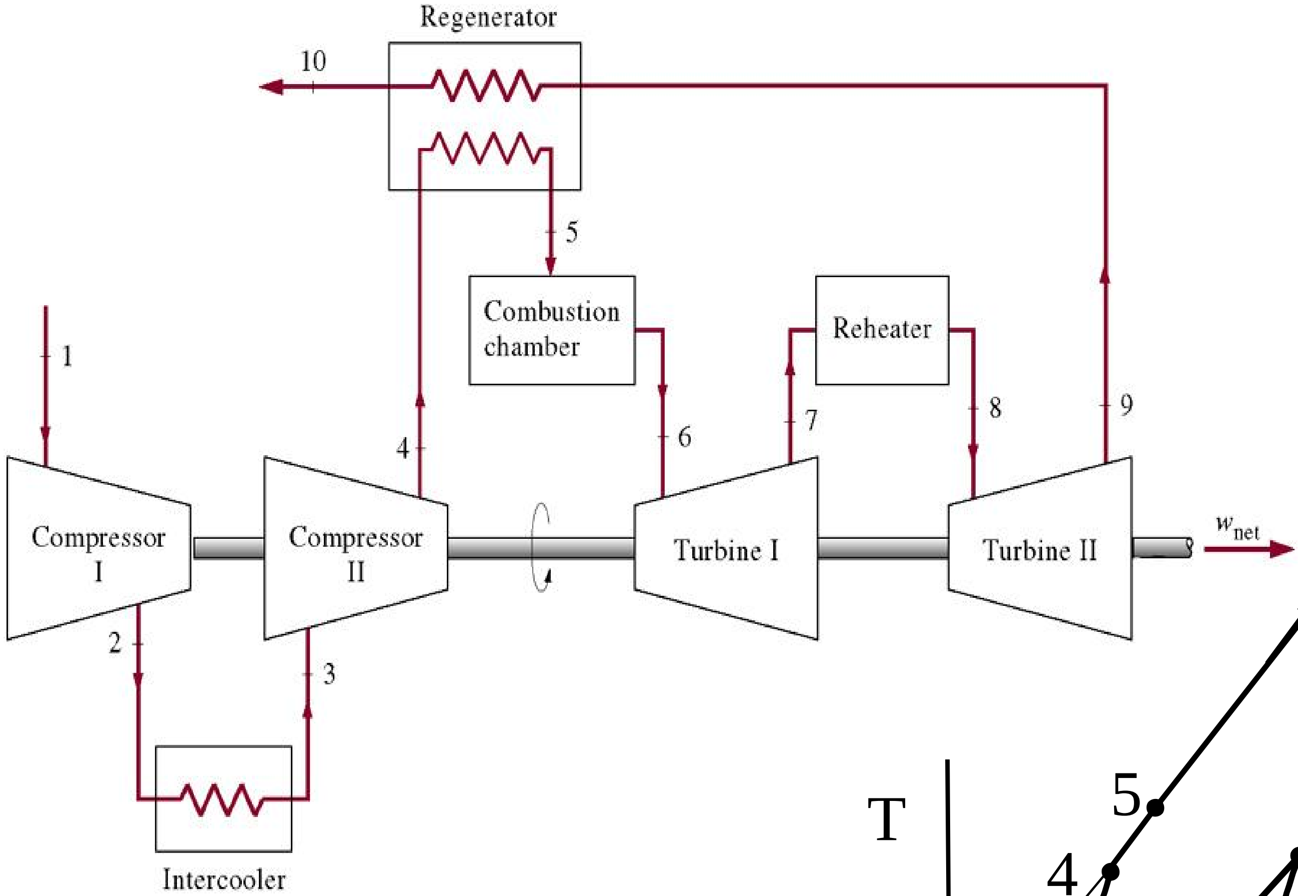




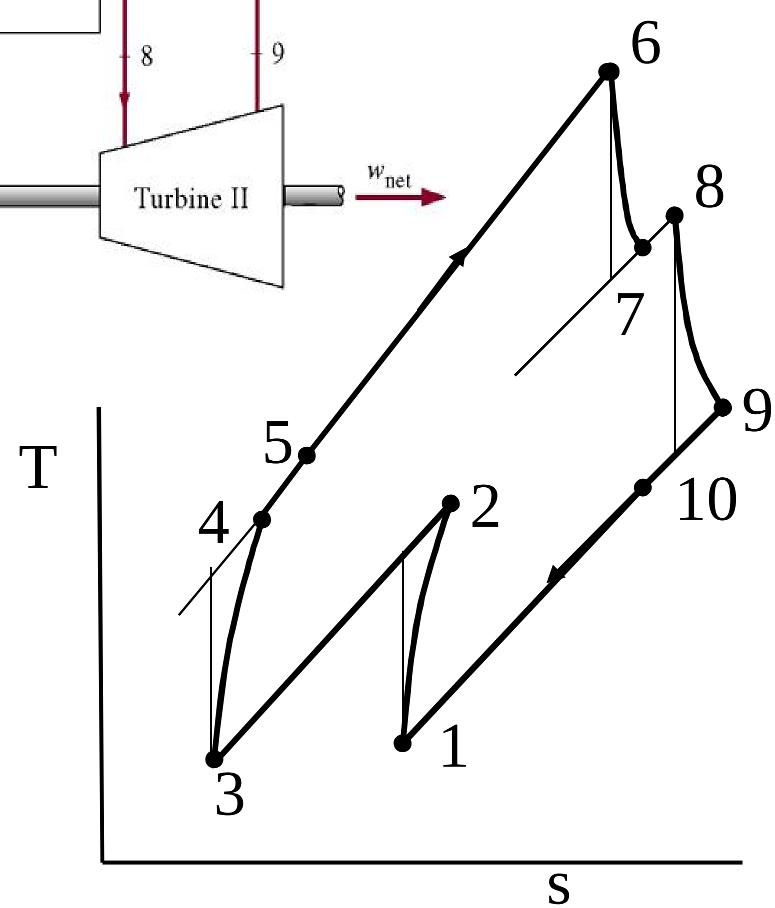
$$\text{Regenerator Effectiveness} = \frac{\text{Actual Heat Transfer}}{\text{Ideal Heatr Transfer}}$$

$$\text{Regenerator Effectiveness} = \frac{h_5 - h_2}{h_4 - h_2}$$

$$\text{Regenerator Effectiveness} = \frac{h_4 - h_6}{h_4 - h_2}$$



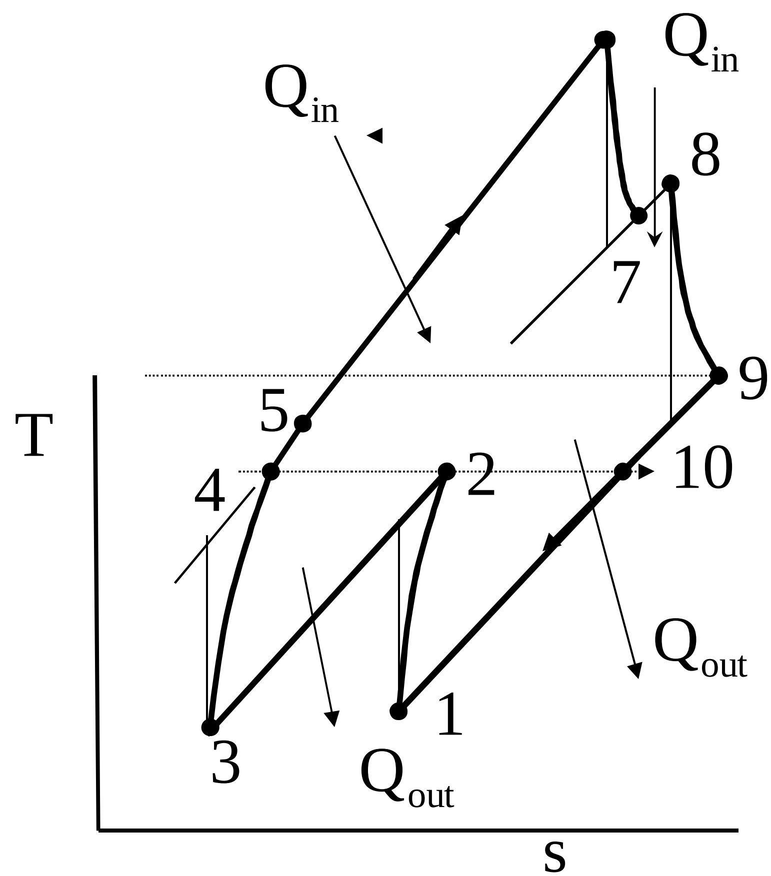
Brayton Cycle with:
- Intercooling
- Regeneration
- Reheat



A gas turbine cycle operates with 2 stages of inter-cooled compression, a regenerator, and two stages of expansion with reheat between them. Air enters the compressor at 100 kpa, 300 K at a volume flow of 5 cubic meters/ sec. The turbine and compressor stages have an equal pressure ratio, isentropic efficiencies of 80 % and the overall cycle pressure ratio is 8. The regenerator effectiveness is 80%. Turbine inlet temperature is 1400 K. Determine:

a) the cycle efficiency.

Pt	T	p	(p_r)	h
1	300	100	1.386	300.19
2s	403.29	283	3.920	404.31
2		283		430.34
3	300	100	1.386	300.19
3s	403.29	283	3.920	404.31
4		283		430.34
5		800		1061.2
6	1400	800	450.50	1515.42
7s	1105.9	283	159.3	1144.73
7		283		1218.9
8	1400	800	450.50	1515.42
8s	1105.9	283	159.3	1144.73
9		283		1218.9
10		100		588.05



Point 1

$v = RT/p = .287 \times 300/100 = .861\,\text{kg/sec}$

$m = 5\text{m}^3/\text{sec}/v = 5.81\,\text{kg/sec}$

$\text{Table A} - 22 \;@\; T = 300,\; h = 300.19\,\text{kJ/kg},\; (p_{r1}) = 1.386$

Point 2s

$\text{stage pressure ratio} = p_r \times p_r = 8, \quad pr = 2.83$

$(p_{r2s}) = (p_{r1s}) \times p_r = 3.92$

$@\;(p_{r2s}) = 3.92,\; h_{2s} = 404.31$

Point 3

$h_2 = h_1 + (h_{2s} - h_1)/.8 = 430.34$

Point 6

$\text{TableA} - 22 \;@\; T = 1400,\; h = 11414.42\,\text{kJ/kg},\; (p_{r1}) = 450.5$

$(p_{r7s}) = (p_{r6s})/p_r = 159.3$

$@\;(p_{r7s}) = 159.3,\; h = 1144.73,\; T = 1105.9$

$h_7 = h_6 - (h_6 - h_{7s})/.8 = 1218.9\,\text{kJ/kg}$

Recuperator Energy Balance

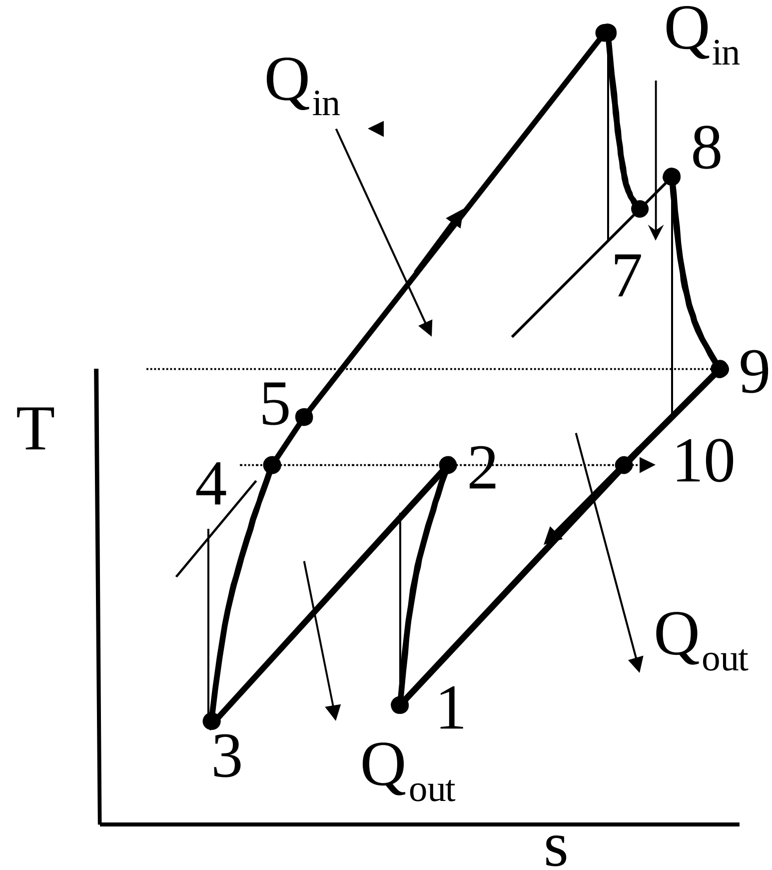
$$\mathring{U} = \frac{Q_{actual}}{Q_{max}} = \frac{h_5 - h_4}{h_9 - h_4} = \frac{h_9 - h_{10}}{h_9 - h_4}$$

Point 5

$h_5 = h_4 + \mathring{U} \times (h_9 - h_4) = 1061.2\,\text{kJ/kg}$

Point 10

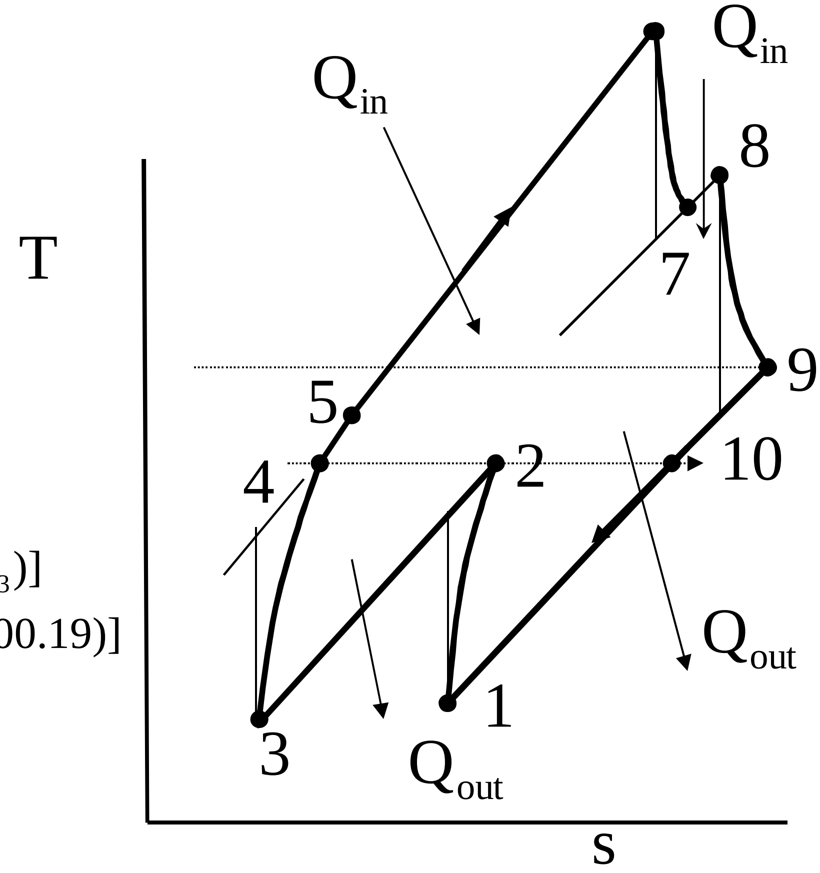
$h_{10} = h_9 - \mathring{U} \times (h_9 - h_4) = 588.05\,\text{kJ/kg}$



$$d_{cycle} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{(h_{10} - h_1) + (h_2 - h_3)}{(h_6 - h_5) + (h_2 - h_3)}$$

$$d_{cycle} = 1 - \frac{\text{combustor} + \text{reheat}}{\text{exhaust} + \text{intercooling}}$$

$$d_{cycle} = 1 - \frac{288.05 + 130.15}{454.22 + 296.52} = 44.3\,\%$$



$$W = \text{Turbine Work} - \text{Compressor Work}$$

$$W = m \times [(h_6 - h_7) + (h_8 - h_9) - (h_2 - h_1) - (h_4 - h_3)]$$

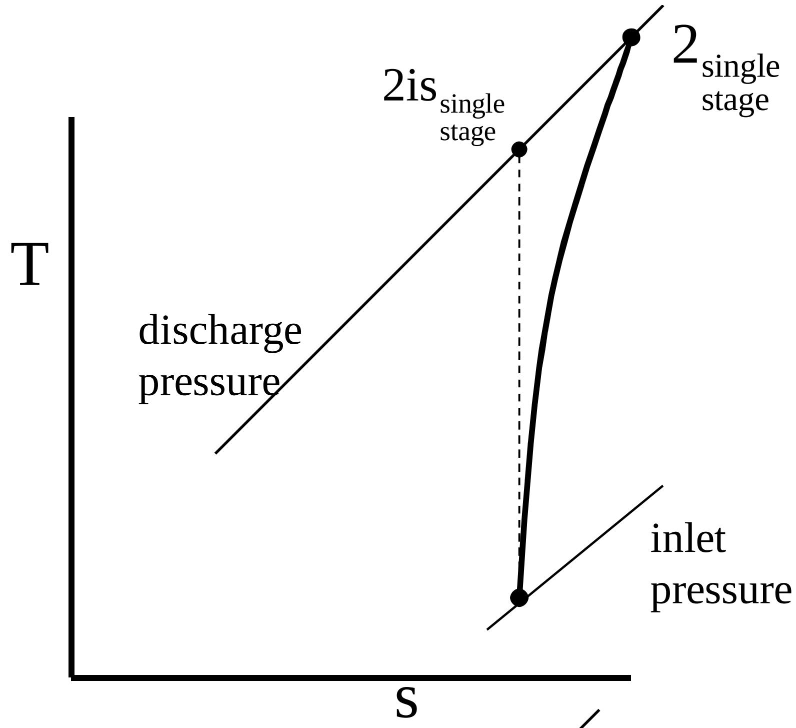
$$W = 5.81 \times 2 \times [(1515.42 - 1218.9) - (430.34 - -300.19)]$$

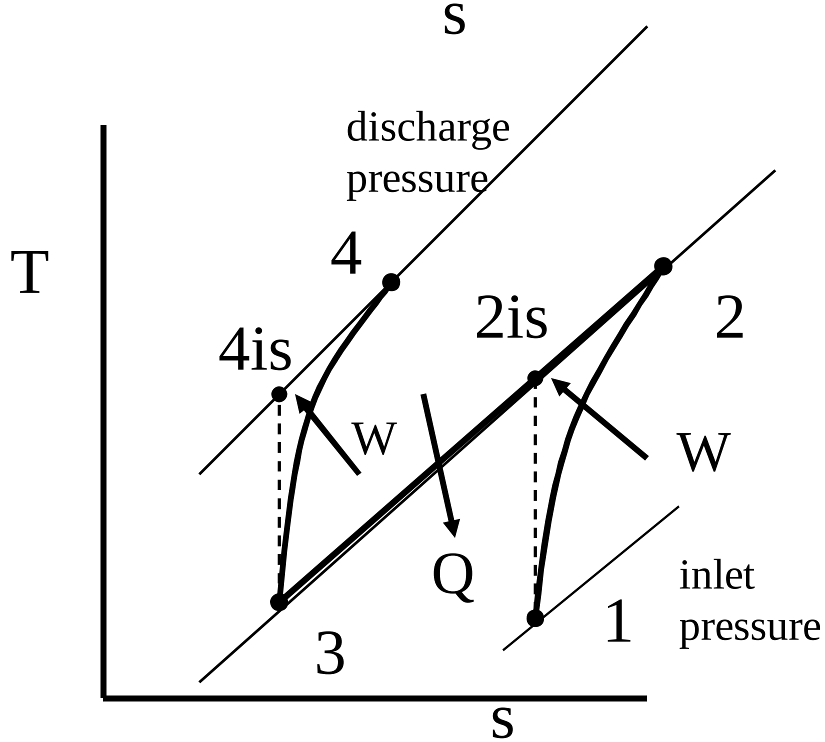
$$W = 5.81 \times 2 \times [(296.52) - (130.15)]$$

$$W = 1921.6\ \text{kJ/sec} = 1921.6\ \text{KW}$$

$$\text{Back Work Ratio} = W_{compressor}/W_{turbine}$$

$$\text{Back Work Ratio} = 130.15/296.52 = .438$$





Intercooled Compression

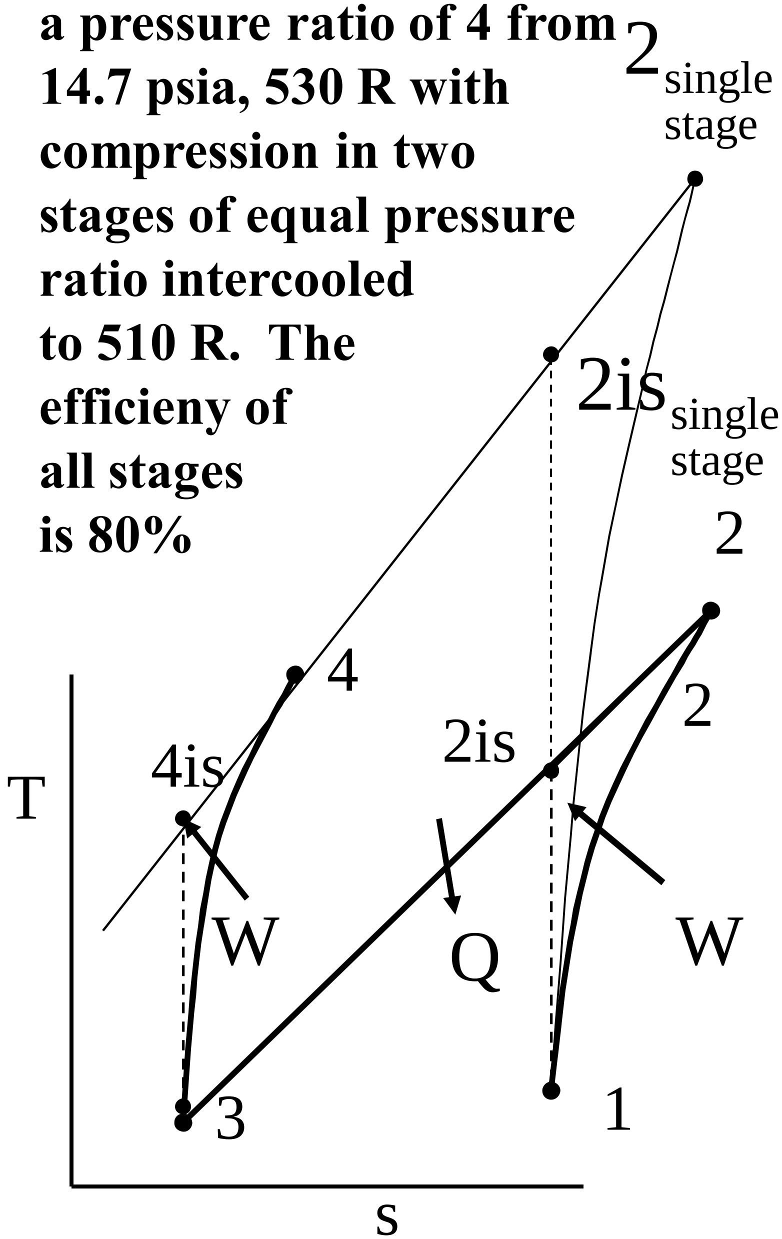
$$w_{1\to 2} = h_2 - h_1$$

$$q_{2\to 3} = h_2 - h_3$$

$$w_{3\to 4} = h_4 - h_3$$

$$T_{2is} = T_1 \left(\frac{p_2}{p_1} \right)^{\frac{k-1}{k}}$$

Compare compression over a pressure ratio of 4 from 14.7 psia, 530 R with compression in two stages of equal pressure ratio intercooled to 510 R. The efficieny of all stages is 80%



$$T_{2is} = T_1\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = 530(2)^{.2857} = 646^{o}\,R$$

$$T_2 = T_1 + \frac{T_{2is} - T_1}{.8} = 530 + \frac{646-530}{.8} = 675^{o}\,R$$

$$w_{12} = c_p\left(T_2 - T_3\right) = .24\times(675-530) = 34.80\,BTU/lb$$

$$q_{2\to3} = c_p\left(T_2 - T_3\right) = .24\times\left(646-530\right) = 32.64\,BTU/lb$$

$$T_{4is} = T_1\left(\frac{p_4}{p_3}\right)^{\frac{k-1}{k}} = 510(2)^{.2857} = 621.69^{o}\,R$$

$$T_4 = T_3 + \frac{T_{4is} - T_3}{.8} = 510 + \frac{621.69-510}{.8} = 649.61^{o}\,R$$

$$w_{3\to4} = c_p\left(T_4 - T_3\right) = .24\times\left(649.61-510\right) = 33.51\,BTU/lb$$

$$w_{\substack{inter\\cooled}} = 34.8 + 33.51 = 68.31\,BTU/lb$$

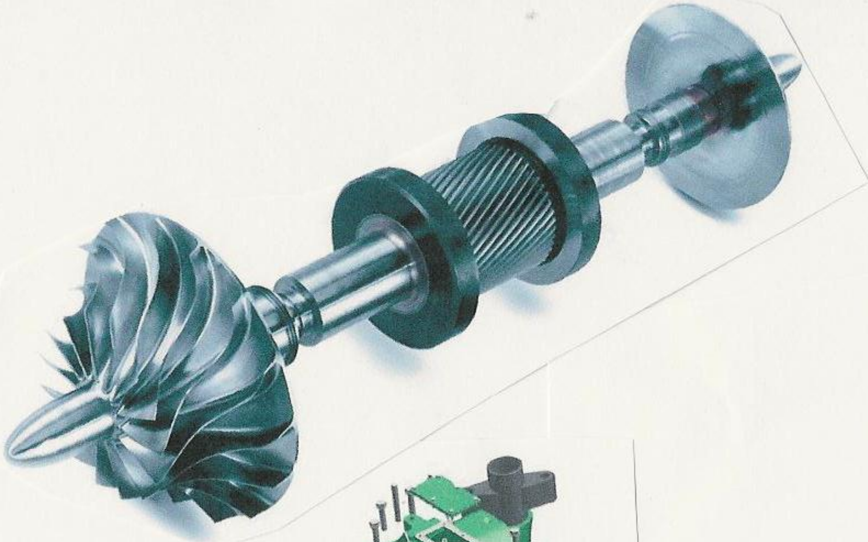
$$T_{2is\,\substack{single\\stage}} = T_1\left(p_{2\,\substack{single\\stage}}/p_1\right)^{\frac{k-1}{k}} = 530\times\left(4\right)^{.2857} = 787.56^{o}\,R$$

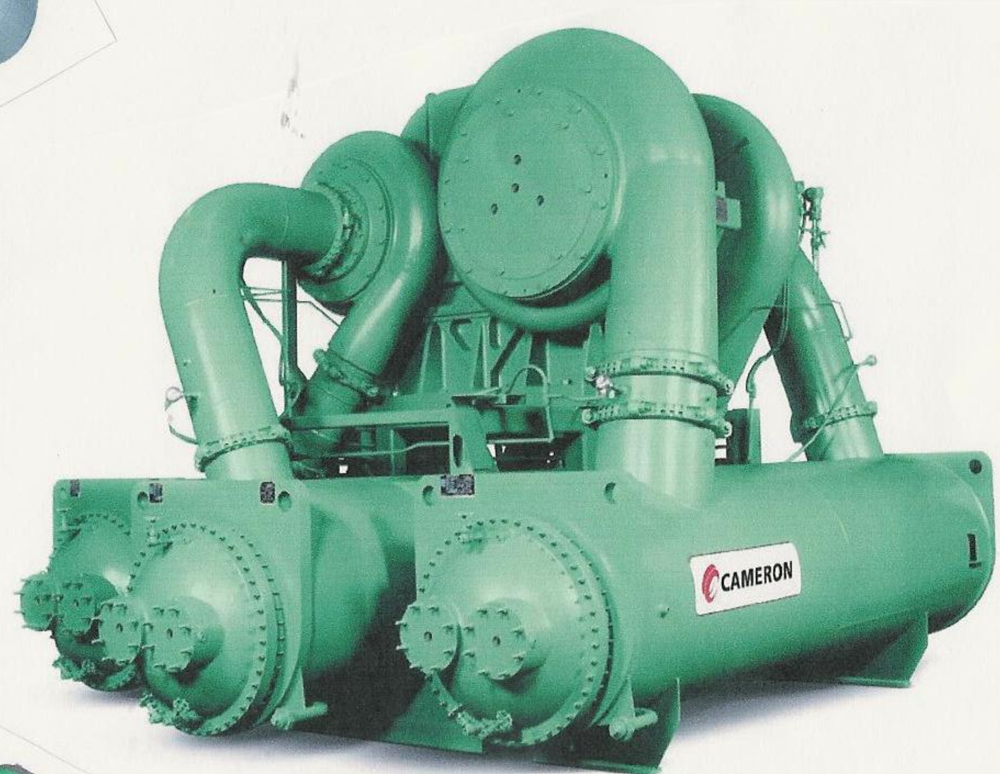
$$T_{\substack{single\\stage}} = T_1 + \frac{T_{2is\,\substack{single\\stage}} - T_1}{.8} = 851.95^{o}\,R$$

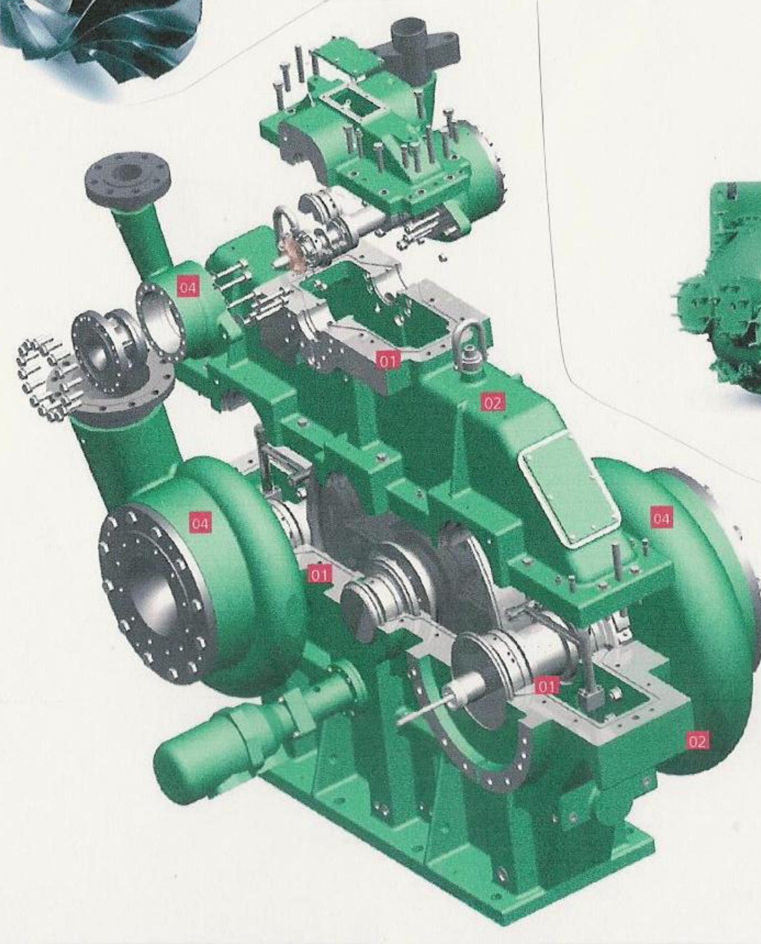
$$w_{\substack{single\\stage}} = c_p\left(T_4 - T_3\right) = .24\times\left(851.95-530\right) = 77.68\,BTU/lb$$

11.4% higher

INTEGRAL GEAR CENTRIFUGAL COMPRESSOR







Cross Sectional View of a Typical 3-rotor Process Gas Compressor

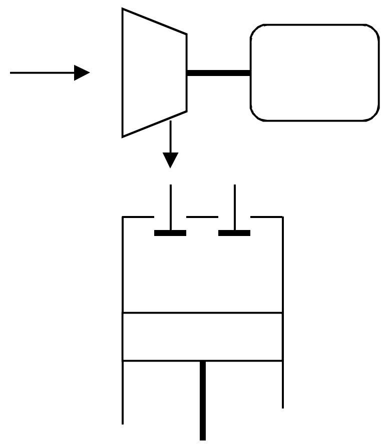
01: One, two or three rotors up to 6-stages per gear box

02: Horizontal splitline(s) for easy access to parts

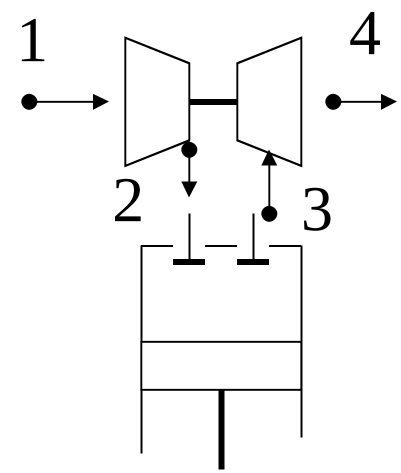
03: Engineered seal designs

04: NACE compliant scrolls and inlets may be manufactured from steel or stainless steel

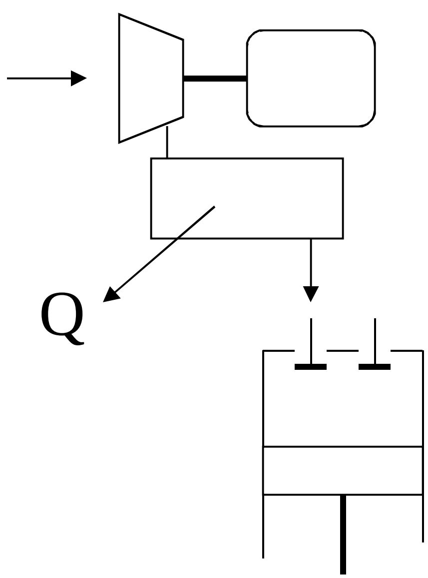
Supercharger



Turbocharger

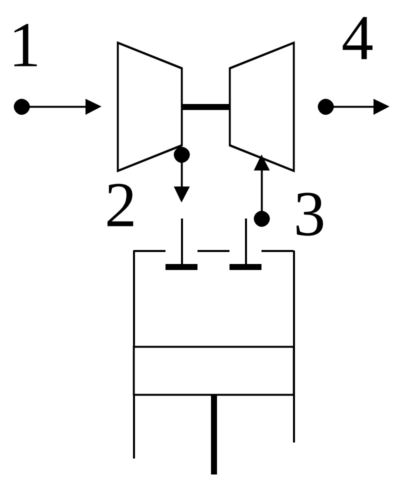


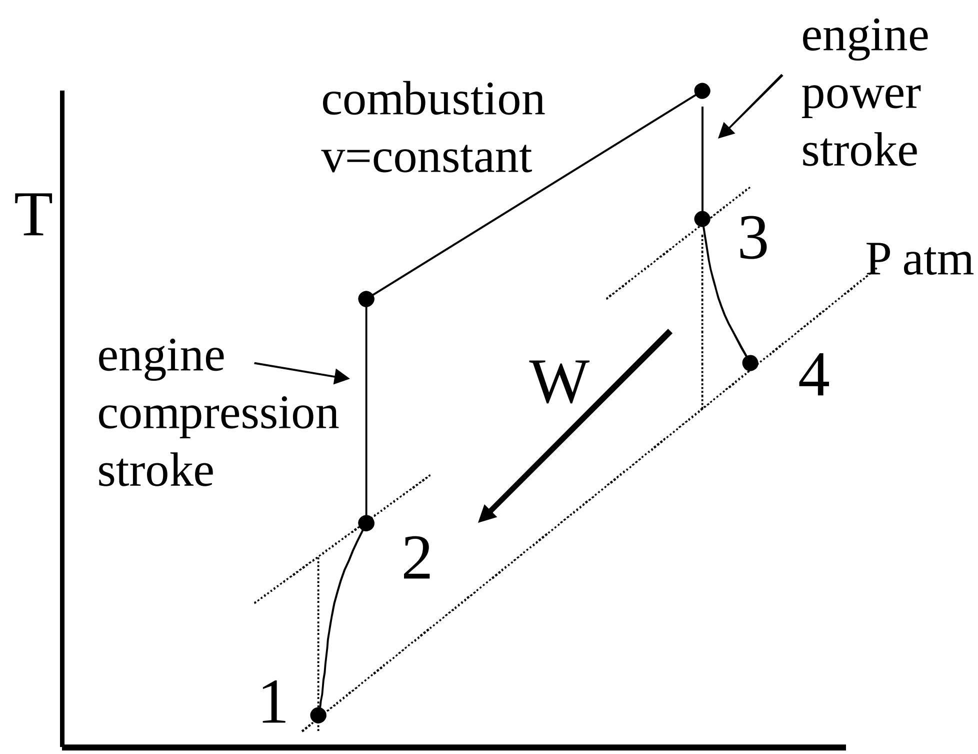
Intercooled Supercharger



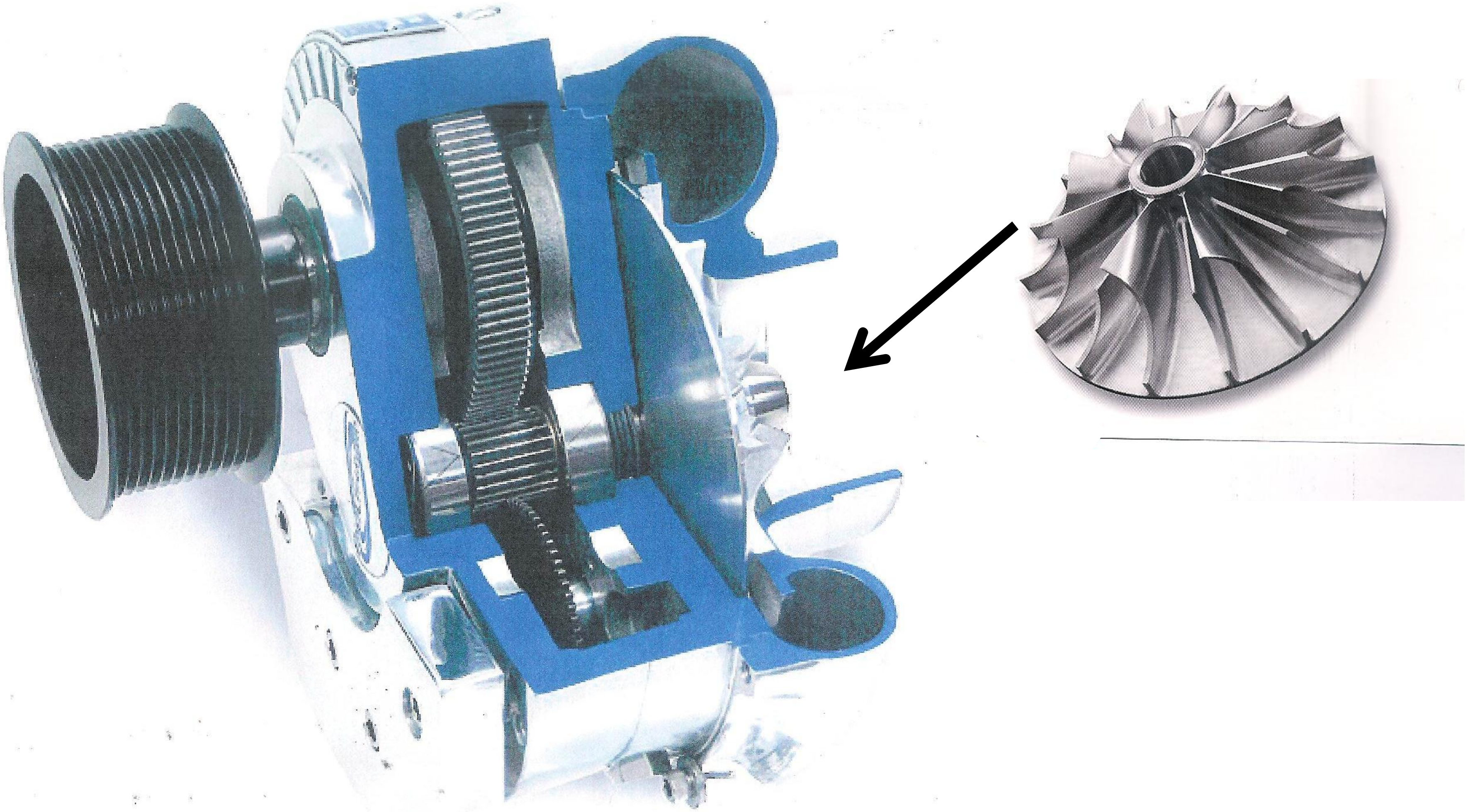
Air Standard Otto Cycle with a Turbocharger

Turbocharger





ProCharger Supercharger



TurboCharger