

# The Second Law implies:

1) Heat Engine

$$\eta = \frac{W}{Q_{\text{in}}} = \frac{Q_{\text{H}} - Q_{\text{L}}}{Q_{\text{H}}} = \frac{T_{\text{H}} - T_{\text{L}}}{T_{\text{H}}}$$

2) Absolute Temperature Scale

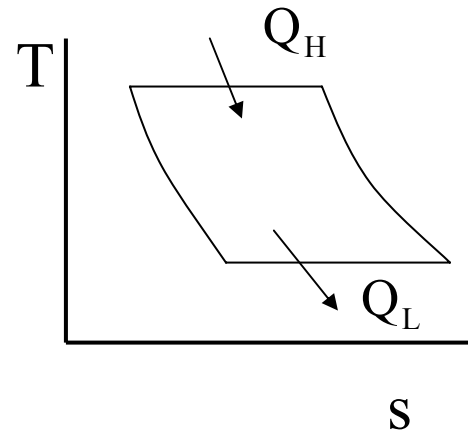
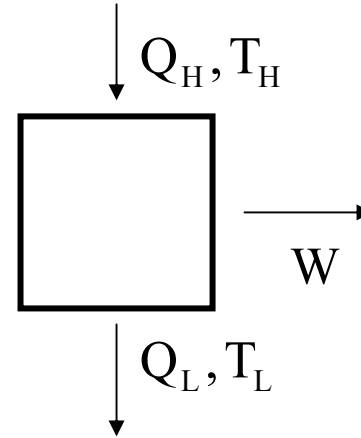
$$\frac{Q_{\text{H}}}{T_{\text{H}}} = \frac{Q_{\text{L}}}{T_{\text{L}}}$$

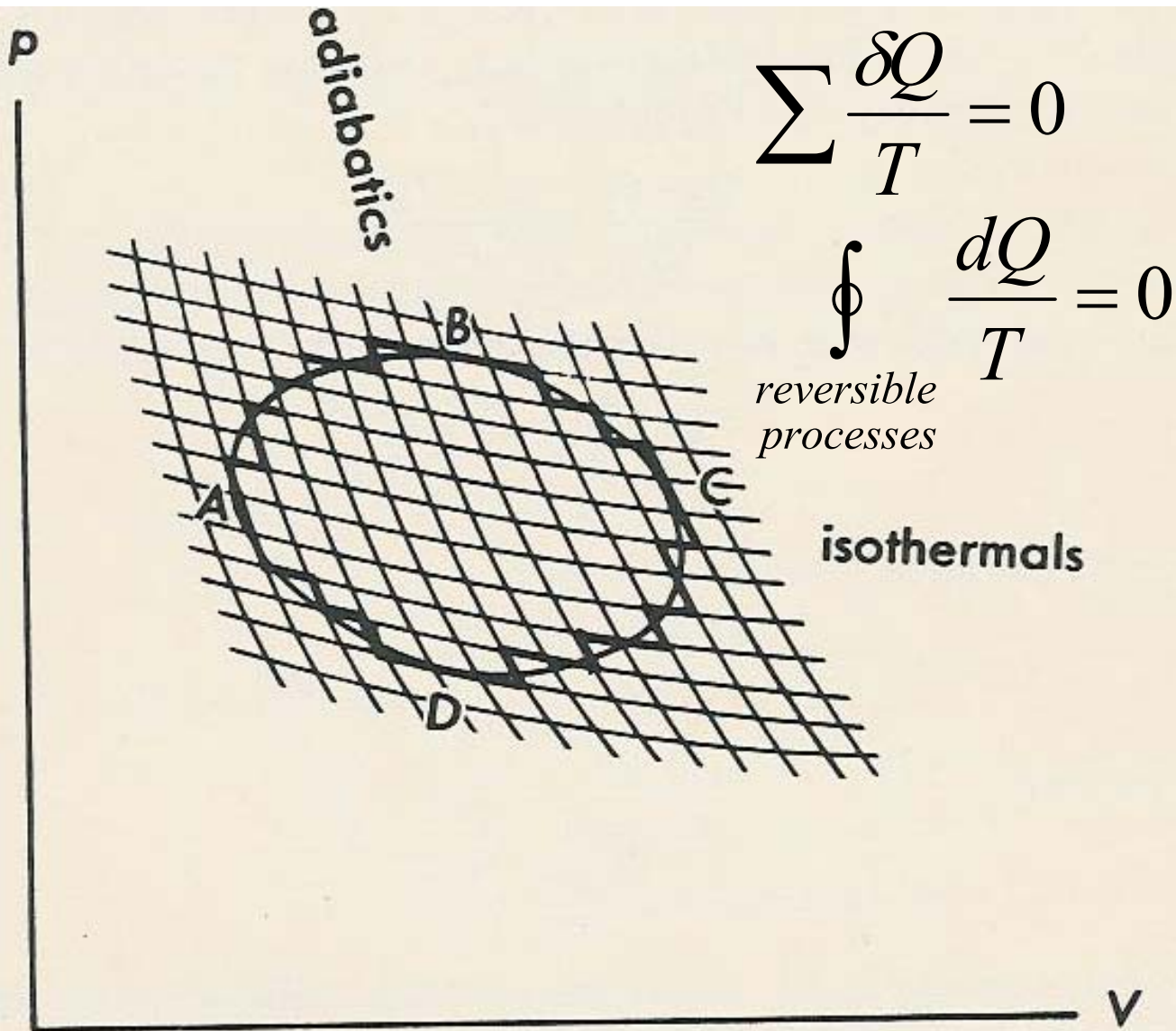
3) For a cycle

$$\sum \frac{Q}{T} = \frac{Q_{\text{H}}}{T_{\text{H}}} - \frac{Q_{\text{L}}}{T_{\text{L}}} = 0$$

4) For an Ideal Gas Cycle

$$\sum \frac{Q}{T} = \frac{Q_{\text{H}}}{T_{\text{H}}} - \frac{Q_{\text{L}}}{T_{\text{L}}} = 0$$

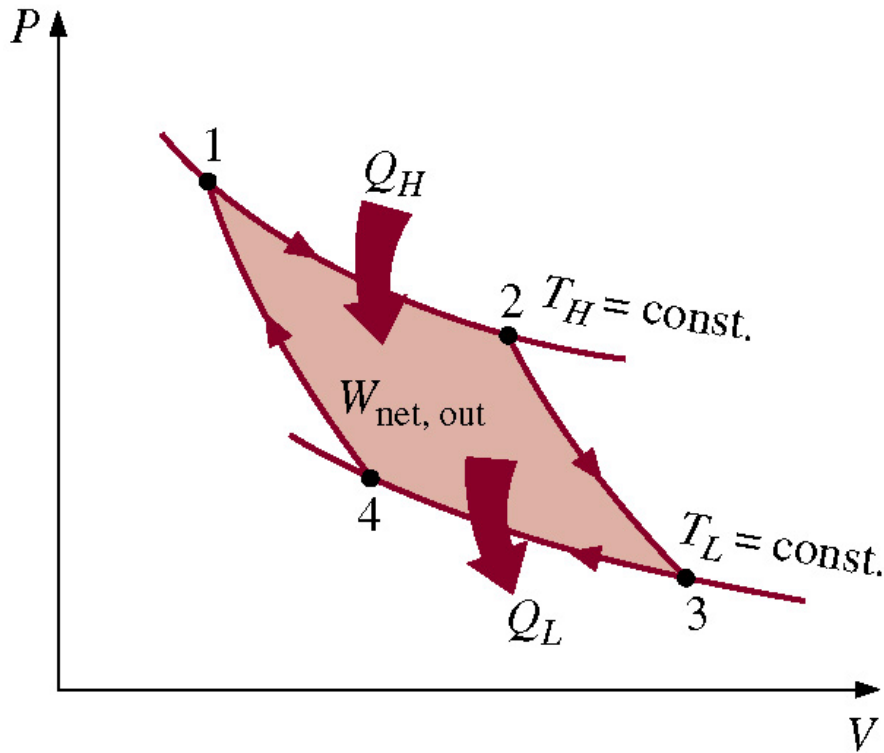




**Fig. 9.2** General Cycle Approximated by Large Number of Carnot Cycles.

# Clausius Inequality

$$\oint \frac{\delta Q}{T} \leq 0$$



for a Reversible Cycle

$$\left( \frac{Q_h - Q_l}{Q_h} \right) = \left( \frac{T_h - T_l}{T_h} \right)$$

$$1 - \frac{Q_l}{Q_h} = 1 - \frac{T_l}{T_h}$$

$$\frac{Q_h}{T_h} - \frac{Q_l}{T_l} = 0$$

$$\oint \frac{\delta Q}{T} = 0$$

for an Irreversible Cycle

$$\left( \frac{Q_h - Q_l}{Q_h} \right) < \left( \frac{T_h - T_l}{T_h} \right)$$

$$1 - \frac{Q_l}{Q_h} < 1 - \frac{T_l}{T_h}$$

$$\frac{Q_h}{T_h} - \frac{Q_l}{T_l} < 0$$

$$\oint \frac{\delta Q}{T} < 0$$

# Entropy Definition and Change

$$\oint \frac{\delta Q}{T} \leq 0 \quad \text{Clausius Inequality}$$

for a cycle composed of a reversible and an irreversible process

$$\oint \frac{\delta Q}{T} = \int_{2 \text{ irrev}}^1 \frac{\delta Q}{T} + \int_{1 \text{ rev}}^2 \frac{\delta Q}{T} \leq 0$$

$$\int_{2 \text{ irrev}}^1 \frac{\delta Q}{T} + S_2 - S_1 \leq 0$$

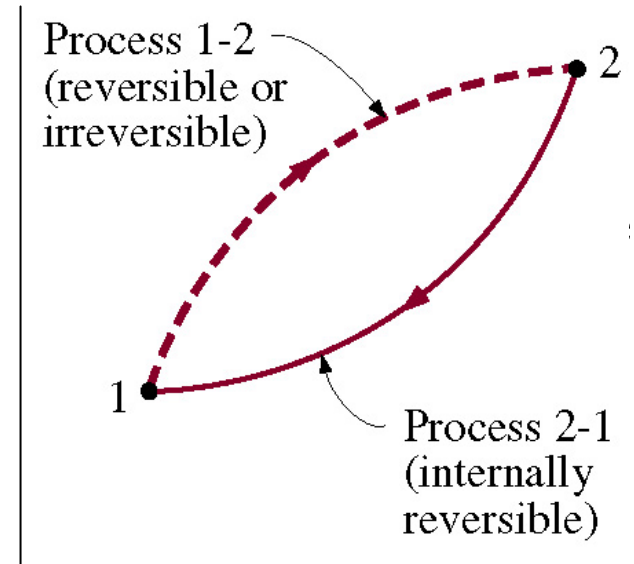
DEFINE A PROPERTY, S, ENTROPY

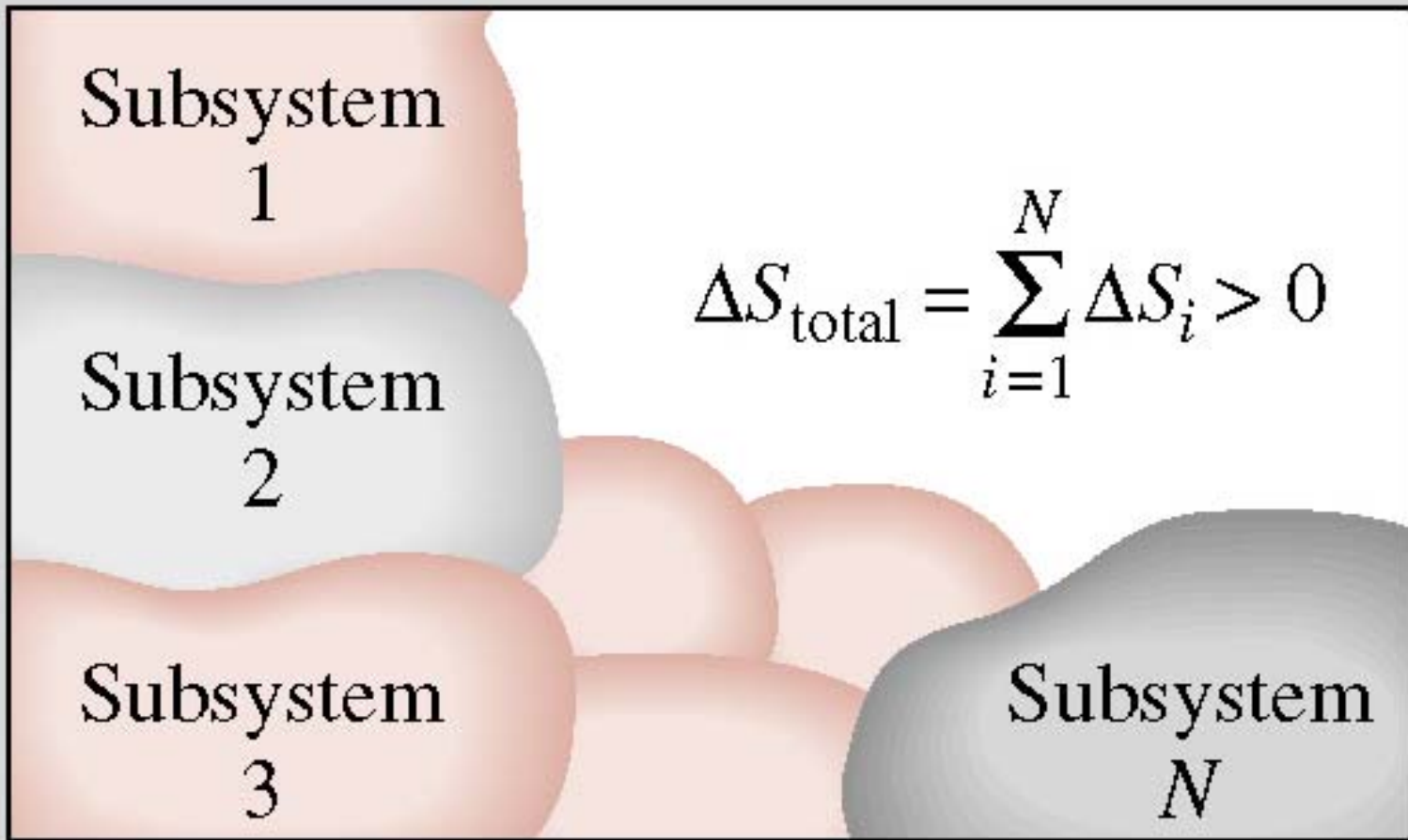
$$\int_{2 \text{ irrev}}^1 \frac{\delta Q}{T} + ds \leq 0$$

$$ds \geq \int_{2 \text{ irrev}}^1 \frac{\delta Q}{T}$$

$$ds \geq \int_{\text{irrev}} \frac{\delta Q}{T} \quad ds = \int_{\text{rev}} \frac{\delta Q}{T}$$

$$\delta Q = \int T ds, \quad Q = T \Delta S$$





Total Entropy Change,  $\Delta S$ , for an isolated system

For reversible systems,  $\Delta S = 0$

For irreversible systems,  $\Delta S > 0$

Liquid water enters an open feed water heater at .8 MPa and 35 C and steam enters at .8 MPa and 350 C. The leaving stream is saturated liquid at pressure of .8 MPa. Determine the ratio of the mass flow rates of the water and steam. Determine the rate at which entropy is produced in the feed water heater.

# PS5.2

@ state point 1

$$m_1 + m_2 = m_3 \quad \text{Mass Balance}$$

$$\frac{m_1}{m_3} + \frac{m_2}{m_3} = 1$$

$$m_1 h_1 + m_2 h_2 = m_3 h_3 \quad \text{Energy Balance}$$

$$\frac{m_1}{m_3} h_1 + \frac{m_2}{m_3} h_2 = h_3$$

$$\left(1 - \frac{m_2}{m_3}\right) h_1 + \frac{m_2}{m_3} h_2 = h_3$$

$$\frac{m_2}{m_3} = \frac{h_3 - h_1}{h_2 - h_1} = \frac{720.87 - 3162.2}{146.64 - 3162.2}$$

$$\frac{m_2}{m_3} = .8096, \quad \frac{m_1}{m_3} = 1 - \frac{m_2}{m_3} = .1904,$$

$$\frac{m_1}{m_2} = .235$$

$$m_3 = 1 \text{ kg}$$

$$\Delta S = m_1 (s_3 - s_1) + m_2 (s_3 - s_2)$$

$$\Delta S = .1904(2.0457 - 7.4107) + .8096(2.0457 - .5051)$$

$$\Delta S = -1.0215 + 1.2473$$

$$\Delta S = .2258 \text{ kJ/kg K}$$

2  
.8 MPa  
35 C

$$h_2 = h_f @ 35 \text{ C}$$

$$h_2 = 146.64 \text{ kJ/kg}$$

$$s_2 = s_f @ 35 \text{ C}$$

$$s_2 = .5051 \text{ kJ/kg K}$$

1  
.8 MPa, 350 C

$$h_1 = 3162.2$$

$$s_1 = 7.4107$$



3

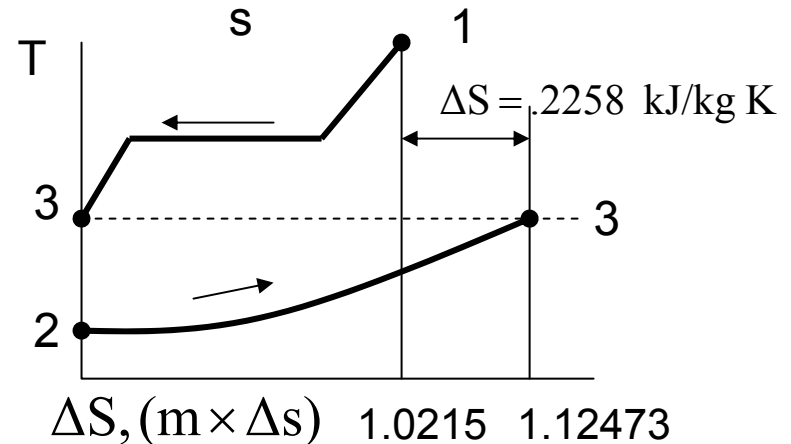
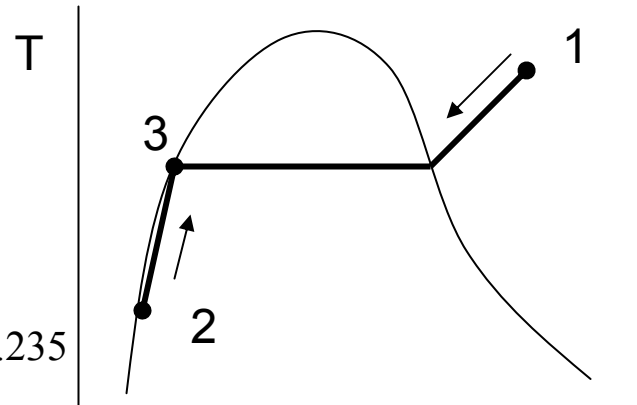
$$p = .8 \text{ MPa}$$

$$h_3 = h_f @ .8 \text{ MPa}$$

$$h_3 = 720.87 \text{ kJ/kg}$$

$$s_3 = s_f @ .8 \text{ MPa}$$

$$s_3 = 2.0457 \text{ kJ/kg K}$$



**Completely Reversible Process** - System and surroundings returned to the original state

**Internally Reversible** - System returned to the original state.

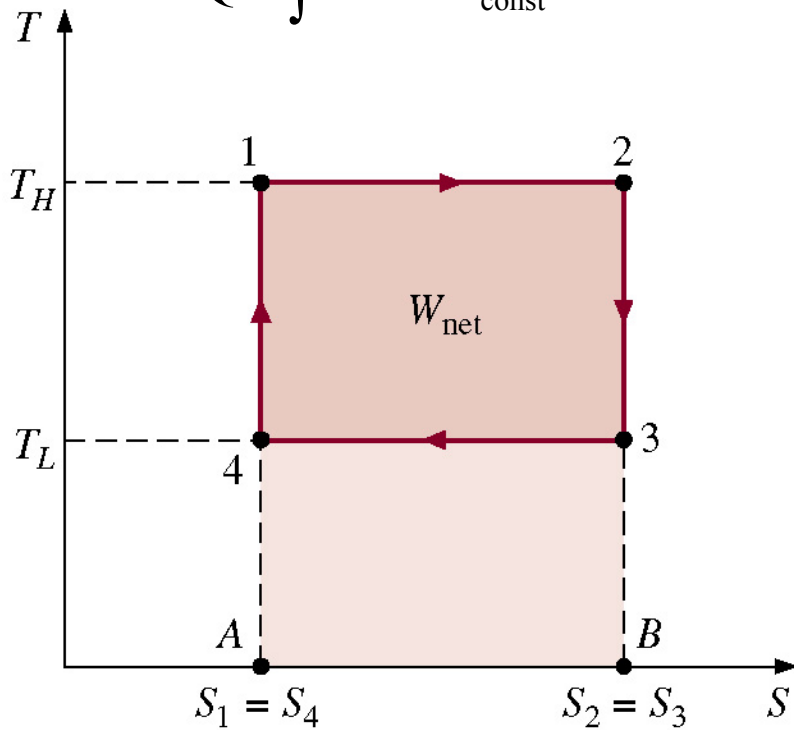
**Externally Reversible** - Surroundings returned to the original state.



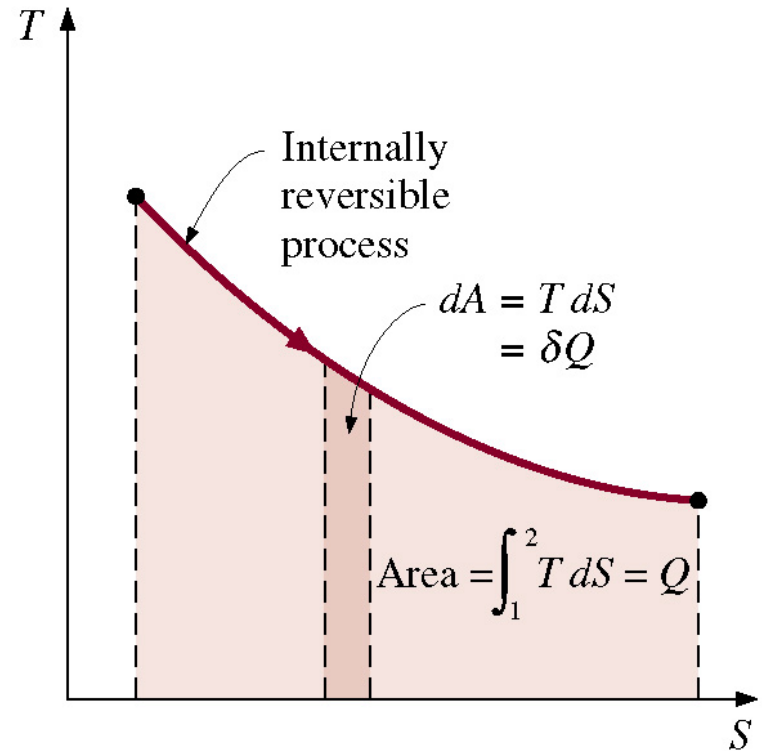
# Temperature Entropy Property Diagrams

$$ds = \int \frac{\delta Q}{T}$$

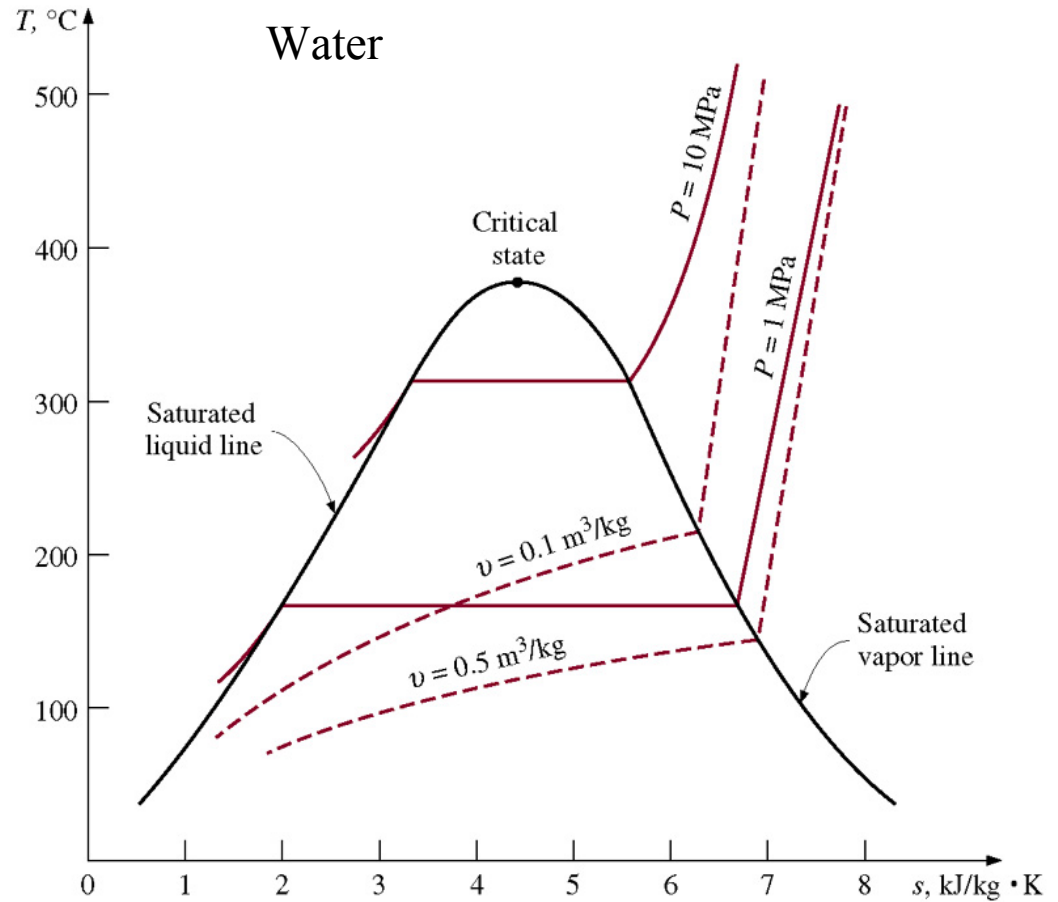
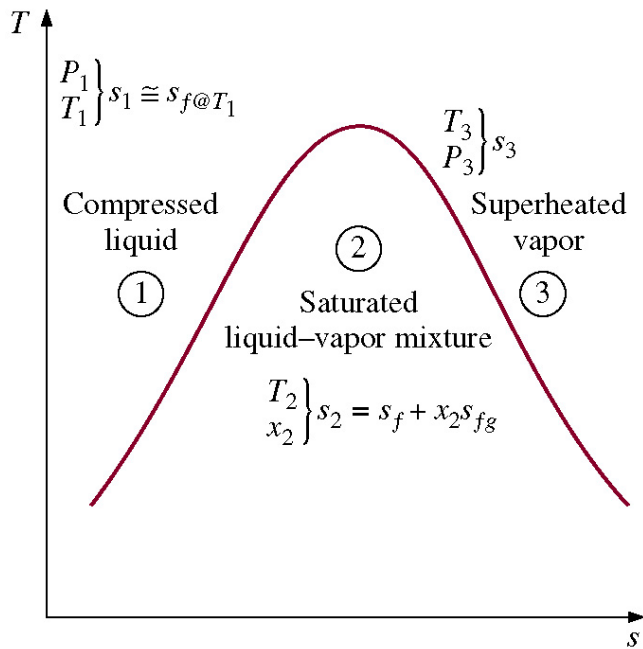
$$Q = \int T ds = T_{\text{const}} \Delta s$$



$$W_{\text{net}} = Q_{\text{in}} - Q_{\text{out}} = (T_H - T_L) \Delta s$$



# Temperature Entropy Property Diagrams



# Entropy Change of an Ideal Gas

$$\delta q = du + \delta w \quad \text{First Law}$$

$$\delta q = Tds \quad \text{Second Law}$$

$$Tds = du + pdv$$

$$ds = \left[ \frac{1}{T} \right] du + \left[ \frac{p}{T} \right] dv$$

For an ideal gas:

$$du = c_v dT \quad \text{and} \quad \frac{p}{T} = \frac{R}{v}$$

$$ds = c_v \frac{dT}{T} + R \frac{dv}{v}$$

from definition,  $h = u + pv$

$$dh = du + pdv + vdp$$

$$du = dh - pdv - vdp$$

Substituting into  $Tds = du + pdv$

$$Tds = dh - pdv - vdp + pdv$$

$$Tds = dh - vdp$$

$$ds = \frac{dh}{T} - \frac{v}{T} dp$$

For an ideal gas,

$$\frac{dh}{T} = c_p \frac{dT}{T} \quad \text{and} \quad \frac{v}{T} dp = R \frac{dp}{p}$$

$$ds = c_p \frac{dT}{T} - R \frac{dp}{p}$$

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

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

TABLE A-17

Ideal-gas properties of air

$T$ K	$h$ kJ/kg	$P_r$	$u$ kJ/kg	$v_r$	$s^\circ$ kJ/kg · K	$T$ K	$h$ kJ/kg	$P_r$	$u$ kJ/kg	$v_r$	$s^\circ$ kJ/kg · K
200	199.97	0.3363	142.56	1707.0	1.29559	580	586.04	14.38	419.55	115.7	2.37348
210	209.97	0.3987	149.69	1512.0	1.34444	590	596.52	15.31	427.15	110.6	2.39140
220	219.97	0.4690	156.82	1346.0	1.39105	600	607.02	16.28	434.78	105.8	2.40902
230	230.02	0.5477	164.00	1205.0	1.43557	610	617.53	17.30	442.42	101.2	2.42644
240	240.02	0.6355	171.13	1084.0	1.47824	620	628.07	18.36	450.09	96.92	2.44356
250	250.05	0.7329	178.28	979.0	1.51917	630	638.63	19.84	457.78	92.84	2.46048
260	260.09	0.8405	185.45	887.8	1.55848	640	649.22	20.64	465.50	88.99	2.47716
270	270.11	0.9590	192.60	808.0	1.59634	650	659.84	21.86	473.25	85.34	2.49364
280	280.13	1.0889	199.75	738.0	1.63279	660	670.47	23.13	481.01	81.89	2.50985
285	285.14	1.1584	203.33	706.1	1.65055	670	681.14	24.46	488.81	78.61	2.52589
290	290.16	1.2311	206.91	676.1	1.66802	680	691.82	25.85	496.62	75.50	2.54175
295	295.17	1.3068	210.49	647.9	1.68515	690	702.52	27.29	504.45	72.56	2.55731
298	298.18	1.3543	212.64	631.9	1.69528	700	713.27	28.80	512.33	69.76	2.57277
300	300.19	1.3860	214.07	621.2	1.70203	710	724.04	30.38	520.23	67.07	2.58810
305	305.22	1.4686	217.67	596.0	1.71865	720	734.82	32.02	528.14	64.53	2.60319
310	310.24	1.5546	221.25	572.3	1.73498	730	745.62	33.72	536.07	62.13	2.61803
315	315.27	1.6442	224.85	549.8	1.75106	740	756.44	35.50	544.02	59.82	2.63280
320	320.29	1.7375	228.42	528.6	1.76690	750	767.29	37.35	551.99	57.63	2.64737
325	325.31	1.8345	232.02	508.4	1.78249	760	778.18	39.27	560.01	55.54	2.66176
330	330.34	1.9352	235.61	489.4	1.79783	780	800.03	43.35	576.12	51.64	2.69013

Isentropic process,  $Q = 0$ ,  $pv^k = \text{constant}$ ,  $\Delta s = 0$ 

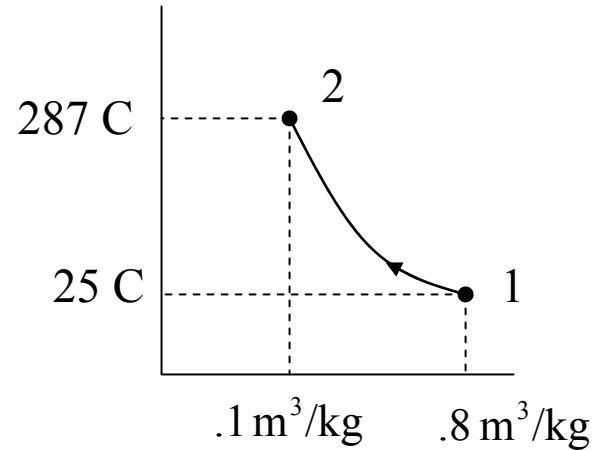
$$\Delta s = c_p \ln\left(\frac{T_2}{T_1}\right) - R \times \ln\left(\frac{p_2}{p_1}\right)$$

$$\Delta s = s_{o2} - s_{o1} - R \times \ln\left(\frac{p_2}{p_1}\right)$$

$$\frac{P_r @ T_1}{P_r @ T_2} = \left(\frac{p_1}{p_2}\right) \quad (7-49)$$

$$\frac{V_r @ T_1}{V_r @ T_2} = \left(\frac{v_1}{v_2}\right) = \left(\frac{V_1}{V_2}\right) \quad (7-50)$$

**Oxygen at .8 cubic meters/kg and 25 C is compressed in a piston cylinder to .1 cubic meter/kg and 287 C. What is the entropy change of the oxygen?**



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

$$s_2 - s_1 = .69 \frac{\text{kJ}}{\text{kg}^\circ\text{K}} \ln\left(\frac{273.15^\circ\text{K} + 287^\circ\text{C}}{273.15^\circ\text{K} + 25^\circ\text{C}}\right) + .259 \frac{\text{kJ}}{\text{kg}^\circ\text{K}} \ln\left(\frac{.1\text{m}^3/\text{kg}}{.8\text{m}^3/\text{kg}}\right)$$

$$s_2 - s_1 = -.105 \frac{\text{kJ}}{\text{kg}^\circ\text{K}}$$

## 6-30

@  $P = 200 \text{ kPa}$ ,  $T = 200^\circ \text{C}$

$$v_1 = 1.0803 \text{ m}^3/\text{kg}$$

$$s_1 = 7.5066 \text{ kJ/kg}$$

@  $T = 80^\circ \text{C}$

$$v_f = .001029 \text{ m}^3/\text{kg}, \quad v_g = 3.407 \text{ m}^3/\text{kg}$$

$$V_1 = V_2$$

$$x = \frac{V_2 - V_f}{V_{fg}} = x \times \frac{1.0802 - .001029}{3.407 - .001029} = .317$$

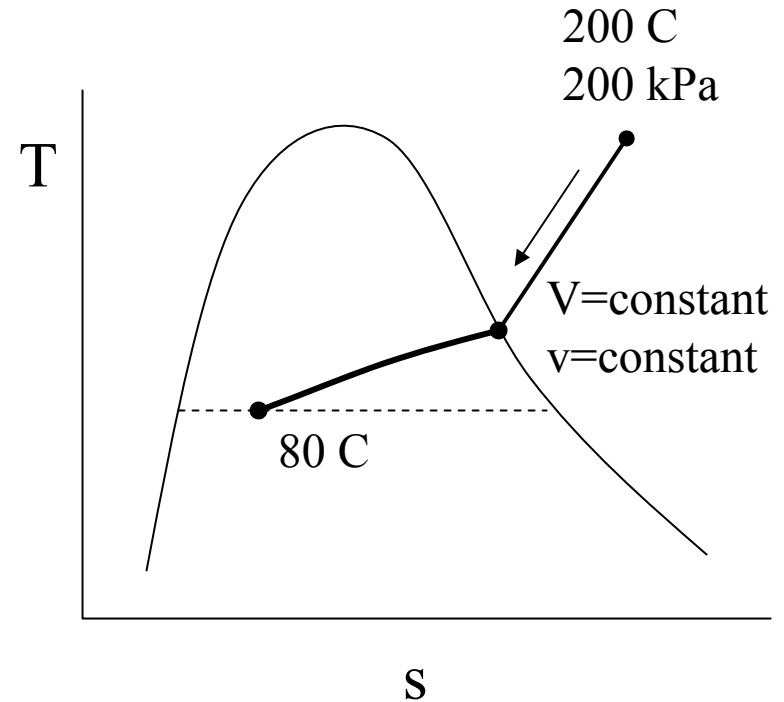
$$s_2 = s_f + x \times s_{fg} = 1.0753 + .317 \times 6.5369$$

$$m = \frac{V_1}{v_1} = .0185 \text{ kg}$$

$$S_2 - S_1 = m \times (s_2 - s_1) = .0185(3.1475 - 7.5066)$$

$$S_2 - S_1 = -.0806 \frac{\text{kJ}}{\text{K}}$$

Cooled, closed steam radiator



**Steam at 200 C and 200 kPa condenses in a 20 liter closed radiator with both the inlet and exit valves closed to a temperature of 80 C. Determine the entropy change of the steam.**

@ P = 200 kPa, T = 200° C

$$v_1 = 1.0803 \text{ m}^3/\text{kg}$$

$$s_1 = 7.5066 \text{ kJ/kg}$$

@ T = 80° C

$$v_f = .001029 \text{ m}^3/\text{kg}, \quad v_g = 3.407 \text{ m}^3/\text{kg}$$

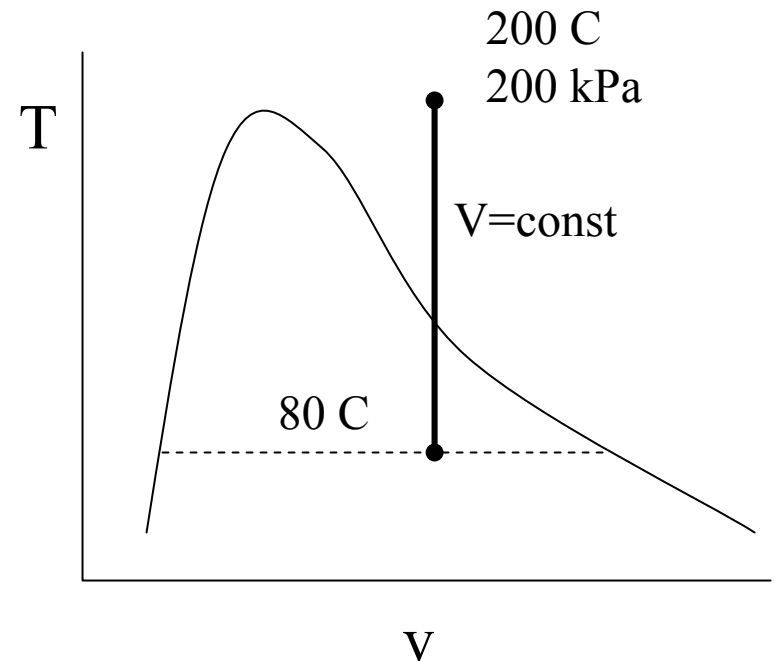
$$V_1 = V_2$$

$$V_1 = V_2$$

$$x = \frac{V_2 - v_f}{v_{fg}} = x \frac{1.0802 - .001029}{3.407 - .001029} = .317$$

$$s_2 = s_f + x \times s_{fg} = 1.0753 + .317 \times 6.5369$$

Cooled, closed steam radiator



$$m = \frac{V_1}{v_1} = \frac{.02 \text{ m}^3}{1.0803 \text{ m}^3/\text{kg}} = .0185 \text{ kg}$$

$$S_2 - S_1 = m \times (s_2 - s_1)$$

$$S_2 - S_1 = .0185(3.1475 - 7.5066)$$

$$S_2 - S_1 = -.0806 \frac{\text{kJ}}{\text{K}}$$

# Isentropic Adiabatic Process

$$\delta Q = dU + \delta W \quad \text{First Law}$$

$$\text{Adiabatic process} \quad \delta Q = 0$$

$$dU + \delta W = 0$$

$$c_v dT + pdv = 0$$

$$\text{for an ideal gas} \quad T = \frac{pv}{R}, \quad dT = \frac{pdv}{R} + \frac{vdp}{R}$$

$$\frac{c_v}{R} pdv + \frac{c_v}{R} vdp + pdv = 0$$

$$\left( \frac{c_v}{R} + 1 \right) pdv + \frac{c_v}{R} vdp = 0$$

$$\left( \frac{1}{k-1} + 1 \right) \frac{dv}{v} + - \left( \frac{1}{k-1} \right) \frac{dp}{p} = 0$$

integrating

$$k \ln v + \ln p = \text{constant}$$

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

$$\text{Isentropic, } \Delta s = 0$$

Ideal Gas

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

$$p_1 v_1^k = p_2 v_2^k$$

$$\frac{p_2}{p_1} = \left( \frac{v_1}{v_2} \right)^k$$

substitute from  $pv = RT$

$$\frac{T_2}{T_1} = \left( \frac{v_1}{v_2} \right)^{k-1} = \left( \frac{p_2}{p_1} \right)^{\frac{k-1}{k}}$$

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

$$s_2 - s_1 = c_p \ln \left( \frac{p_2}{p_1} \right)^{\frac{k-1}{k}} - (c_p - c_v) \ln \left( \frac{p_2}{p_1} \right)$$

$$s_2 - s_1 = c_p \frac{k-1}{k} \ln \left( \frac{p_2}{p_1} \right) - (c_p - c_v) \ln \left( \frac{p_2}{p_1} \right)$$

$$s_2 - s_1 = \left( \frac{p_2}{p_1} \right) \left( c_p \frac{k-1}{k} - (c_p - c_v) \right)$$

$$s_2 - s_1 = \left( \frac{p_2}{p_1} \right) \left( c_p \frac{\frac{c_p - c_v}{c_p} - c_v}{\frac{c_p}{c_v}} - (c_p - c_v) \right) = 0$$

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

is also constant entropy



$$Q = \Delta U + W \quad \text{First Law}$$

$$dQ = dU + dW$$

$$dQ = Tds \quad \text{Second Law}$$

$$dW = pdv \quad \text{Boundary Work}$$

$$du = c_v dT \quad \text{u property definition}$$

substituting,

$$Tds = du + pdv$$

$$h = u + pv \quad \text{h property definition,}$$

h is an exact differential

$$dh = du + dv + vdp$$

substituting,

$$Tds = dh - pdv - vdp + pdv$$

$$Tds = dh - vdp$$

$$\text{for } Q = Tds = 0$$

$$dh = vdp$$

### **Example: water pumped from 10 psia to 30 psia**

$$w = h_2 - h_1 = v(p_2 - p_1)$$

$$w = \frac{(30\text{psia} - 10\text{psia}) \times 144\text{psf/psi}}{62.4\text{lb/ft}^3}$$

$$w = \frac{1509 \frac{\text{lb}_f}{\text{ft}^2}}{62.4 \frac{\text{lb}_m}{\text{ft}^2} \frac{1}{\text{ft}}} = 69.1 \frac{\text{ft lb}_f}{\text{lb}_m}, \quad (\text{ft of fluid})$$

$$w = 69.1 \frac{\text{ft lb}_f}{\text{lb}_m} \times \frac{1 \text{ BTU}}{778 \text{ ft lb}_f} = 69.1 \text{ BTU/lb}_m$$

$$w = .0888 \text{ BTU/lb}$$

### **Example: water pumped from 100 kPa to 300 kPa**

$$w = v(p_2 - p_1)$$

$$w = .0010432 \times (300 - 100)$$

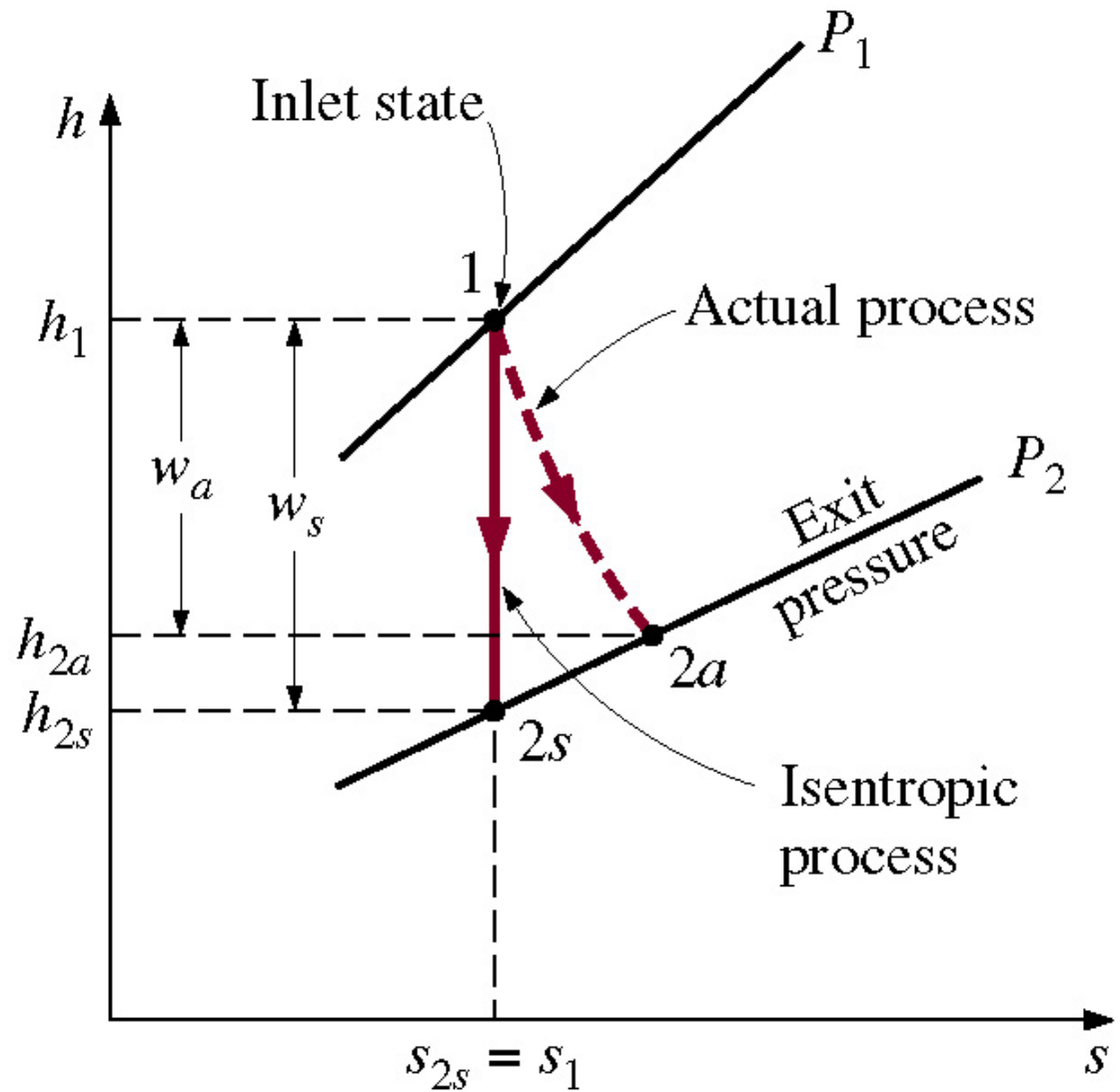
$$w = .02086 \frac{\text{m}^3}{\text{kg}} \text{ kPa}, \quad \text{kJ/kg}$$

# Expansion Process

$$\eta = \frac{\text{Actual Work}}{\text{Isentropic Work}}$$

$$\eta = \frac{w_a}{w_s}$$

$$\eta = \frac{h_1 - h_{2a}}{h_1 - h_{2s}}$$



**3 kg/sec of steam expands in an 90 % efficient turbine from 8 MPa, 500 C to 30 kPa. Determine the exit temperature and power of the turbine.**

Pt	T	p	h	s
1	500° C	8 MPa	3398.3	6.724
1'		30 kPa	2267.9	6.7240
2	69.1° C	30 kPa	2308.9	

$$\text{@}30\text{kPa } x = \frac{s_1 - s_g}{s_{fg}} = \frac{6.724 - .9439}{6.8247} = .847$$

$$h_1' = h_f + x \times h_{fg}$$

$$h_1' = 289.23 + .847 \times 2336.1 = 2267.9 \text{ kJ/kg}$$

$$\eta = \frac{W_{\text{actual}}}{W_{\text{reversible}}} = \frac{h_1 - h_2}{h_1 - h_1'}$$

$$W = \eta \times (h_1 - h_1')$$

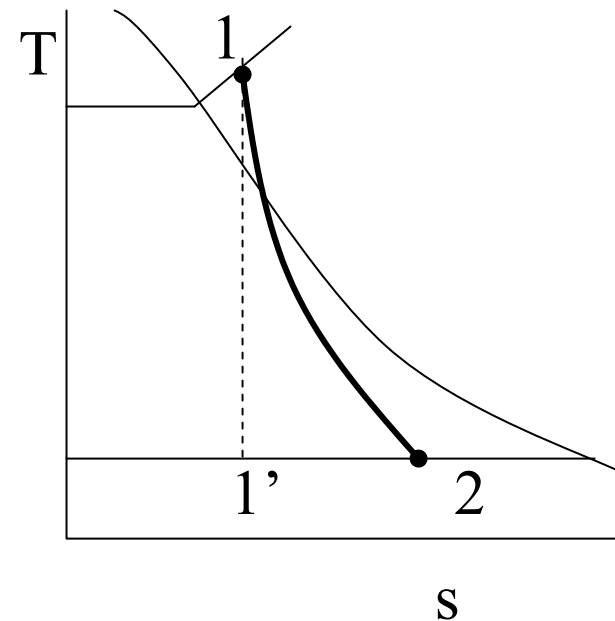
$$W = .9 \times (3398.3 - 2267.9) = 1017.4 \text{ kJ/kg}$$

$$h_2 = h_1 - W = 3398.3 - 1017.4 = 2380.9$$

$h_2$  is less than  $h_g$  @ 30 kPa (.3 bar)  $\Rightarrow$  two phase

$$T_2 = T_{\text{saturation}} \text{ @ } 30 \text{ kPa } (.3 \text{ bar})$$

$$\text{Power} = m \times W = 3 \text{ kg/sec} \times 1017.4 \text{ kJ/kg} = 3052 \text{ KW}$$



**What is the work done by 3 kg/sec of nitrogen expanded from 900 kPa, 50 C to 100 kPa at an 85% efficiency.**

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

$$T_{1is} = T_1 \left( \frac{100}{900} \right)^{.2857}$$

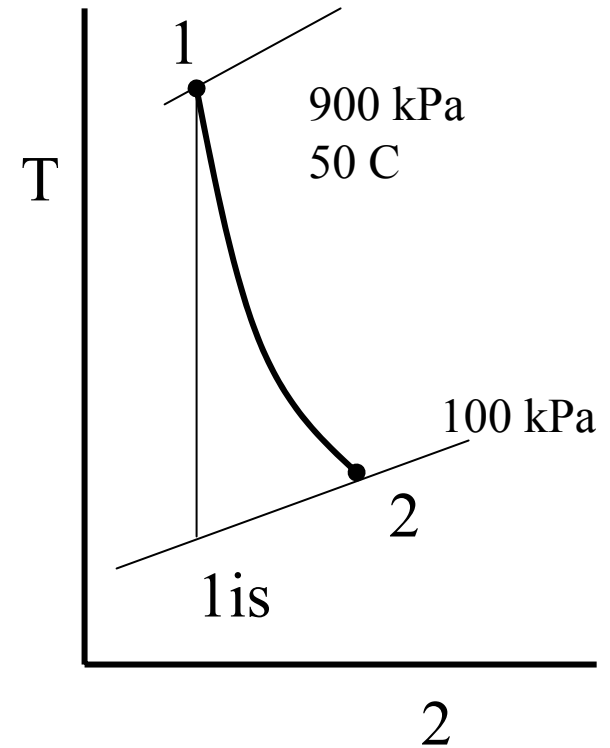
$$T_{1is} = (50 + 273)(.5338)$$

$$T_{1is} = 172.4^{\circ} \text{K}$$

$$\eta = \frac{W_{\text{actual}}}{W_{\text{isentropic}}} = .85$$

$$W_{\text{actual}} = .85 \times 3 \text{ kg/sec} \times 1.039 \times (323^{\circ} \text{K} - 172.4^{\circ} \text{K})$$

$$W_{\text{actual}} = 399. \text{kJ}$$

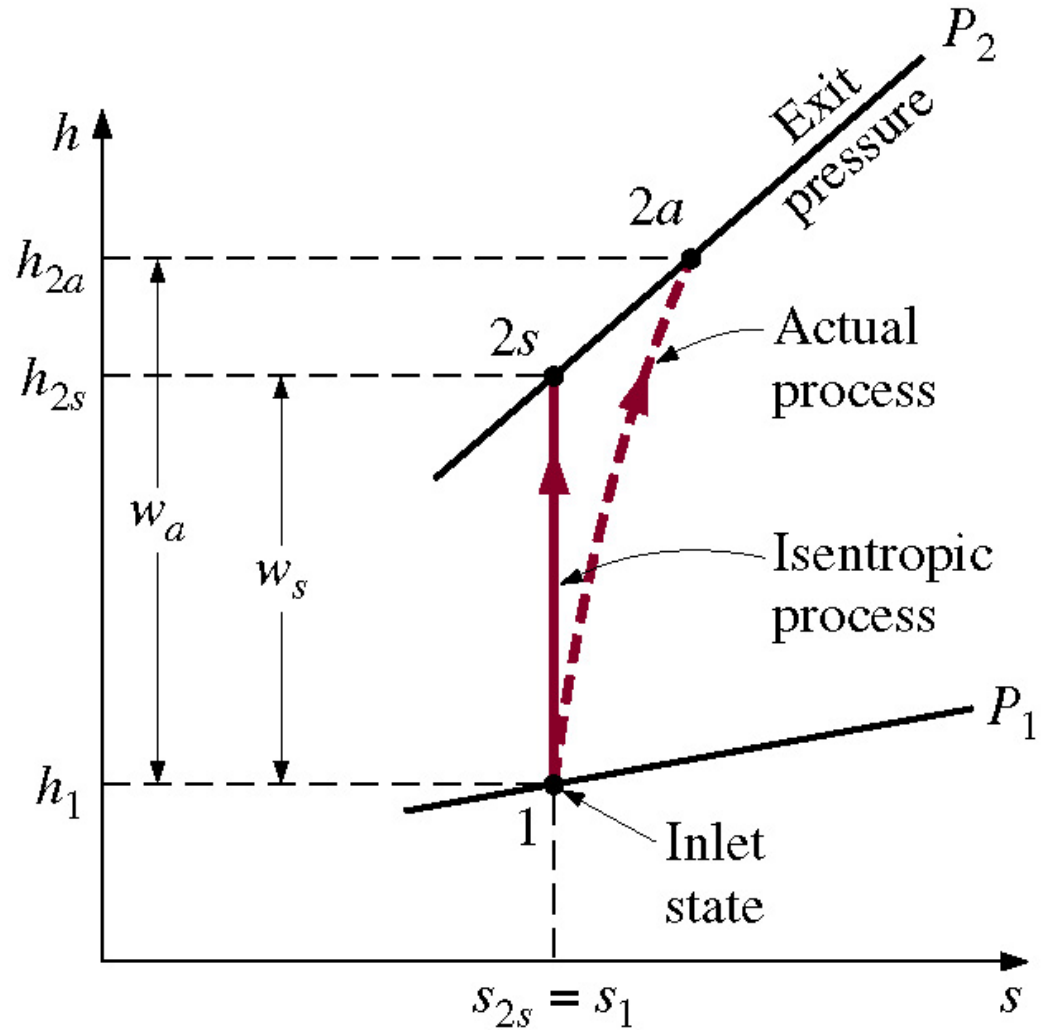


# Compression Process

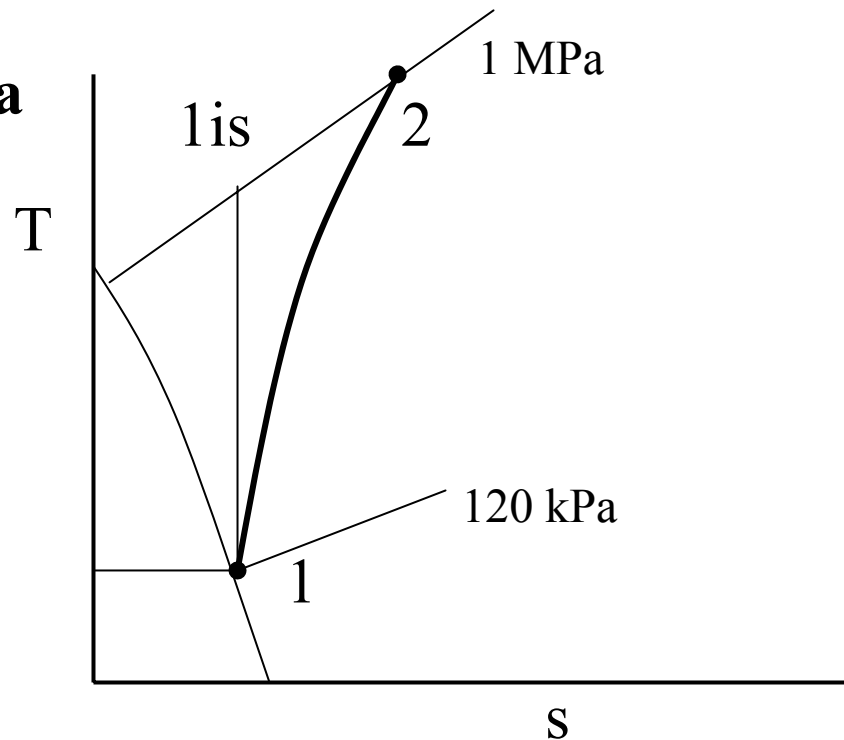
$$\eta = \frac{\text{Isentropic Work}}{\text{Actual Work}}$$

$$\eta = \frac{W_s}{W_a}$$

$$\eta = \frac{h_1 - h_{2s}}{h_1 - h_{2a}}$$



**.3 cubic meters/sec of R-134a is compressed at 80% efficiency from saturated vapor at 120 kPa to 1 MPa. What is the discharge temperature and work?**



@ 120 kPa,  $T_1 = -22.36^\circ\text{C}$

$h_1 = h_g = 233.86\text{kJ/kg}$

$s_1 = s_g = .9354\text{kJ/kg}^\circ\text{K} = s_{1is}$

$v_1 = v_g = .1614\text{m}^3/\text{kg}$

$m_1 = \frac{V}{v} = \frac{.3/60}{.1614} = .31\text{kg/sec}$

@ 1 MPa

Pt	T	h	s
1	<b>57.7</b>	288.91	
	50	280.19	.9428
1is		<b>277.84</b>	.9354
	40	268.68	.9066

a)  $h_{1is} = 277.84$  by interpolation

$\eta = \frac{h_{1is} - h_1}{h_2 - h_1} = .8$

$h_2 = h_1 + (h_{1is} - h_1) / .8$

$h_2 = 233.86 + (277.84 - 233.86) / .8$

$h_2 = 288.91\text{kJ/kg}$

$T_2 = 57.7^\circ\text{C}$  by interpolation

b)  $W = m(h_2 - h_1)$

$W = .31\text{ kg/sec} \times (288.91 - 233.86)$

$W = 1.71\text{kJ/sec} = 1.71\text{KW}$

Air compressed from 15 psia, 60° F to 30 psia at 85% efficiency.

$$\frac{T_2}{T_1} = \left( \frac{p_2}{p_1} \right)^{\frac{k-1}{k}}$$

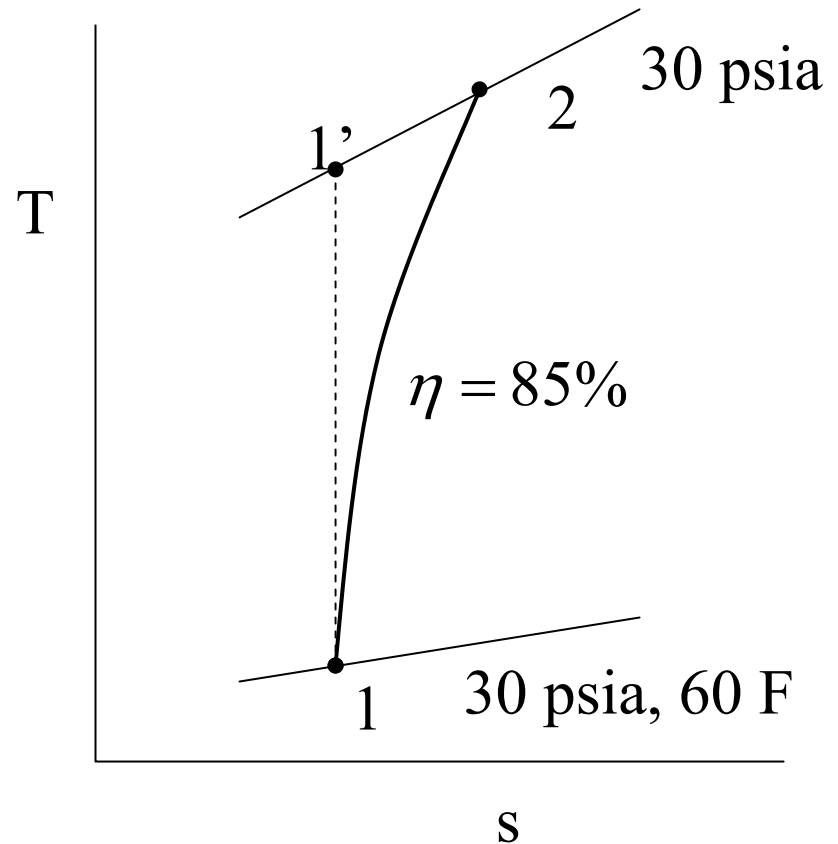
$$T_1' = T_1 \left( \frac{30}{15} \right)^{.2857}$$

$$T_1' = 520 \times 1.219 = 633.9^\circ \text{R}$$

$$\eta = \frac{h_1' - h_1}{h_2 - h_1} = \frac{c_p(T_1' - T_1)}{c_p(T_2 - T_1)}$$

$$T_2 = T_1 + \left( \frac{633.9 - 520}{.85} \right) = 654.^\circ \text{R}$$

$$T_2 = 194^\circ \text{F}$$



# W=0 Expansion Process

## SteadyFlowEnergyEquation

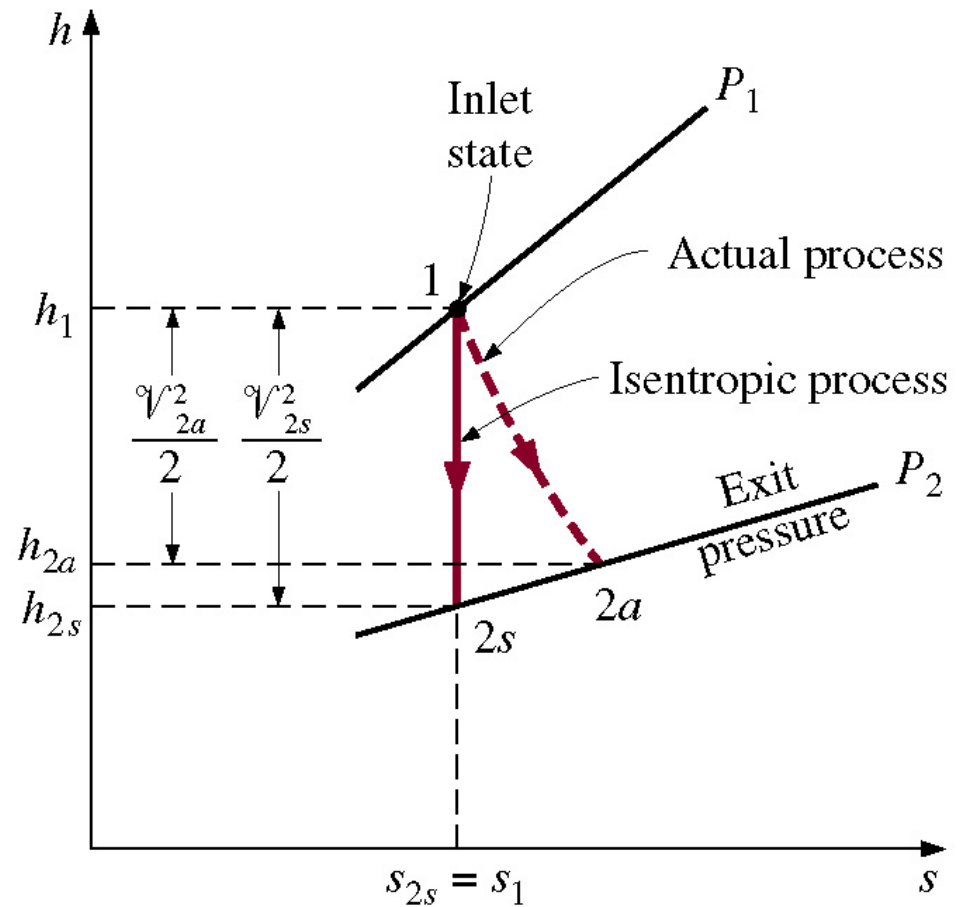
$$H_1 + \frac{V_1^2}{2} = H_2 + \frac{V_2^2}{2}$$

for  $V_1 = 0$

$$h_1 = h_{2a} + \frac{V_{2a}^2}{2 \times m}$$

$$h_1 = h_{2s} + \frac{V_{2s}^2}{2 \times m}$$

$$\eta = \frac{h_1 - h_{2a}}{h_1 - h_{2s}} = \frac{V_{2a}^2}{V_{2s}^2}$$





## AIR TABLE - Table A-17, A-17E

a) variable specific heat

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

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

$$s_2 - s_1 = \int c_p \frac{dT}{T} - \int R \frac{dp}{p} \quad (6-34)$$

$$s_2 - s_1 = s_2^\circ - s_1^\circ - R \times \ln\left(\frac{p_2}{p_1}\right)$$

Table base 0°F, 0°C

b)

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

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

**Air undergoes an adiabatic, isentropic expansion from 900 Kpa, 1000 K to 100 kPa.**

@ room temperature ideal gas values,

$$c_p = 1.050, \quad k = 1.4$$

$$T_2 = T_1 \left( \frac{p_2}{p_1} \right)^{\frac{k-1}{k}} = 1000 \left( \frac{1}{9} \right)^{\frac{1.4-1}{1.4}} = 533.8^\circ \text{K}$$

@1000°K constant values,

$$c_p = 1.142, \quad k = 1.336$$

$$T_2 = T_1 \left( \frac{p_2}{p_1} \right)^{\frac{k-1}{k}} = 1000 \left( \frac{1}{9} \right)^{\frac{1.336-1}{1.336}} = 575.5^\circ \text{K}$$

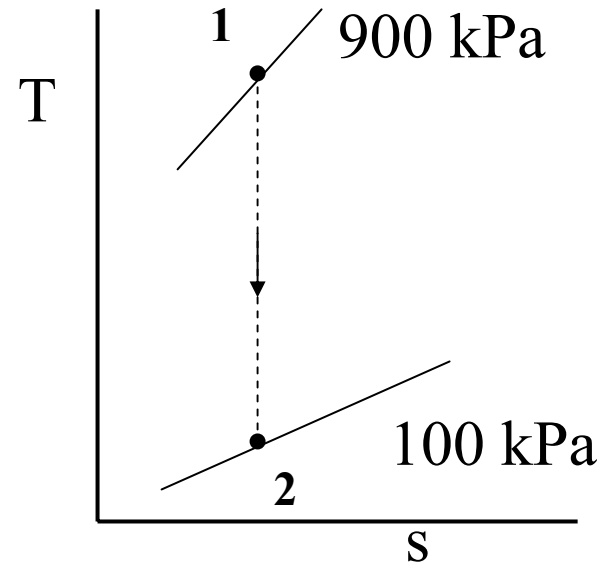
Table A-17 variable specific heat

@1000°K,  $p_{r1} = 114.$ ,  $v_{r1} = 25.17$

$$\frac{p_2}{p_1} = \frac{p_{r2}}{p_{r1}}$$

$$p_{r2} = p_{r1} \left( \frac{p_2}{p_1} \right) = 114 \times \frac{100}{900} = 12.667$$

@  $p_{r2} = 12.667$ ,  $T_2 = 560^\circ \text{K}$



$$v_2 = \frac{RT}{p} = \frac{.286 \times 560.}{100 \text{ kPa}} = 1.6016 \text{ m}^3/\text{kg}$$

Table A-17  $T_2 = 560^\circ \text{R}$ ,  $v_{r2} = 127.$

$$\frac{v_2}{v_1} = \frac{v_{r2}}{v_{r1}}$$

$$v_1 = v_2 \times \frac{v_{r1}}{v_{r2}} = 1.6016 \text{ m}^3/\text{kg} \frac{127.}{647.9} = .3139 \text{ m}^3/\text{kg}$$

$$\text{Using Ideal Gas Law } v_1 = \frac{RT}{p} = \frac{.286 \times 100.}{900 \text{ kPa}}$$

$$v_1 = .3178 \text{ m}^3/\text{kg} \quad (1.2\% \text{ difference})$$

Steam at 800 psia and 900 F enters an adiabatic turbine and leaves at 40 psia .  
 What is the maximum amount of work that the turbine can deliver?

$$h_1 = 1456, \text{ BTU/lb}$$

$$s_1 = 1.6413 \text{ BTU/}^\circ\text{R lb}$$

$$s_2 = s_1$$

$$@s_2 = 1.6413 \text{ and } p = 40 \text{ psia}$$

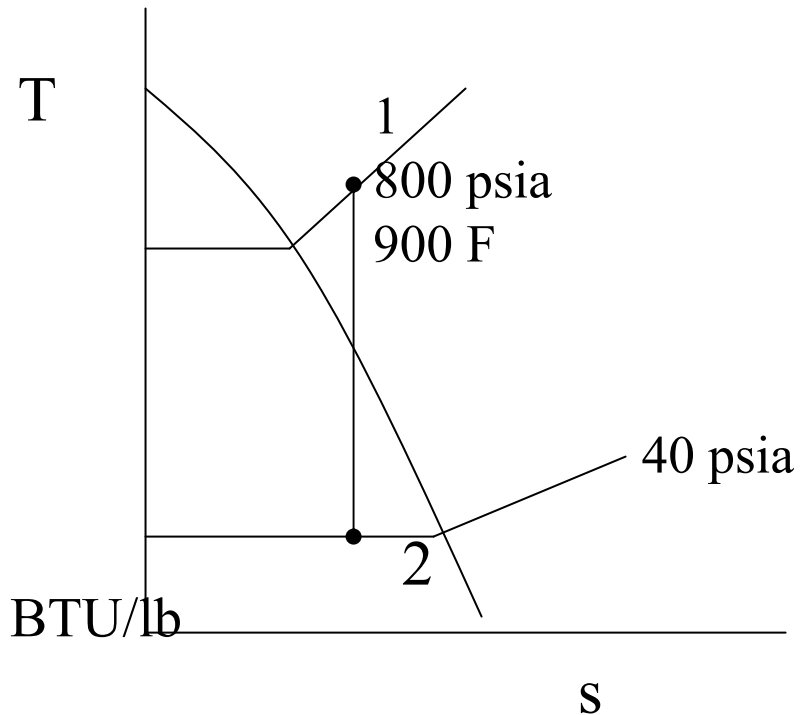
$$x = \frac{s_2 - s_f}{s_{fg}} = \frac{1.6413 - .39214}{1.2845} = .972$$

$$h_2 = h_f + x \times h_{fg}$$

$$h_2 = 236.14 + .972 \times 933.69$$

$$h_2 = 1143.7 \text{ BTU/lb}$$

$$W_{\max} = h_1 - h_2 = 1456 - 1143.7 = 311.3 \text{ BTU/lb}$$



$$h_1 = 3658.8 \text{ BTU/lb}$$

$$s_1 = 7.1693$$

$$s_1' = s_1 = 7.1693$$

$$x = \frac{7.1693 - 1.0912}{6.5019}$$

$$x = .9348$$

$$h_1' = h_f + x \times h_{fg}$$

$$h_1' = 340.54 + .9348 \times 2304.7$$

$$h_1' = 2495.26 \text{ Btu/lb}$$

@ 50 kPa, 100 C

$$h_2 = 2682.4 \text{ Btu/lb}$$

$$s_2 = 7.6954$$

$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2} + \frac{W}{m}$$

$$W = m \times \left( h_1 + \frac{V_1^2}{2} - h_2 - \frac{V_2^2}{2} \right)$$

$$8000 \text{ kJ/sec} = m \times \left( 3658.8 - 2682.4 + \left( \frac{80^2}{2} - \frac{140^2}{2} \right) \times \frac{1}{1000} \right)$$

$$8000 \text{ kJ/sec} = m \times (875.9 - 13.2) = 8.3 \text{ kg}$$

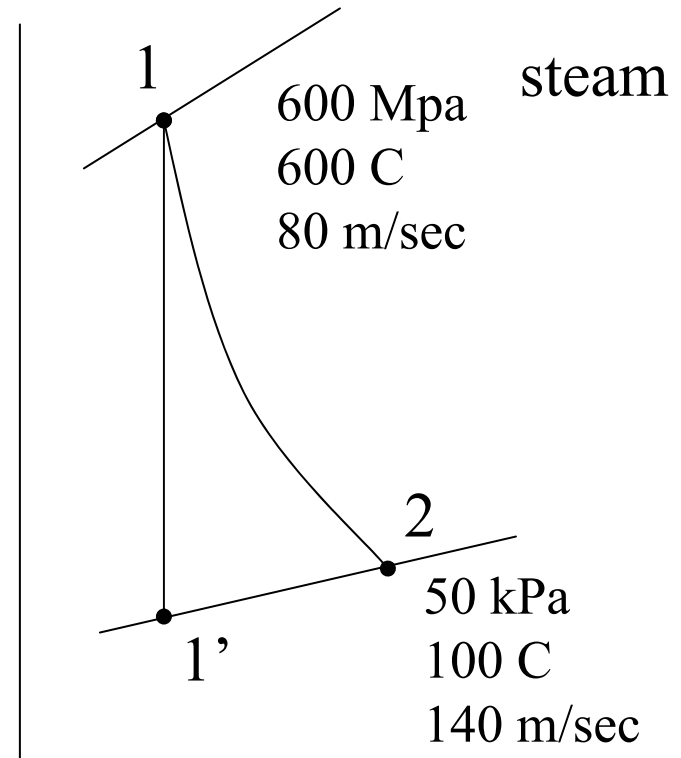
$$\Delta S = m \times (s_2 - s_1) = 8.3 \text{ kg} \times (7.6953 - 7.1693) = 5.765 \text{ kJ/K}$$

$$W_{\text{isentropic}} = 8.3 \text{ kg} \times (3658.8 - 2494.97 - 13.2)$$

$$W_{\text{isentropic}} = 9550 \text{ KW}$$

$$\eta = \frac{W_{\text{actual}}}{W_{\text{isentropic}}} = \frac{8000}{9550} = 83.8\%$$

The power output of an adiabatic turbine is 8 MW. Steam enters the turbine at 600 C, 6 MPa and 80 m/sec. Steam leaves the turbine at 50 kPa, 100 C and 140 m/sec. Determine a) the turbine steam mass flow rate, b) the isentropic efficiency of the turbine. c) the entropy change in the expansion process



Consider the effect of varying the isentropic efficiency of an adiabatic nozzle from 80% to 100% on the nozzle exit temperature and pressure. Inlet conditions and the exit velocity are held constant. Air enters the nozzle at 60 psia, 1020 F and a low velocity. Air leaves the nozzle at with a velocity of 800 ft.sec.

For  $\eta_{\text{nozzle}} = 90\%$

@  $T_1 = 1480^\circ\text{R}$ ,  $p_{r1} = 53.04$ ,  $h_1 = 363.89$  BTU/lb

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

$$h_2 = h_1 + \frac{V_2^2 - V_1^2}{2} = 363.89 + \frac{800^2}{2} \times \frac{1 \text{ BTU/lb}}{(778 \times 32.2) \text{ ft}^2/\text{sec}^2}$$

$h_2 = 351.1$  BTU/lb actual exit enthalpy

@  $h_2 = 351.1$  BTU/lb Table A-17E  $T_2 = 1431.3^\circ\text{R}$

$$\eta = \frac{h_1 - h_2}{h_1 - h_1'}$$

$$h_1' = h_1 - (h_1 - h_2)/.9 = 363.89 - (363.89 - 351.1)/.9$$

$$h_1' = 349.68 \text{ BTU/lb}$$

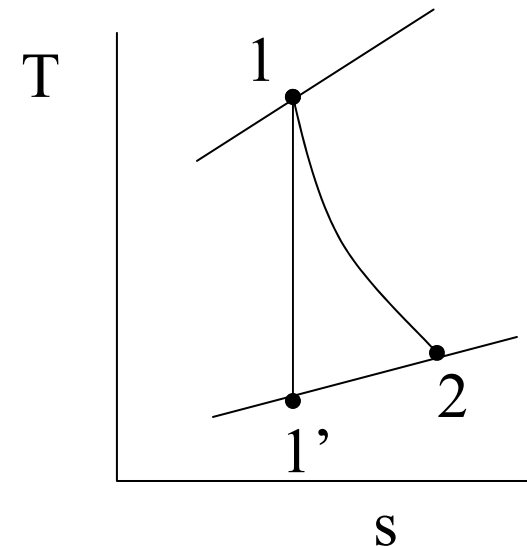
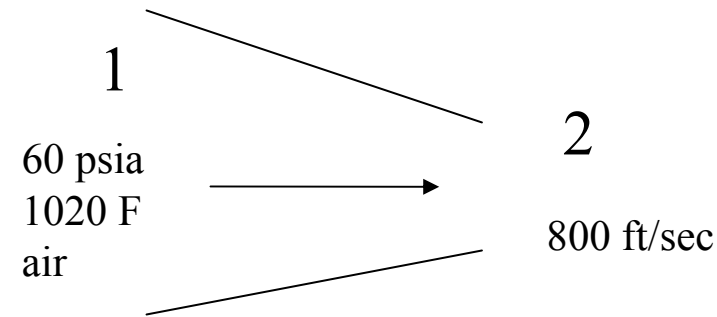
Table A-17E @  $h = 349.68$  BTU/lb,  $P_{r2} = 46.04$

$$\frac{p_2}{p_1} = \frac{p_{r2}}{p_{r1}}$$

$$p_2 = p_1 \frac{p_{r2}}{p_{r1}} = 60 \text{ psia} \times \frac{46.04}{53.04} = 52.1 \text{ psia}$$

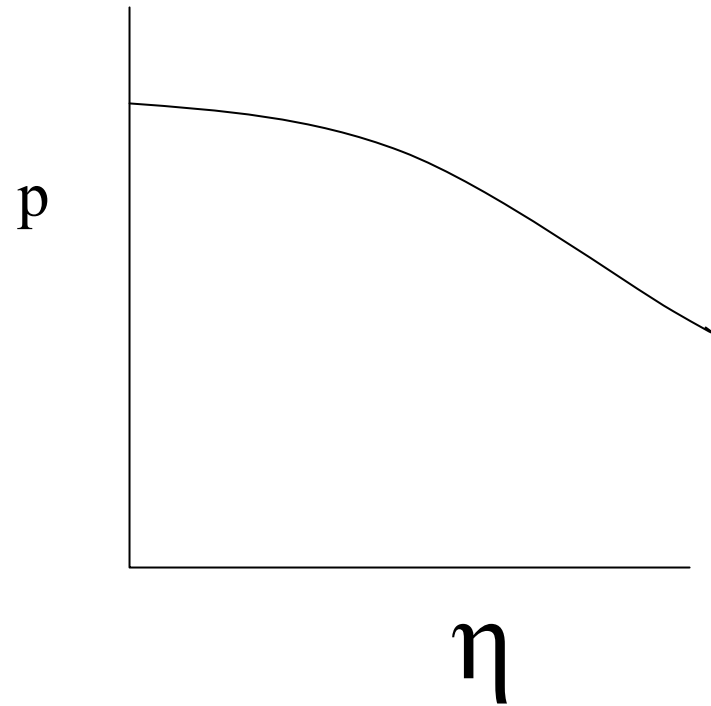
$$p_2 = 52.1 \text{ psia}$$

$p_2$  will vary with efficiency.



$p_2$  varies with efficiency

$\eta$	$h_1'$	$p_{r2}$	$p_2$
1.	351.1	46.694	52.82
.9	349.7	46.04	52.10
.8	347.9	45.206	51.14



Steam enters a two-stage adiabatic turbine at a flow rate of 15 kg/sec, a pressure of 7MPa and a temperature of 500 C. After the first stage at a pressure of 1MPa 10% of the steam is extracted to be used in a heating process. Steam leaves the second stage of the turbine at 50 kPa. Determine the power out put of the turbine for an isentropic expansion in both stages and for an isentropic efficiency of 88% in both stages.

Pt	T	p	h	s
1	500	7MPa	3411.4	6.8
1'		1MPa		6.8
1''		50 kPa		6.8
2		1MPa		
3		50 kPa		

@1 MPa

T	h	s
250	2943.1	6.9265
	2879.4	6.8
200	2827.9	6.6957

$$\text{ratio} = \frac{6.8 - 6.6956}{6.9265 - 6.6956} = .452$$

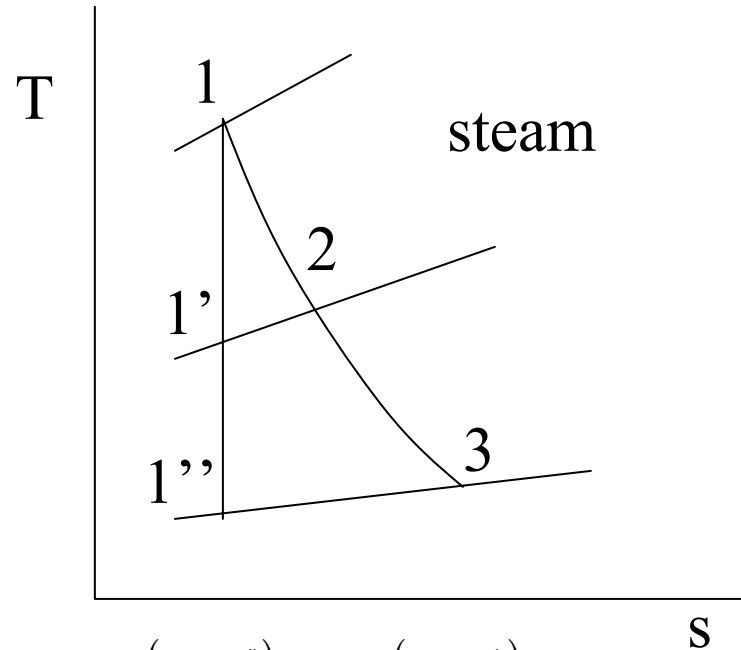
$$h_1' = 2880.$$

@ 50 kPa

$$x = \frac{6.8 - 1.0912}{6.5019} = .878$$

$$h_1'' = 340.54 + .878 \times 2304.7$$

$$h_1'' = 2364.07 \text{ kJ/kg}$$



$$a) W_{\text{isentropic}} = .9 \times m(h_1 - h_1'') + .1 \times m(h_1 - h_1')$$

$$W_{\text{isentropic}} = .9 \times 15 \times (3410.4 - 2364.07) + .1 \times 15(3410.4 - 2880.)$$

$$W_{\text{isentropic}} = 15,054 \text{ KW}$$

$$b) \eta = \frac{W_{\text{actual}}}{W_{\text{isentropic}}} = .88$$

$$W_{\text{actual}} = .88 \times 15,054 \text{ KW} = 13,247 \text{ KW}$$

## SECOND LAW OF THERMODYNAMICS

### Kelvin Planck Statement of the Second Law

It is impossible to construct an engine which, operating in a cycle, will produce no other effect than the extraction of heat from a single heat reservoir and the performance of a equivalent amount of work.

### Clausius Statement of the Second Law

It is impossible to have a system operating in a cycle which transfers heat from a cooler to a hotter body without work being done on the system by the surroundings.

$$\oint_{\text{reversible process}} \frac{dQ}{T} = 0$$

$$\oint_{\text{irreversible process}} \frac{dQ}{T} < 0$$

$$ENTROPY = \Delta S = \int_{\text{reversible process}} \frac{dQ}{T}$$

For a Reversible Process

$$(S_2 - S_1) = 0$$

For an Irreversible process

$$(S_2 - S_1) > 0$$

For an ideal gas

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

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