ENERGY SYSTEM CYCLES

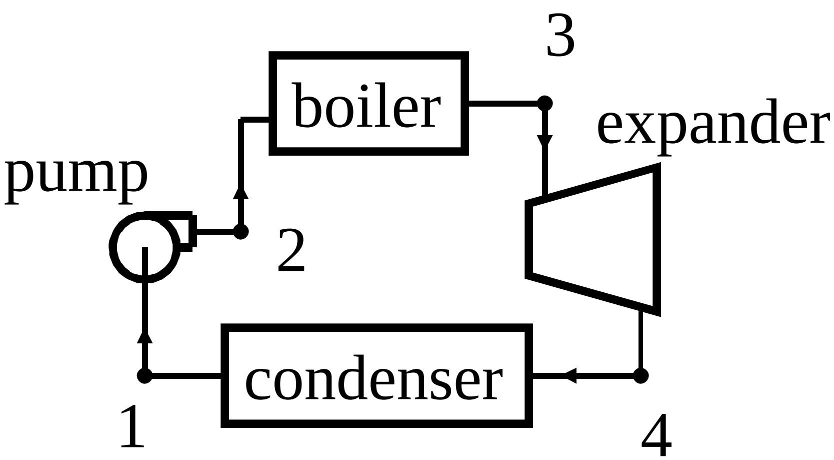
CONCEPTS

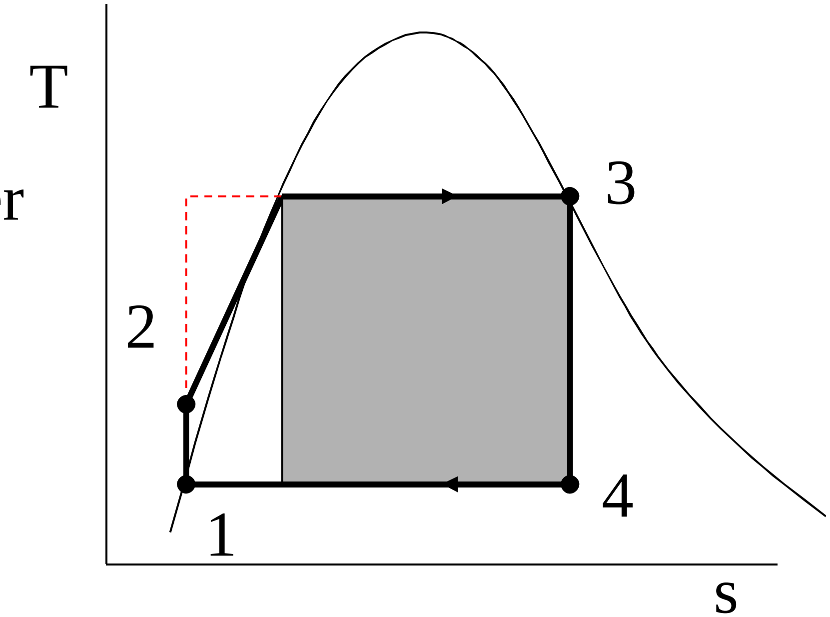
- System
- Properties
- State Point
- Process
- Cycle

CYCLE	THERMODYNAMIC SYSTEM	WORKING FLUID	PROCESS
Power	Closed	Ideal Gas	$p = c$
Refrigeration	Open	$c_p, c_v = c$	$v = c$
	Unsteady	$c_p, c_v = f(T)$	$T = c$
		Real Gas	$h = c$
		steam	$s = c$
		refrigerant	$u = c$
		Phase	$Q = 0$
		single phase	$W = 0$
		two phase	

Lenoir	Power	Closed	Air	$p = c, v = c, Q = 0$
Otto	Power	Closed	Air	$v = c, Q = 0$
Diesel	Power	Closed	Air	$p = c, v = c, Q = 0$
Dual	Power	Closed	Air	$p = c, v = c, Q = 0$
Brayton	Power	Open	Air	$p = c, Q = 0$
Rankine	Power	Open	steam, 2 phase	$p = c, Q = c$
superheat				
reheat				
regeneration				
Reversed Brayton	Refrigeration	Open	Air	$p = c, Q = 0$
Vapor Compression	Refrigeraton	Open	Refrigerants, 2 phase	$p = c, h = c, Q = 0$

SIMPLE RANKINE CYCLE





Steady Flow, Open System - region in space

Steady Flow Energy Equation for Processes

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

Pump Process, $1 \Rightarrow 2$, $Q = 0$, $W_{in} = m(h_2 - h_1)$

Boiler Process, $2 \Rightarrow 3$, $W = 0$, $Q_{in} = m(h_3 - h_2)$

Expansion Process, $3 \Rightarrow 4$, $Q = 0$, $W_{out} = m(h_3 - h_4)$

Condenser Process, $4 \Rightarrow 1$, $W = 0$, $Q_{out} = m(h_4 - h_1)$

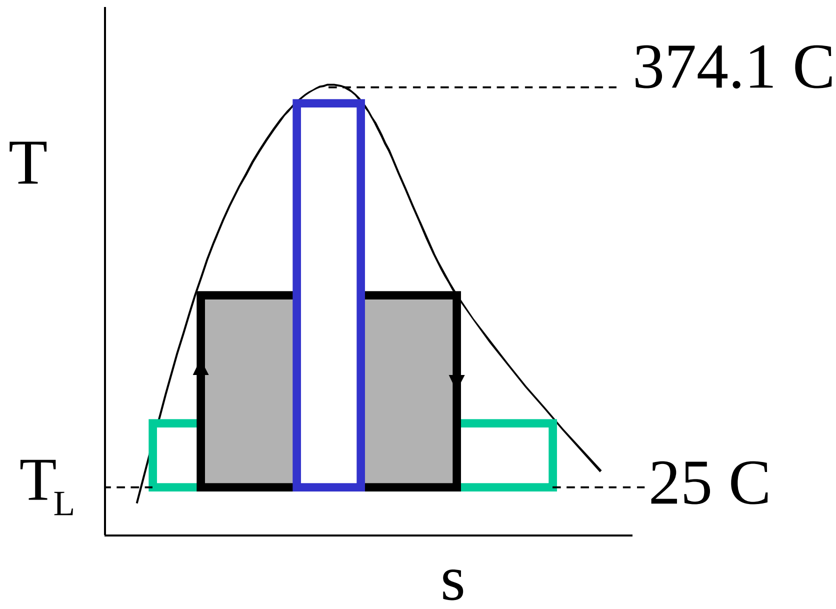
First Law for Cycles

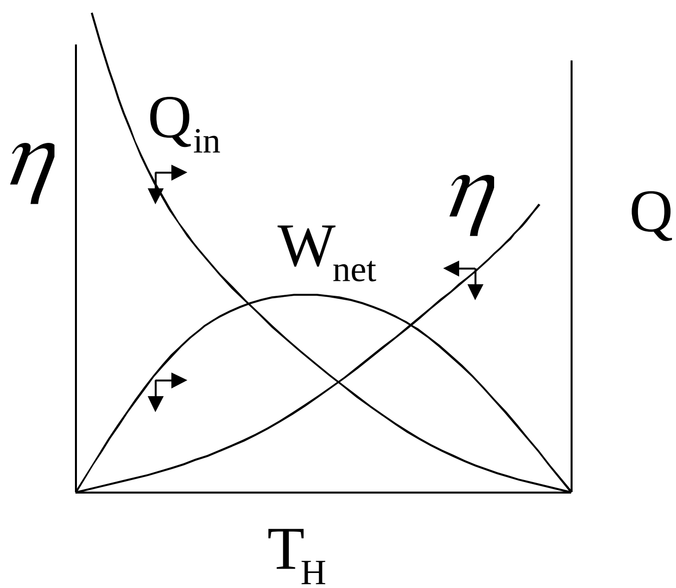
$$\oint_{cycle} \delta Q = \oint_{cycle} \delta W$$

$$\sum_{cycle} Q = \sum_{cycle} W$$

$$\eta_{cycle} = \frac{W_{net}}{Q_{in}} = \frac{\sum_{cycle} W}{Q_{in}}$$

CARNOT CYCLE WITH WATER





$$\eta_{Carnot} = 1 - \frac{T_L}{T_H}$$

$$Q_{in} = T_H \Delta S$$

$$W_{net} = \eta \times Q_{in}$$

W_{net} maximum at :

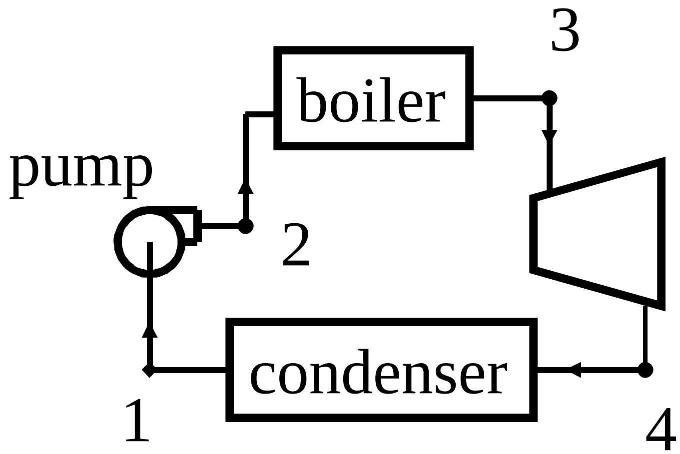
$T = 240$ C

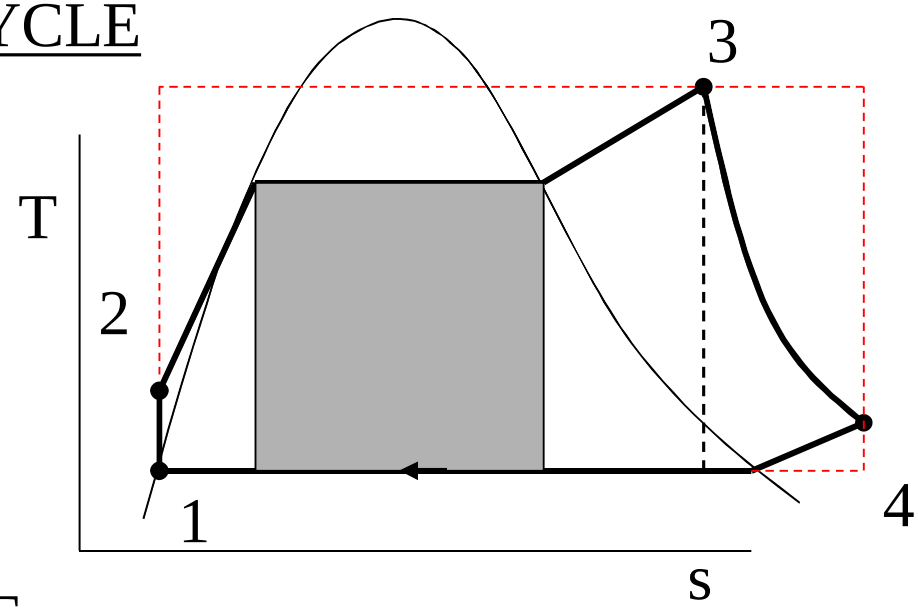
$\eta_{Carnot} = 41.9\ \%$

$W_{net} = 740.$ kJ/kg

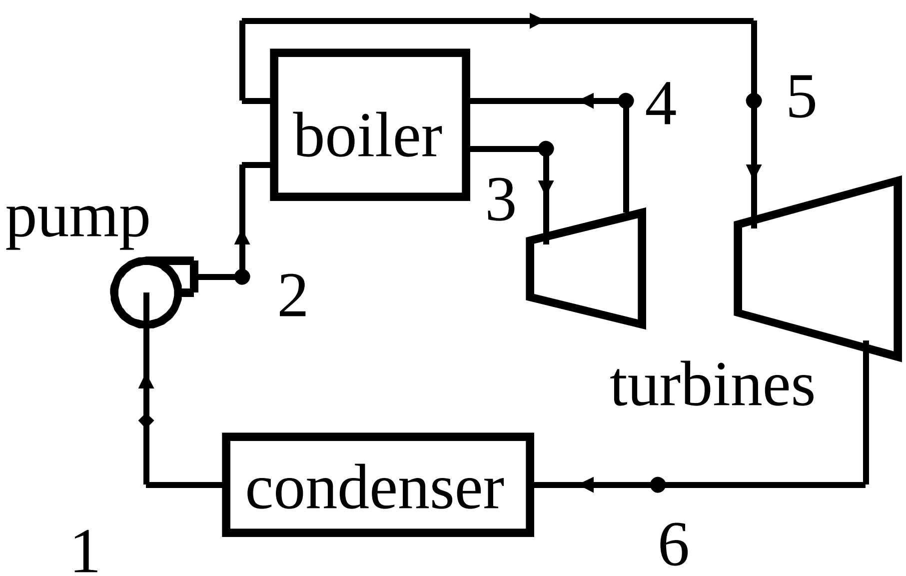
maximum area

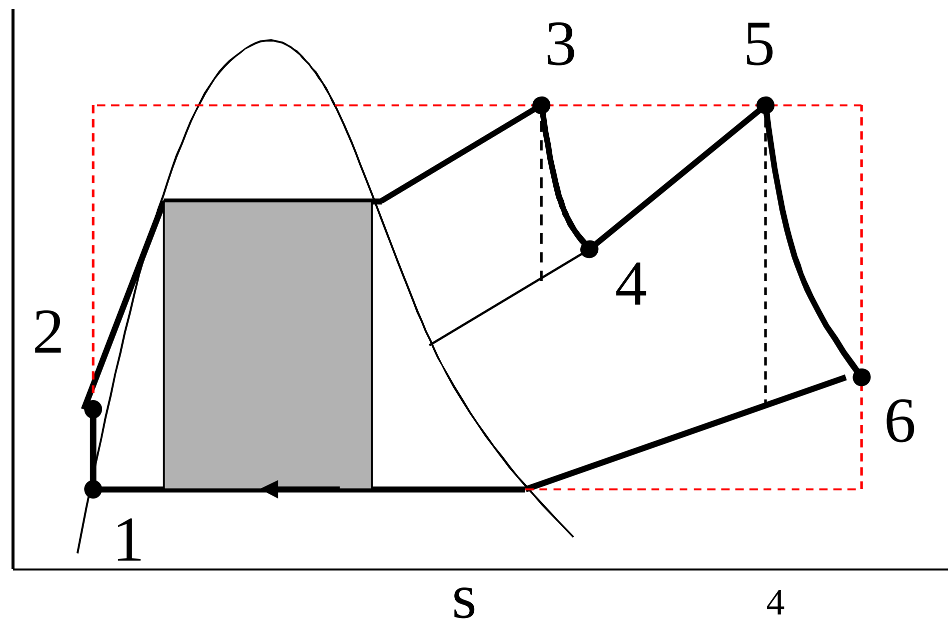
SUPERHEAT RANKINE CYCLE





REHEAT RANKINE CYCLE





$Q = \Delta U + W$ First Law

$dq = du + dw$

$dq = Tds$ Second Law

$dw = pdv$ Boundary Work

subsitiuting for dq and dw,

$Tds = (du) + (pdv)$

$h = u + pv$ h property definition, h is an exact differential

$dh = du + pdv + vdp$

subsitiuting for du,

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

$Tds = dh - vdp$

for an adiabatic process, $Q = Tds = 0$

$dh = vdp$

$h = \int vdp$

Example: water pumped from 15 psia to 30 psia

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

$$w = \frac{(30\text{psia} - 15\text{psia}) \times 144\text{psi/psf}}{62.4\text{lb/ft}^3}$$

$$w = \frac{2160\,\frac{\text{lb}_f}{\text{ft}^2}}{62.4\,\frac{\text{lb}_m}{\text{ft}^2}\,\frac{1}{\text{ft}}} = 34.6\,\frac{\text{ft lb}_f}{\text{lb}_m},\ \text{(ft of fluid)}$$

$$w = 34.6\,\frac{\text{ft lb}_f}{\text{lb}_m} \times \frac{1\,\text{BTU}}{778\,\text{ft lb}_f} = .044\,\text{BTU/lb}_m$$

Example: water pumped from 100 kPa to 300 kPa

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

$$w = .0010432\,\text{m}^3/\text{kg} \times (300\,\text{kPa} - 100\,\text{kPa})$$

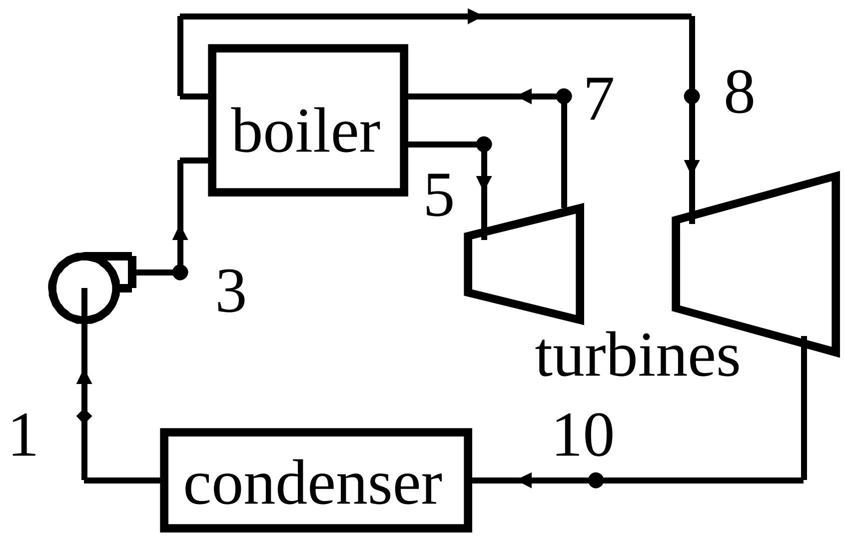
$$w = .2086\,\frac{\text{m}^3}{\text{kg}}\,\text{kPa},\quad \text{kJ/kg}$$

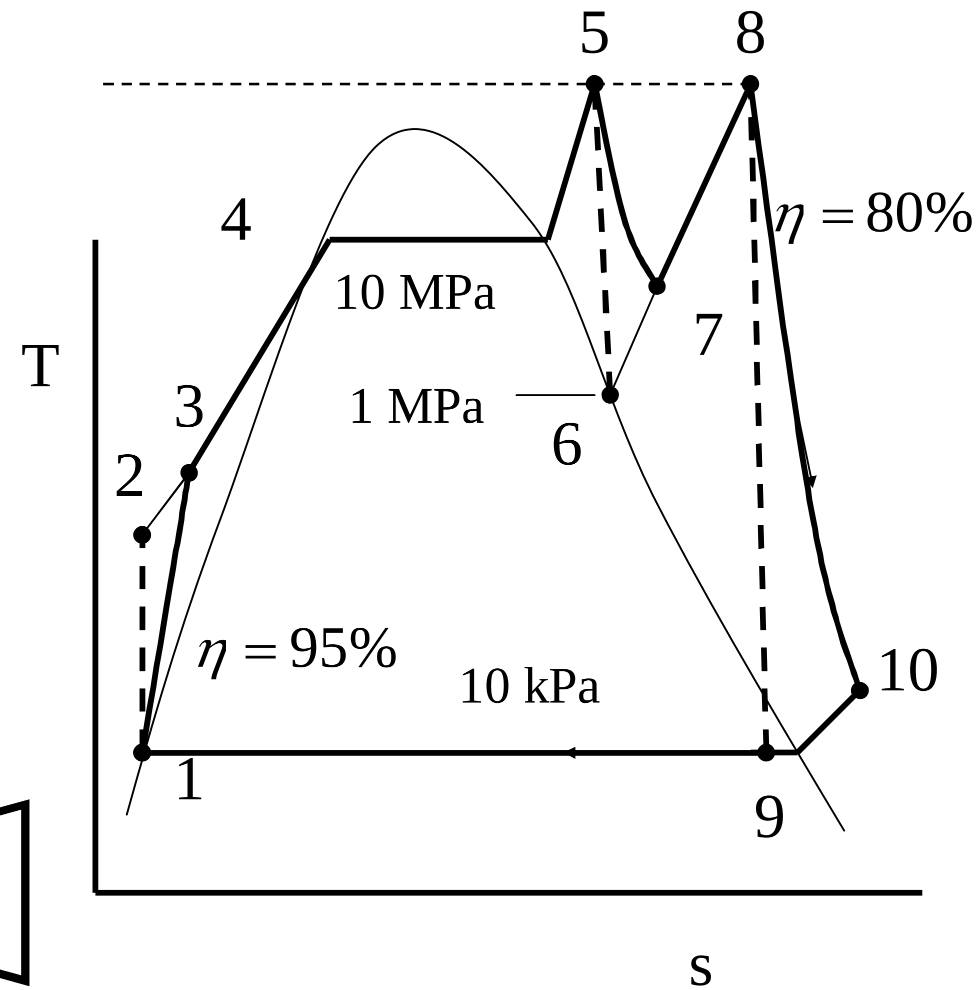
A steam power plant runs on a reheat cycle and produces 80 MW. The turbine inlet conditions are 10 MPA , 500 C and 1 MPA, 500 C. The condenser operates at 10 kPa. The efficiency of the turbines is 80%. The efficiency of the pump is 95%. Determine:

a) the turbine exit conditions

b) the cycle efficiency and

c) the mass flow rate of the steam.





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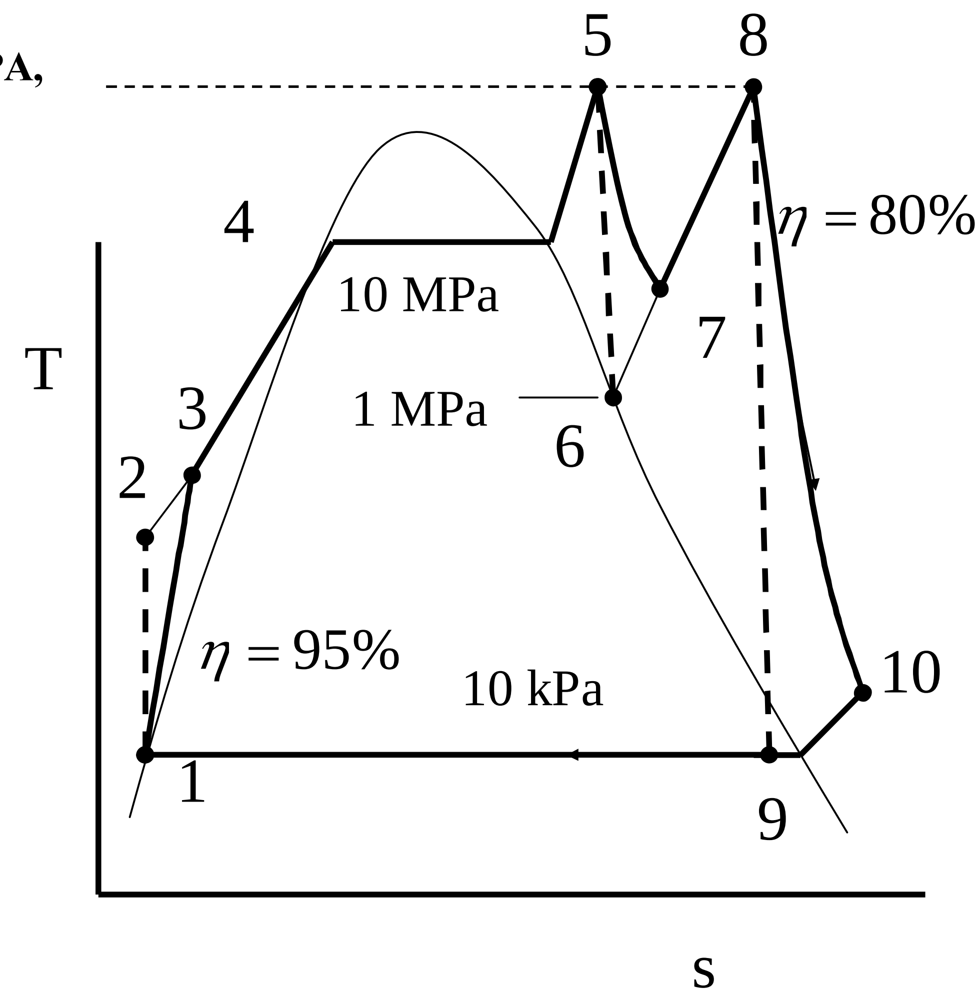
Pt	T	p	h	s	v
1	45.81	10 kPa	191.81	.6492	.001010
2		10 MPa		.6492	
3		10 MPa			
4		10 MPa			
5	500	10 MPa	3375.1	6.5995	
6		1 MPa		6.5995	
7		1 MPa			
8	500	1 MPa	3479.1	7.7642	
9		10 kPa		7.7642	
10		10 kPa			



compressed liquid water, Table A-7, $p_2 = 10\text{MPa}$

T	h	s
60	259.43	.8260
	$s_2 = s_1 = .6492$	
40	176.37	.5685

$$h_2 = 202.39\ \text{kJ/kg}$$

$$W_{\text{pump actual}} = \frac{W_{\text{pump ideal}}}{.95} = \frac{h_2 - h_1}{.95}$$

$$W_{\text{pump actual}} = \frac{202.39 - 191.81}{.95} = 11.14\ \text{kJ/kg}$$

$$h_3 = h_1 + W_{\text{pumpactural}} = 191.81 + 11.14$$

$$h_3 = 203.95\ \text{kJ/kg}$$

$$W_{\text{pump}} = \frac{v \times \Delta p}{\eta} = \frac{.001010 \times (10{,}000 - 10)}{.95}$$

$$W_{\text{pump}} = 10.71\ \text{kJ/kg}$$

$@\,1\,\text{MPa}, s_6 = s_5$

T	h	s
200	2828.3	6.6956
	$s_6 = s_5 = 6.5995$	
179.88	2777.1	6.5850

$$h_6 = 2784.11\ \text{J/kg}$$

$$\eta = \frac{h_5 - h_7}{h_5 - h_6}$$

$$h_7 = h_5 - .8 \times (h_5 - h_6)$$

$$h_7 = 3373.7 - .8 \times (3373.7 - 2784.11)$$

$$h_7 = 2902.03\ \text{kJ/kg}$$

$@\,10\ \text{kPa},\ s_9 = s_8$

$$x = \frac{s_8 - s_f}{s_{fg}} = \frac{7.7642 - .6492}{7.4996} = .9487$$

$$h_9 = 191.81 + x \times 2392.8 = 2460.86\ \text{kJ/kg}$$

$$\eta = \frac{h_8 - h_{10}}{h_8 - h_9} = .8$$

$$h_{10} = h_8 - .8 \times (h_8 - h_9)$$

$$h_{10} = 3479.1 - .8 \times (3479.1 - 2460.86)$$

$$h_{10} = 2664.51\ \text{kJ/kg} \qquad (h_{sat} = 2519.8, \approx 90^{O}\text{C})$$

$$Q_{in} = (h_8 - h_7) + (h_5 - h_3)$$

$$Q_{in} = (3479.1 - 2902.03) + (3375.1 - 203.95)$$

$$Q_{in} = 3748.22 \text{ kJ/kg}$$

$$Q_{out} = (h_{10} - h_1) = (2664.51 - 191.81) = 2472.7 \text{ kJ/kg}$$

$$W = (h_5 - h_7) + (h_8 - h_{10}) - W_{pump}$$

$$W = (3375.1 - 2902.03) + (3479.1 - 2664.51) - 11.28$$

$$W = 472.74 + 814.11 - 11.28 = 1276.38 \text{ kJ/kg}$$

$$\oint dQ = \oint dW$$

$$Q_{in} - Q_{out} = W_{net}$$

$$3748.22 - 2472.7 = 1275.52$$

$$\eta_{cycle} = \frac{W_{net}}{Q_{in}} = \frac{1276.38}{3748.22} = 34.05\%$$

$$m = \frac{\text{Total Work}}{\text{Specific Work}} = \frac{80{,}000 \text{kJ/sec}}{1275.527} = 62.72 \text{ kg/sec}$$

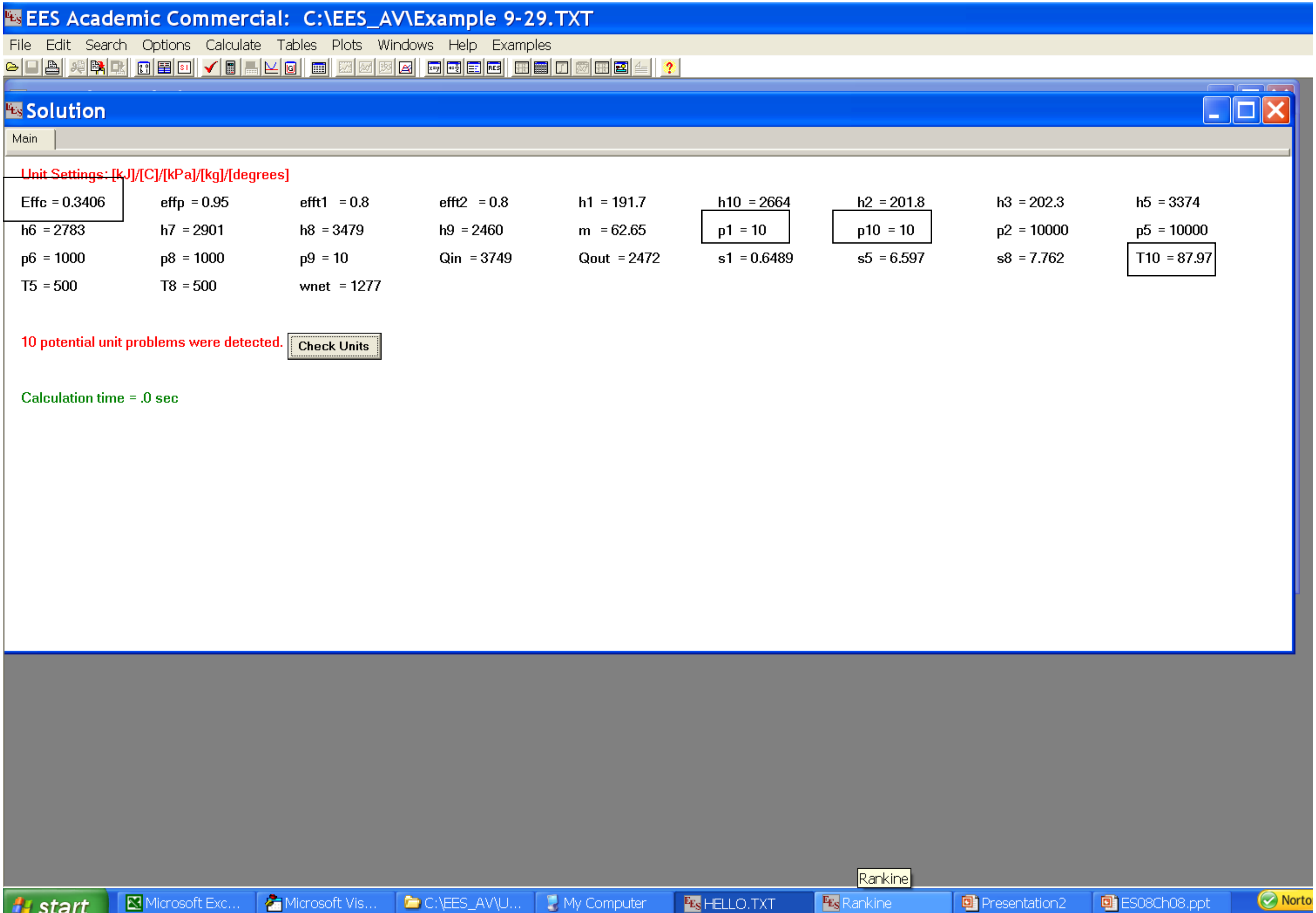
EES Academic Commercial: C:\EES_AV\Example 9-29.TXT

File Edit Search Options Calculate Tables Plots Windows Help Examples

EES Model

```
p1= 10
p2=10000
effp=.95
efft1=.80
efft2=.8
T5=500
p5=p2
p6=1000
p8=p6
p9=p1
p10=p9
T8=500

h1=enthalpy(STEAM, p=p1, x=0)
s1=entropy(STEAM, p=p1, x=0)
h2=enthalpy(STEAM,p=p2,s=s1)
    h3=h1+(h2-h1)/effp
h5=enthalpy(STEAM,T=T5,p=p5)
s5=entropy(STEAM, T=T5,p=p5)
h6=enthalpy(STEAM, p=p6,s=s5)
    h7=h5-(h5-h6)*efft1
h8=enthalpy(STEAM,p=p8,T=T8)
s8=entropy(STEAM,p=p8,T=T8)
h9=enthalpy(STEAM, p=p9,s=s8)
    h10=h8-(h8-h9)*efft2
T10=temperature(STEAM, p=p10, h=h10)
   Qin=(h5-h3)+(h8-h7)
  Qout=(h10-h1)
  Effc=1-(Qout/Qin)
  wnet=Qin-Qout
  m=80000/wnet
```


EES Academic Commercial: C:\EES_AV\Example 9-29.TXT
File Edit Search Options Calculate Tables Plots Windows Help Examples
Solution
Main
Unit Settings: [kJ]/[C]/[kPa]/[kg]/[degrees]
Effc = 0.3406
effp = 0.95
efft1 = 0.8
efft2 = 0.8
h1 = 191.7
h10 = 2664
h2 = 201.8
h3 = 202.3
h5 = 3374
h6 = 2783
h7 = 2901
h8 = 3479
h9 = 2460
m = 62.65
p1 = 10
p10 = 10
p2 = 10000
p5 = 10000
p6 = 1000
p8 = 1000
p9 = 10
Qin = 3749
Qout = 2472
s1 = 0.6489
s5 = 6.597
s8 = 7.762
T10 = 87.97
T5 = 500
T8 = 500
wnet = 1277
10 potential unit problems were detected.
Check Units
Calculation time = .0 sec
Rankine
start
Microsoft Exc...
Microsoft Vis...
C:\EES_AV\U...
My Computer
HELLO.TXT
Rankine
Presentation2
ES08Ch08.ppt

REGENERATION RANKINE CYCLE

open feed water heater

$$Q_{in} = 1 \times (h_6 - h_5)$$

$$Q_{out} = (1 - x) \times (h_8 - h_1)$$

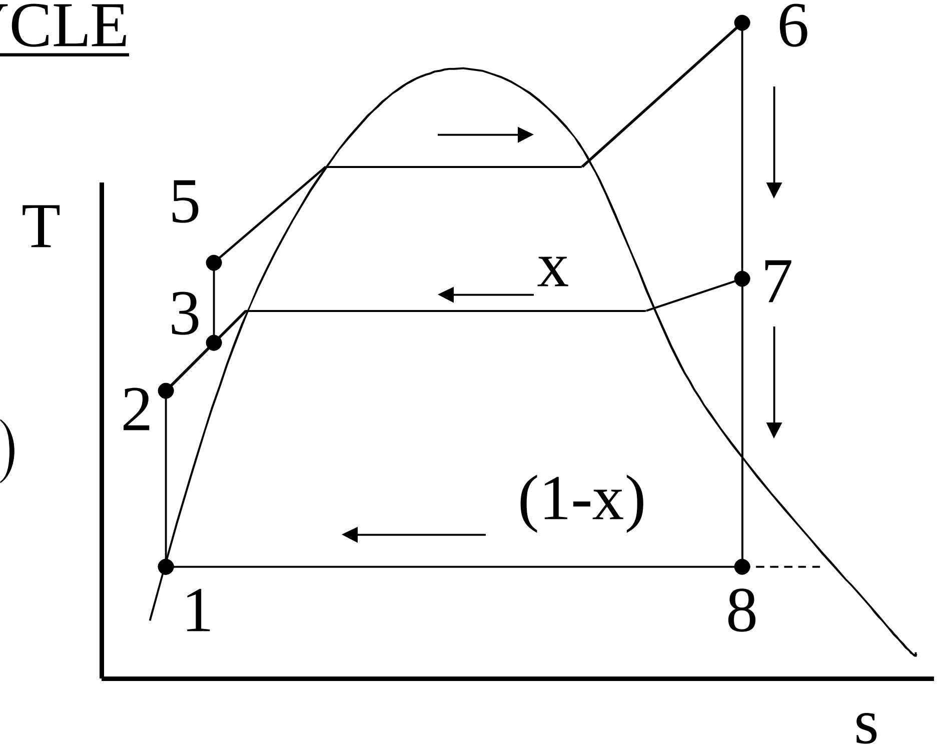
$$W_{pump} = (1 - x) \times (h_2 - h_1) + 1 \times (h_5 - h_3)$$

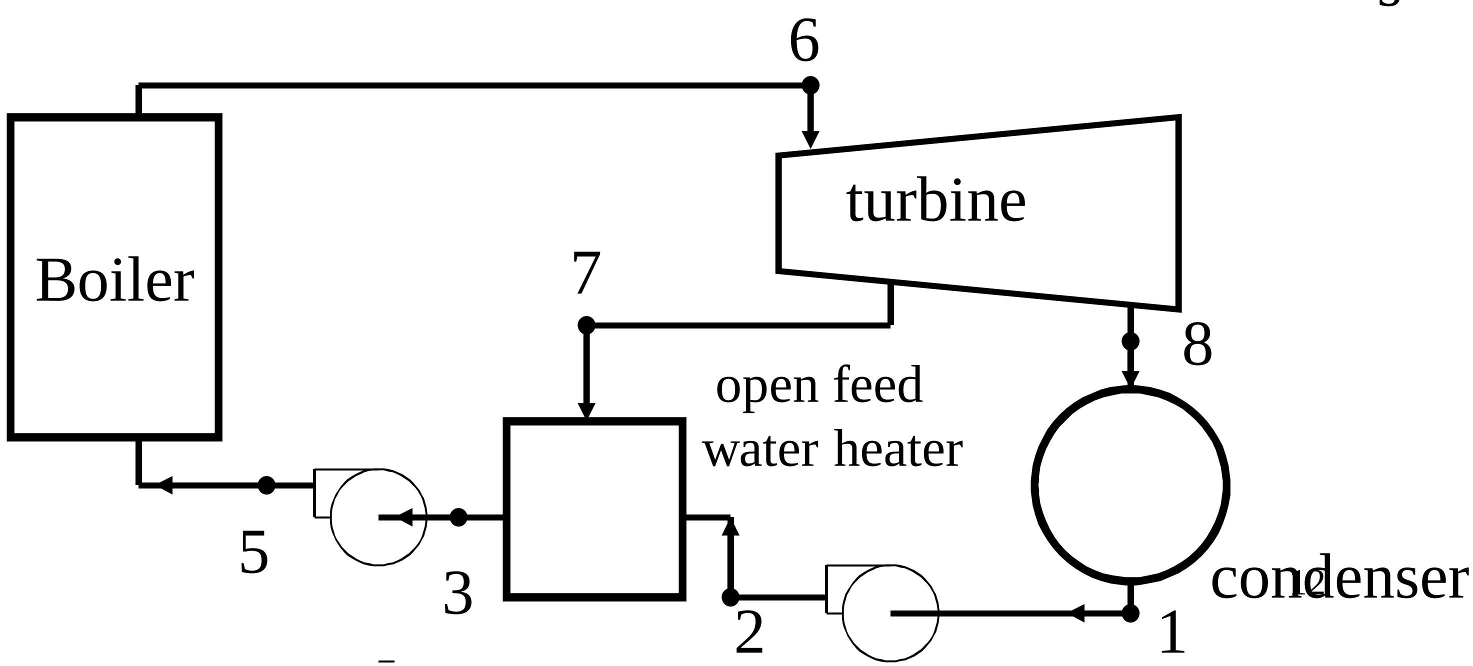
$$W_{turbine} = 1 \times (h_6 - h_7) + (1 - x) \times (h_7 - h_8)$$

Heater Energy Balance

$$(1 - x) \times h_2 + x \times h_7 = 1 \times h_3$$

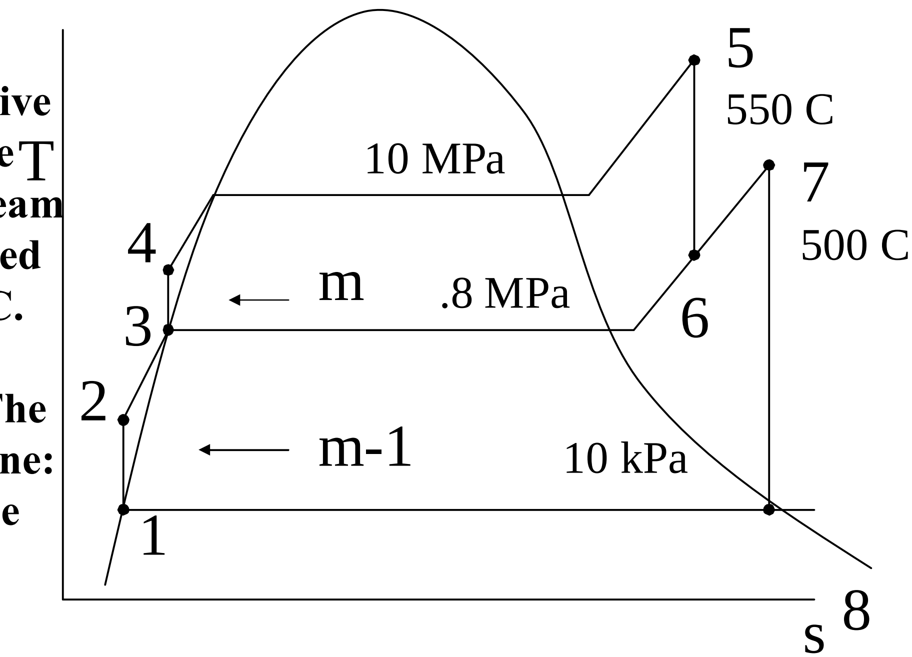
$$\sum_{cycle} Q = \sum_{cycle} W$$





A steam power plant runs on a regenerative cycle and produces 80 MW. The turbine inlet conditions are 10 MPA , 550 C. Steam is extracted at .8 MPA to feed an open feed water heater the rest is reheated to 500 C. The condenser operates at 10 kPa.
The efficiency of the turbines is 100%. The efficiency of the pump is 100%. Determine:
a) the turbine exit conditions, b) the cycle efficiency and c) the mass flow rate of the steam.

A steam power plant runs on a regenerative cycle and produces 80 MW. The turbine inlet conditions are 10 MPA , 550 C. Steam is extracted at .8 MPA to feed an open feed water heater the rest is reheated to 500 C. The condenser operates at 10 kPa. The efficiency of the turbines is 100%. The efficiency of the pump is 100%. Determine: a) the turbine exit conditions, b) the cycle efficiency and c) the mass flow rate of the steam.



Pt	T	p	h	s	v
1		10kPa	191.81		.00101
2		.8 MPa			
3		.8 MPa	720.87	2.0457	.001115
4		10 MPa			
5	550	10. MPa	3502.	6.7585	
6				6.7585	
7	500	.8 MPa	3481.3	7.8692	
8		10 kPa		7.8692	

$$@10\ \text{kPa},\quad s_f = .6492, s_g = 8.1488$$

$$x_8 = \frac{7.8692 - .6492}{8.1488 - .6492} = .9627$$

$$h_8 = h_f + x \times h_{fg}$$

$$h_8 = 191.81 + .9627 \times 2392.1$$

$$h_8 = 2494.68\ \text{kJ/kg}$$

$$@10\ \text{MPa and } s = 2.0457$$

Table A - 7 Compressed Liquid

$$h = 731.28\ \text{kJ/kg}$$

$$h_2 = h_1 + v_1 \times (p_3 - p_2)$$

$$h_2 = 191.81 + .00101 \times (800 - 10) = 192.61 \text{ kJ/kg}$$

@ .8 MPa

T	h	s
200	2839.8	6.8177
		6.7585
170.41	2768.3	6.6616

$$h_6 = 2812.63 \text{ kJ/kg}$$

Energy Balance

q lost by steam = q gained by water

$$m_1(h_6 - h_3) = (1 - m_1)(h_3 - h_2)$$

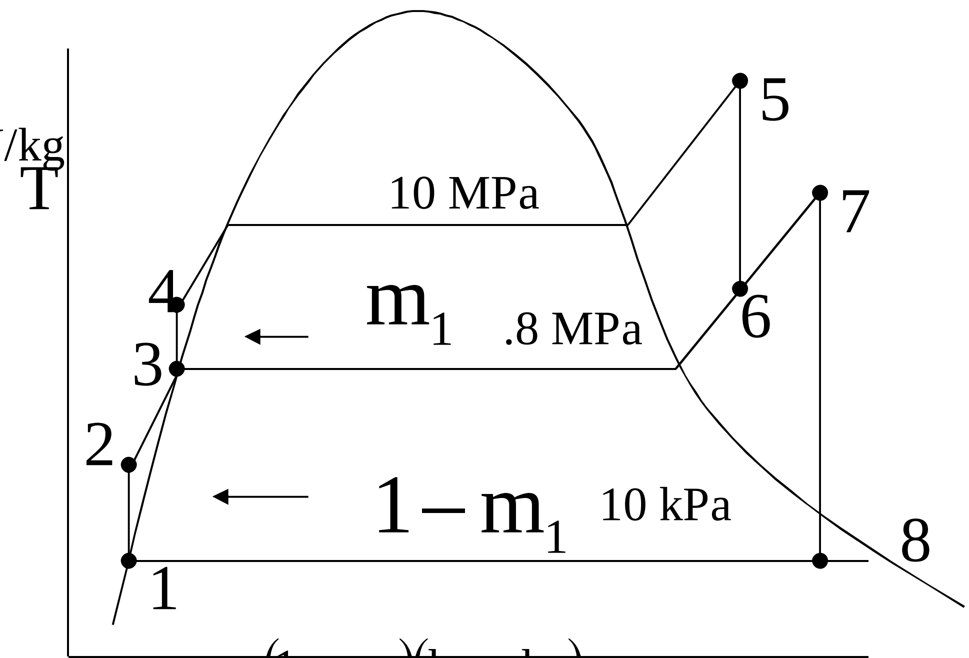
$$m_1 = \frac{h_3 - h_2}{h_6 - h_2}$$

$$m = \frac{720.87 - 192.61}{2812.63 - 192.61} = .2016$$

$$q_{in} = 1 \text{ kg/sec } (h_5 - h_4) + (1 - .2016)(h_7 - h_6)$$

$$q_{in} = (3502. - 731.28) + .7984 \times (3481.3 - 2812.63)$$

$$q_{in} = 2770.72 + 533.87 = 3304.59 \text{ kJ/kg}$$



$$q_{out} = (1 - m_1)(h_8 - h_1)$$

$$q_{out} = .7984(2494.68 - 191.81)$$

$$q_{out} = 1838.61 \text{ kJ/kg}$$

a) $$m = \frac{W}{W_{net}} = \frac{80{,}000}{q_{in} - q_{out}}$$

$$m = \frac{80{,}00}{3304.59 - 1838.61} = 54.57 \text{ kg/sec}$$

b) $$\eta = \frac{w_{net}}{q_{in}} = \frac{1465.98}{3304.59} = 44.36\%$$

REGENERATIONRANKINE CYCLE

closed feed water heater

$$Q_{in} = 1 \times (h_6 - h_5)$$

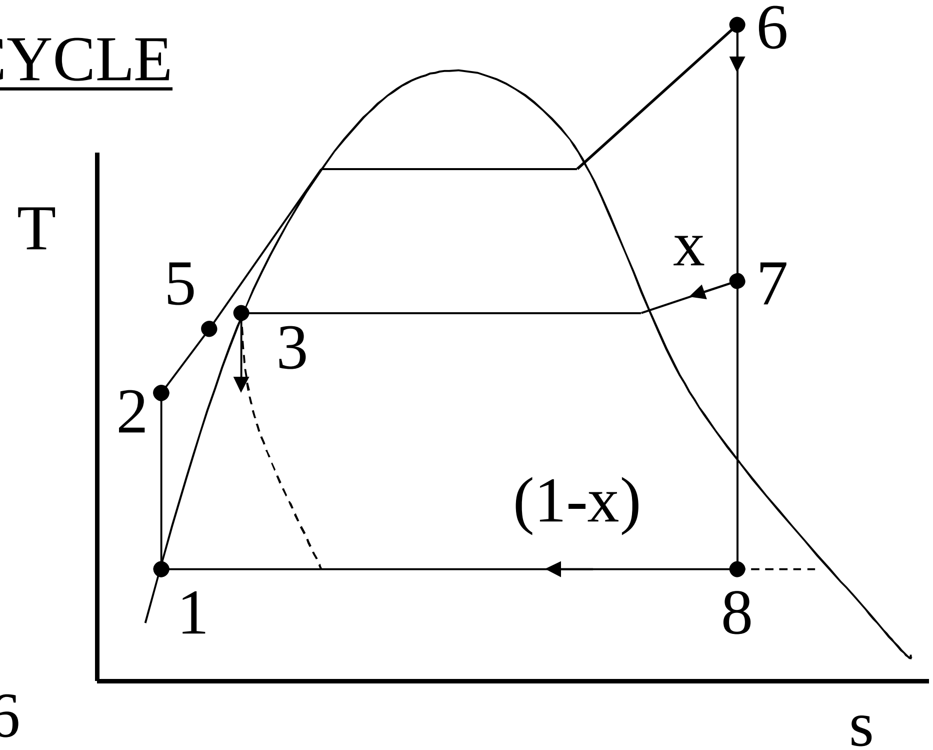
$$Q_{out} = (1 - x) \times (h_8 - h_1) + x \times (h_3 - h_1)$$

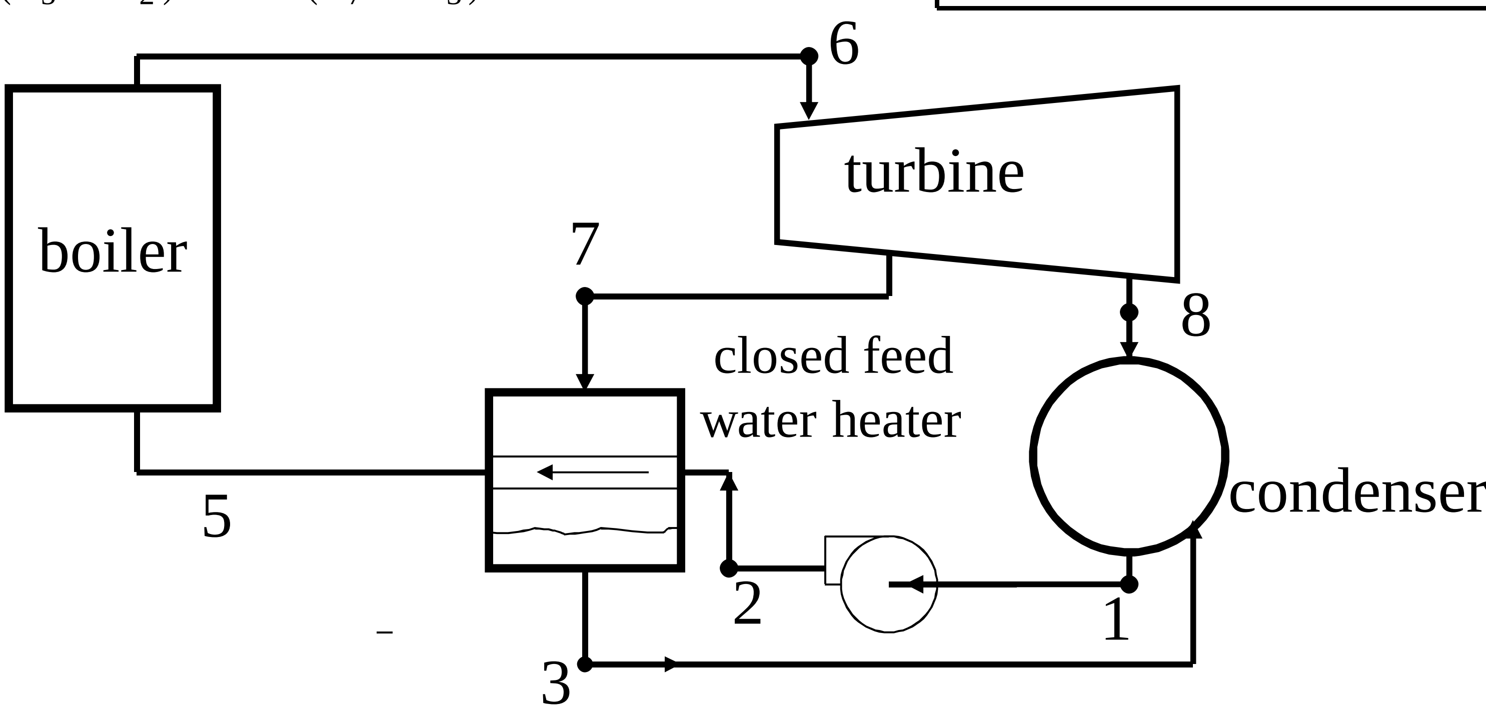
$$W_{pump} = 1 \times (h_2 - h_1)$$

$$W_{turbine} = 1 \times (h_6 - h_7) + (1 - x) \times (h_7 - h_8)$$

Heater Energy Balance

$$1 \times (h_5 - h_2) = x \times (h_7 - h_3)$$





REGENERATIONRANKINE CYCLE

closed feed water heater

$$Q_{in} = 1\times(h_6 - h_5)$$

$$Q_{out} = (1-x)\times(h_8 - h_1)$$

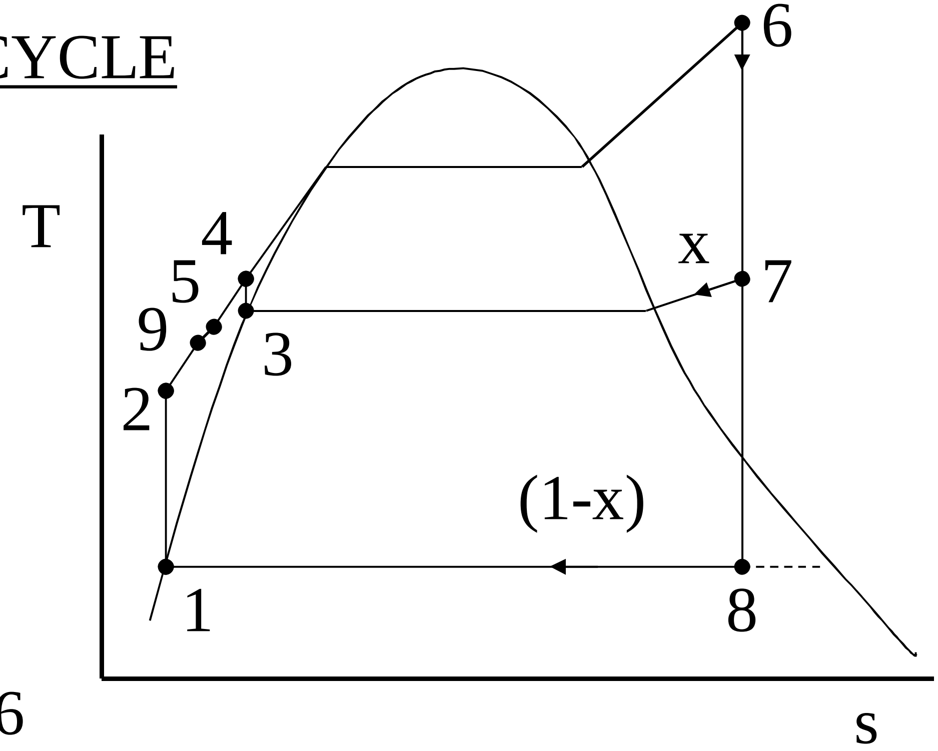
$$W_{pump} = (1-x)\times(h_2 - h_1) + x\times(h_4 - h_3)$$

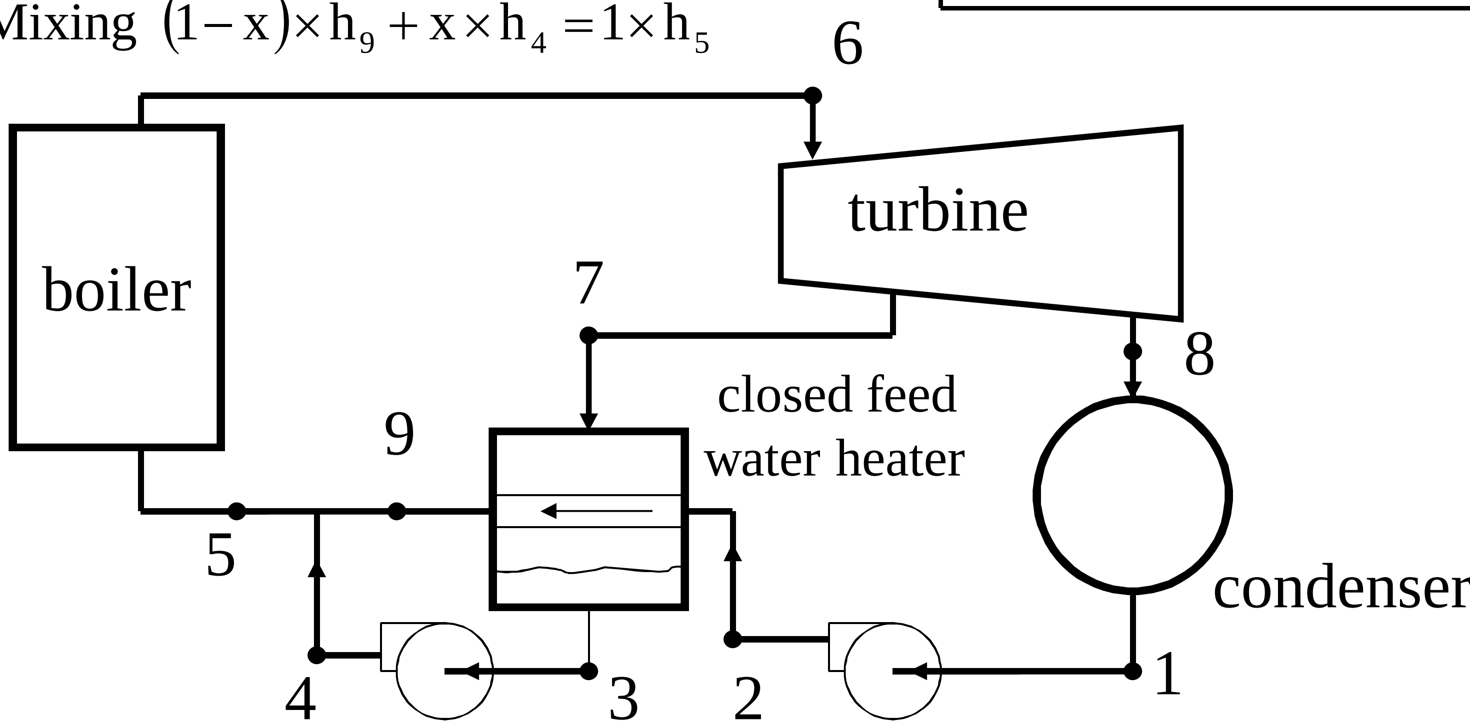
$$W_{turbine} = 1\times(h_6 - h_7) + (1-x)\times(h_7 - h_8)$$

Energy Balances

Heater $(1-x)\times(h_9 - h_2) = x\times(h_7 - h_3)$

Mixing $(1-x)\times h_9 + x\times h_4 = 1\times h_5$

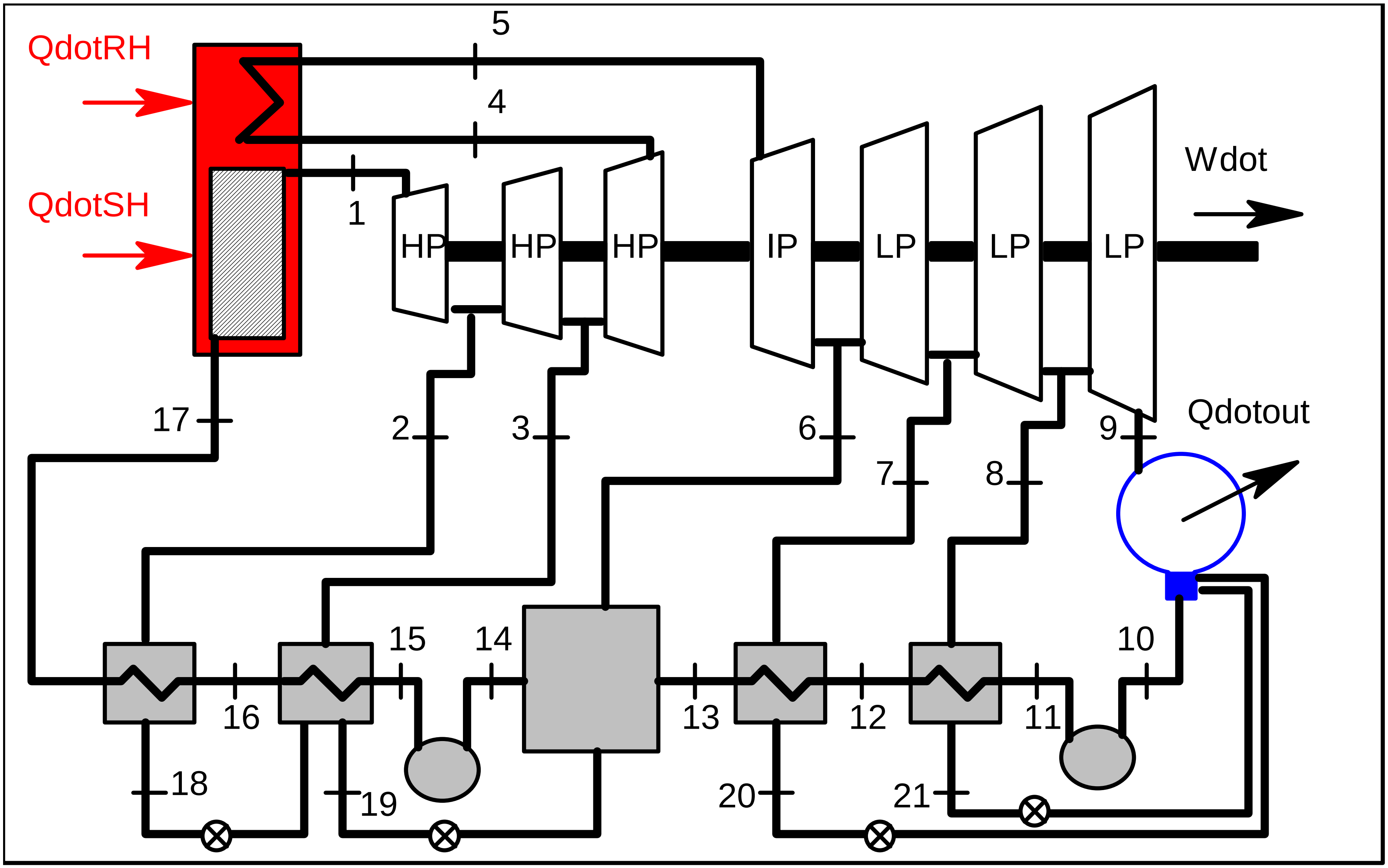




Regenerative, Reheat Rankine Cycle _similar to Figure 8-12, page 374

2 high pressure feed water heaters, 2 low pressure feed water heaters

1 open feed water heater, 1 stage of reheat



<u>OPEN CYCLE ANALYSIS TOOL KIT</u>

1. **Properties**
   - Ideal Gas
   - Gas Tables
   - Fluid Properties- steam, refrigerant tables
2. **Processes**
3. **Energy Balances (First Law)**
4. **<u>Component</u> Performance**
   - Turbine Efficiency
   - Compressor Efficiency
   - Heat Exchanger Effectiveness
   - Approach Temperature
5. **<u>Cycle</u> Performance**
   - Cycle Efficiency
   - Carnot Efficiency
   - Cycle COP
   - Carnot COP

1. PROPERTIES

IDEAL GAS $v = \frac{RT}{p}, \quad V = m\frac{RT}{p}$ (3-10)

$$u = c_v \int dT = c_v (T_2 - T_1) \qquad (4\text{-}25)$$

$$h = c_p \int dT = c_p (T_2 - T_1) \qquad (4-26)$$

$$s_2 - s_1 = c_v \ln\left(\frac{T_2}{T_1}\right) + R \ln\left(\frac{v_2}{v_1}\right) \qquad (7\text{-}33)$$

$$s_2 - s_1 = c_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{p_2}{p_1}\right) \qquad (7-34)$$

GAS TABLE, A – 17, A – 17E

h, u, s^o, p_r, v_r as functions of Absolute Temperature

$$v = \frac{RT}{p}, \quad V = m\frac{RT}{p}$$

$$\frac{p_{r1}}{p_{r2}} = \frac{p_1}{p_2}, \quad (7\text{-}49) \qquad \frac{v_{r1}}{v_{r2}} = \frac{v_1}{v_2} = \frac{V_1}{V_2} \quad (7\text{-}50)$$

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

$$s_2 - s_1 = s^0(T_2) - s^0(T_1) - R \ln\left(\frac{p_2}{p_1}\right) \qquad (7-39)$$

FLUID PROPERTIES - steam, R – 134a

Pressure Table -

v, u, h, s, T as functions of Pressure

Temperature Table -

v, u, h, s, P as functions of Temperature

$$ű = ű_f + x \times ű_{fg} \qquad (3-4)$$

$$x = \frac{ű - ű_f}{ű_{fg}} \qquad (3\text{-}5)$$

where ű can be v, u, h or s

quality, $x = \frac{m_g}{m}$ (3 – 3)

Superheat Table -

v, u, h, and s, as functions of T and p

Compressed Liquid Table -

v, u, h, and s, as functions of T and p

2.PROCESSES

ISENTROPIC PROCESS –

Adiabatic, $Q = 0$, $\varphi S = 0$, Reversible

Ideal Gas $- pv^k = \text{constant}$

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1} \quad (7\text{-}42)$$

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} \quad (7\text{-}43)$$

$$\frac{p_2}{p_1} = \left(\frac{v_1}{v_2}\right)^{k} \quad (7-44)$$

Real Gas

$s_1 = s_2$

3. ENERGY BALANCES

Open Systems

Steady Flow Equation form of First Law

$$Q = m \times \varphi(u + pv + \frac{V^2}{2} + \jmath\, gh) + W_{shaft} \quad (5\text{-}38)$$

Open adiabatic systems with $Q = 0$,

turbines, compressors (5-40)

$H_{in} = H_{out} + W$, $\quad W = m \times (h_1 - h_2)$

pumps

$W = m \times (h_1 - h_2) = v(p_2 - p_1)$

Open systems with $W = 0$,

heat exchangers, boiler, condensers,

feed water heaters

$H_{in} = H_{out} + Q$, $\quad Q = m \times (h_1 - h_2)$

Open systems with W and $Q = 0$,

throttling process, valves

$H_{in} = H_{out}$, $\quad h_1 = h_2$

Heat Exchangers

$\varphi Q_{cold\ fluid} = \varphi Q_{hot\ fluid}$

$m_{cold} \times (h_{cold\ out} - h_{cold\ in}) = m_{hot} \times (h_{hot\ out} - h_{hot\ in})$

Mixing

$m_1 + m_2 = m_3$

$m_1 h_1 + m_2 h_2 = m_3 h_3$

For Cycle

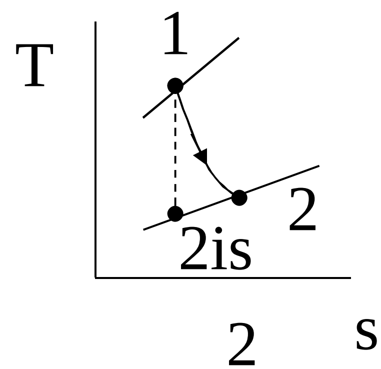
$$\sum_{cycle} Q = \sum_{cycle} W \qquad d_{cycle} = \frac{W_{net}}{Q_{in}}$$

4. COMPONENT PERFORMANCE

TURBINE EFFICIENCY

$$\eta_{TURBINE} = \frac{W_{actual}}{W_{isentropic}} \qquad (7-60)$$

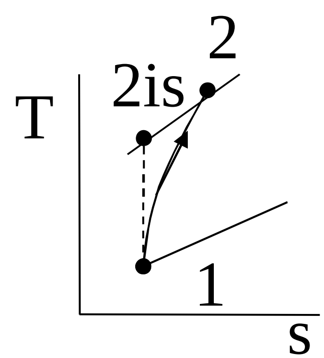
$$\eta_{TURBINE} = \frac{h_1 - h_2}{h_1 - h_{2\,isentropic}} \qquad (7-61)$$



COMPRESSOR AND PUMP EFFICIENCY

$$\eta_{COMPRESSOR} = \frac{W_{isentropic}}{W_{actual}} \qquad (7-62)$$

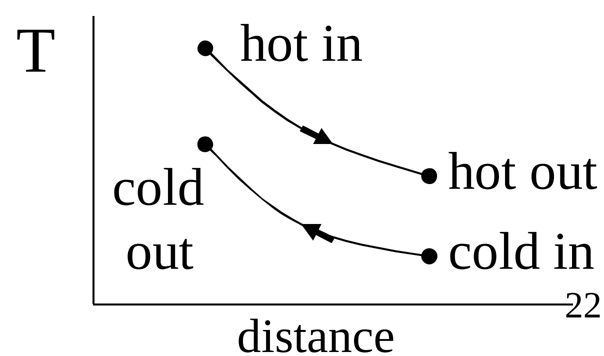
$$\eta_{COMPRESSOR} = \frac{h_{2\,isentropic} - h_1}{h_2 - h_1} \qquad (7-63)$$



HEAT EXCHANGER EFFECTIVENESS

$$\varepsilon = \frac{\text{Actual Q}}{\text{Maximum Q}} \qquad (5-23)$$

$$\varepsilon = \frac{h_{hot\ in} - h_{hot\ out}}{h_{hot\ in} - h_{cold\ in}} = \frac{h_{cold\ out} - h_{cold\ in}}{h_{hot\ in} - h_{cold\ in}} \qquad (5-23)$$



APPROACH TEMPERATURE

$T_{hot\ in} - T_{cold\ out}$ and $T_{hot\ out} - T_{cold\ in}$

5. CYCLE PERFORMANCE

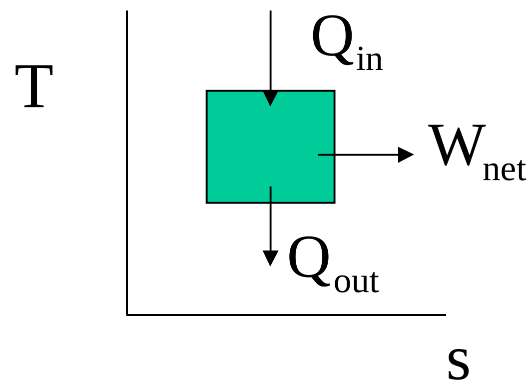
CYCLE EFFICIENCY

$$W = Q_{in} - Q_{out}$$

$$\eta_{CYCLE} = \frac{W_{net}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}}$$

$$\eta_{CYCLE} = 1 - \frac{Q_{out}}{Q_{in}} \qquad (6-5)$$

$$\eta_{\substack{CARNOT\\CYCLE}} = \frac{T_H - T_L}{T_H} = 1 - \frac{T_L}{T_H} \qquad (6\text{-}18)$$



CYCLE COEFFICIENT OF PERFORMANCE

$$COP_{refrigeration} = \frac{Q_{in}}{W} = \frac{Q_{in}}{Q_{in} - Q_{out}} \qquad (6\text{-}9)$$

$$COP_{heatpump} = \frac{Q_{out}}{W} = \frac{Q_{out}}{Q_{in} - Q_{out}} \qquad (6-11)$$

$$COP_{\substack{CARNOT\\refrigeration}} = \frac{T_L}{T_H - T_L} \qquad (6-20)$$

$$COP_{\substack{CARNOT\\heat\ pump}} = \frac{T_H}{T_H - T_L} \qquad (6-21)$$