Lebanese university

Faculty of engineering

Branch I

Energy Production project

I. Given:

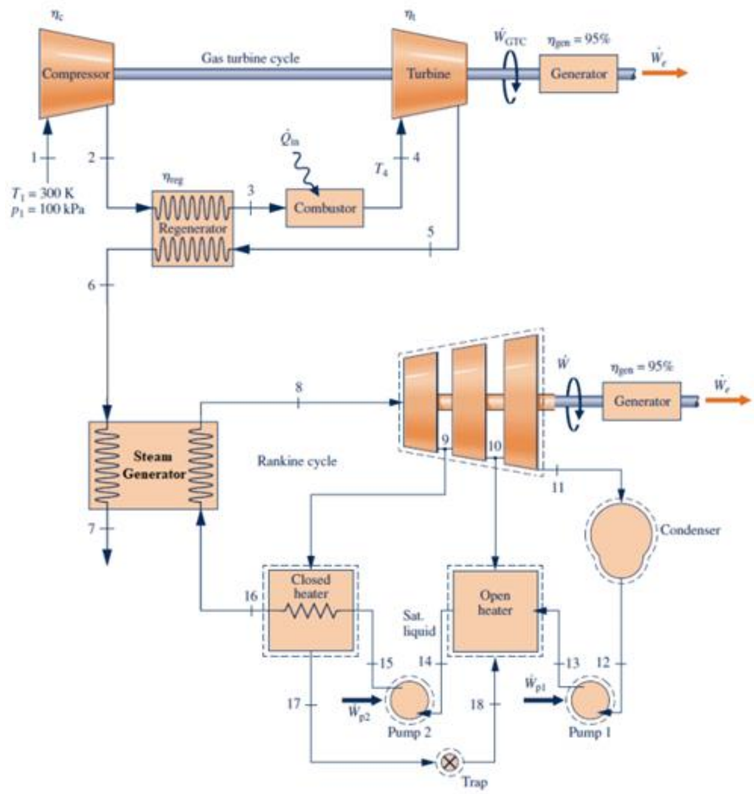
1. Gas power cycle parameters:

- Gas turbine electric power=200 MW
- $\eta_{is,comp} = 83\%$ $\eta_{is,Turb} = 73\%$
- The compressor compression ratio: $r_c = 9.2$
- The turbine expansion ratio: $r_{tur} = 8.6$
- The regenerator effectiveness: $\eta_{reg} = 78\%$
- Fuel: gas
- Heating value: 44400 KJ/Kg
- Excess of air=140 %
- Gas composition on mass basis: C=61% ; H=31% ; O=6.7% ; S=1.3%

2. For Rankine cycle

- P_8=50 bar
- T_8=370 °C
- T_{cond}=24
- Efficiency of the boiler: $\eta_{boiler} = 86\%$

II. Part A:



1. The air-fuel ratio in the first combustor:

Gas composition on mass:

$$\begin{cases} C = 61\% \\ H = 31\% \\ O = 6.7\% \\ S = 1.3\% \end{cases}$$

for 1 Kg of fuel:

the complete combustion:

$$\left[\frac{0.61}{12}\,C + 0.31\,H + \frac{0.067}{16}\,O + \frac{0.013}{32}\,S\right] + A[O_2 + 3.762N_2] \rightarrow B\,CO_2 + D\,H_2O + E\,N_2 + F\,SO_2$$

Balance:

$$"C": \frac{0.61}{12} = B \ \Rightarrow B = 0.05083$$

$$"H": 0.31 = 2D \ \Rightarrow D = 0.155$$

$$"S": \frac{0.013}{32} = F \ \Rightarrow F = 4.0625 * 10^{-4}$$

$$"O": \frac{0.067}{16} + 2A = 2B + D + 2F \ \Rightarrow A = 0.12665$$

$$"\mathrm{N_2}": A * 3.762 = E \ \Rightarrow E = 0.4764$$

Thus, the air fuel ratio is

$$[\frac{A}{F}]_{stoe} = \frac{n_{O_2} * M_{O_2}}{\% O_2} \cdot \frac{1}{m_{fuel}} = \frac{0.12665*32}{0.23} \cdot \frac{1}{m_{fuel}} = 17.62\ Kg_{air}/Kg_{fuel}$$

$$\%\ Excess\ of\ air = \frac{\left[\frac{A}{F}\right]_{real} - \left[\frac{A}{F}\right]_{stoe}}{\left[\frac{A}{F}\right]_{stoe}} * 100 = 140$$

$$\Rightarrow \frac{\left[\frac{A}{F}\right]_{real} - 17.62}{17.62} * 100 = 140 \Rightarrow \left[\frac{A}{F}\right]_{real} = 42.288\ Kg_{air}/Kg_{fuel}$$

2. The adiabatic flame temperature (T_4), T_3, T_5, T_6 and thermal efficiency of Brayton cycle:

To calculate the adiabatic flame temperature, we use the formula:

$$H.H.V. = m_{dfg} * \overline{Cp}_{dfg} * (T_F - T_{st}) + m_{H_2O} * h_{fg}$$

The mass of fuel gases per 1 Kg of fuel:

$$m_{fg} = m_{fuel} + m_{air} = 1 + 42.288 = 43.288\ \ Kg_{air}/Kg_{fuel}$$

the complete combustion:

$$\left[\frac{0.61}{12}\ C + 0.31\ H + \frac{0.067}{16}\ O + \frac{0.013}{32}\ S\right] + A_1[O_2 + 3.762N_2]$$
$$\rightarrow B\ CO_2 + D\ H_2O + E_1\ N_2 + F\ SO_2 + G\ O_2$$

Balance:

$$B = 0.05083 \quad D = 0.155 \quad F = 4.0625 * 10^{-4}$$

$$A_1 = 2.4 * A = 2.4 * 0.12665 \Rightarrow A_1 = 0.304$$

$$\text{"O"}: \frac{0.067}{16} + 2A_1 = 2B + D + 2F + 2G \Rightarrow G = 0.177$$

$$\text{"N}_2\text{"}: A_1 * 3.762 = E_1 \Rightarrow E_1 = 1.144$$

$$\frac{P_{\mathrm{H}_2O}}{P_{flue\ gases}} = \frac{n_{\mathrm{H}_2O}}{n_{flue\ gases}}$$

$$= \frac{0.155}{0.05083 + 0.155 + 1.144 + 4.0625 * 10^{-4} + 0.177}$$

$$\Rightarrow \frac{P_{\mathrm{H}_2O}}{P_{flue\ gases}} = 0.1015$$

We have $P_2 = P_3 = P_{flue\ gases} = 9.2\ bar$

$$\Rightarrow P_{\mathrm{H}_2O} = 0.1015 * 9.2 = 0.9338\ bar$$

From thermodynamic tables:

$$\frac{h_{fg} - 2265.7}{0.9338 - 0.9} = \frac{2258 - 2265.7}{1 - 0.9} \Rightarrow h_{fg} = 2263.1\ KJ/Kg$$

Finally, we can begin the iterative procedure:

$$H.H.V. = m_{dfg} * \overline{Cp}_{dfg} * (T_F - T_{st}) + m_{H_2O} * h_{fg}$$

$$m_{H_2O} = 0.155 * 18 = 2.79\ \ Kg_{H_2O}/Kg_{fuel}$$

$$\Rightarrow 44400 - 2.79 * 2263.1 = 43.288\,\overline{Cp}_{dfg} * \left(T_g - 300\right)$$

$$\Rightarrow 38085.951 = 43.288\,\overline{Cp}_{dfg} * \left(T_g - 300\right)$$

$$\overline{Cp}_{dfg} = \sum m_{fi} * Cp_i$$

Substance	n	M	m	m_{fi}
CO_2	0.05083	44	2.236	0.0523
H_2O	0.155	18	2.79	0.0653
O_2	0.177	32	5.664	0.133

N_2	1.144	28	32.032	0.749
SO_2	4.0625*10^-4	64	0.026	6.082*10^-4
$\sum$			42.748	1

	mfi	$T_g = 1000\ K$	$T_g = 1100\ K$
CO_2	0.0523	1.238	1.2637
H_2O	0.0653	2.2862	2.354
O_2	0.133	1.085	1.0997
N_2	0.749	1.1645	1.1849
SO_2	6.082*10^-4	0.8511	0.8621
		Cp=1.231	Cp=1.254
2nd term of the equation		37301.3	43426.52

By interpolation: $T_g = \frac{38085.951-43426.52}{37301.3-43426.52} * (1000-1100) + 1100$

$$\Rightarrow T_g = T_4 = 1012.81\ K$$

$$T_1 = 300\ K \qquad P_1 = 100\ KPa = 1\ bar$$

The compression ratio: $r_c = \frac{P_2}{P_1} = 9.2 \ \Rightarrow P_2 = 9.2\ bar$

$$\frac{T_{2s}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = 1.885 \ \Rightarrow T_{2s} = 565.5\ K$$

$$\eta_{is,comp} = \frac{T_{2s} - T_1}{T_2 - T_1} = 0.83 \Rightarrow \frac{565.5 - 300}{T_2 - 300} = 0.83 \Rightarrow T_2 = 619.88\ K$$

The expansion ratio: $P_2 = P_3 = P_4 = 9.2\ bar$

$$r_{turb} = \frac{P_4}{P_5} = 8.6 \ \Rightarrow P_5 = 1.07\ bar$$

$$\frac{T_{5s}}{T_4} = \left(\frac{P_5}{P_4}\right)^{\frac{k-1}{k}} = 0.5407 \ \Rightarrow T_{5s} = 547.63\ K$$

$$\eta_{is,turbine} = \frac{T_4 - T_5}{T_4 - T_{5s}} = 0.73 \Rightarrow T_5 = 673.21\ K$$

The effectiveness of the regenerator: $\eta_{reg.} = 0.78$

$$\eta_{reg.} = \frac{h_3 - h_2}{h_5 - h_2} = \frac{Cp(T_3 - T_2)}{Cp(T_5 - T_2)} \Rightarrow T_3 = 661.48\ K$$

At the regenerator:

$$\dot{m}_{air}(h_3 - h_2) = \dot{m}_{fg}(h_5 - h_6) \Rightarrow \dot{m}_{air}Cp_{air}(T_3 - T_2) = \dot{m}_{fg}Cp_{fg}(T_5 - T_6)$$

$$\Rightarrow T_5 - T_6 = \frac{\dot{m}_{air}Cp_{air}}{\dot{m}_{fg}Cp_{fg}}(T_3 - T_2)$$

With $\frac{\dot{m}_{fg}}{\dot{m}_{air}} = \frac{\dot{m}_{fuel}+\dot{m}_{air}}{\dot{m}_{air}} = 1 + \frac{\dot{m}_{fuel}}{\dot{m}_{air}} = 1 + \frac{1}{42.288} = 1.024$

$$\Rightarrow T_5 - T_6 = \frac{1}{1.024} * \frac{1.005}{1.234} * (661.48 - 619.88) = 41.612$$

$$\Rightarrow T_6 = 640.124\ K$$

The Brayton cycle efficiency:

$$\eta_{th,Brayton} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$$

$$\dot{Q}_{in} = \left(\dot{m}_{fuel} + \dot{m}_{air}\right)Cp_{fg}(T_4 - T_3) = \dot{m}_{fg}Cp_{fg}(T_4 - T_3)$$

And $\dot{W}_{net} = \dot{m}_{fg}Cp_{fg}(T_4 - T_5) - \dot{m}_{air}Cp_{air}(T_2 - T_1)$

$$= \dot{m}_{fg}\left[Cp_{fg}(T_4 - T_5) - \frac{\dot{m}_{air}}{\dot{m}_{fg}}Cp_{air}(T_2 - T_1)\right]$$

$$= \dot{m}_{fg}\left[1.234(T_4 - T_5) - \frac{1.005}{1.024}Cp_{air}(T_2 - T_1)\right]$$

$$\dot{W}_{net} = 105.1214\dot{m}_{fg}$$

$$\eta_{th,Brayton} = \frac{105.1214\dot{m}_{fg}}{433.54\dot{m}_{fg}} = 24.3\ \%$$

3. <u>The fuel mass flow rate and the flue gases mass flow rate for the specified electric power:</u>

$$\dot{W}_{net} = \frac{P_{elec}}{\eta_{gen.}} = \frac{200}{0.95} = 210.526\ MW$$

$$\dot{W}_{net} = 105.1214\dot{m}_{fg} = 210.526 * 10^3$$

$$\Rightarrow \dot{m}_{fg} = 2002.7\ Kg/s$$

$$\frac{\dot{m}_{fg}}{\dot{m}_{air}} = 1.024 \Rightarrow \dot{m}_{air} = 1955.76\ Kg/s$$

$$\dot{m}_{fg} = \dot{m}_{air} + \dot{m}_{fuel} \Rightarrow \dot{m}_{fuel} = 46.8\ Kg/s$$

4. <u>Combined thermal efficiency:</u>

$$P_8 = 50\ bar \qquad T_8 = 370℃ \qquad (state\ 8)$$

From the thermodynamic table (table A-3) → the state 8 is superheated vapor

So, from table A-4 and by interpolation:

For P=40 bar: $\frac{h-3117.2}{370-360} = \frac{3213.6-3117.2}{400-360} \Rightarrow h = 3141.3\ KJ/Kg$

$$\frac{s-6.6215}{370-360} = \frac{6.769-6.6215}{400-360} \Rightarrow s = 6.6584\ KJ/Kg.K$$

For P=60 bar: $\frac{h-3071.1}{370-360} = \frac{3177.2-3071.1}{400-360} \Rightarrow h = 3097.625\ KJ/Kg$

$$\frac{s-6.3782}{370-360} = \frac{6.5408-6.3782}{400-360} \Rightarrow s = 6.41885\ KJ/Kg.K$$

For $P = P_8 = 50\ bar$

$$\frac{h_8-3141.3}{50-40} = \frac{3097.625-3141.3}{60-40} \Rightarrow h_8 = 3119.46\ KJ/Kg$$

$$\frac{s_8-6.6584}{50-40} = \frac{6.41885-6.6584}{60-40} \Rightarrow s_8 = 6.5386\ KJ/Kg.K$$

State 9:

$$\Delta T_{opt} = \frac{T_{B,Sat} - T_{C,sat}}{n+1}$$

With $P_8 = 50bar = P_{boiler} \rightarrow T_{B,sat} = 264$ ℃ (from table A-3)

And n: is the number of feed water heater in the cycle. (n=2)

$$\Rightarrow \Delta T_{opt} = \frac{264-24}{2+1} = 80℃$$

$$T_{opt} = T_9 = T_{B,sat} - \Delta T_{opt} = 264 - 80 = 184\ ℃$$

From table A-2: (at $T = T_{opt}$)

By interpolation:

$$\frac{P_9 - 10.02}{184-180} = \frac{12.54-10.02}{190-180} \Rightarrow P_9 = 11.028\ bar$$

$$\frac{s_g - 6.5863}{11.028-10} = \frac{6.4448-6.5863}{15-10} \Rightarrow s_g = 6.557\ KJ/Kg.K$$

$$s_g > s_8 = 6.5386\ KJ/Kg.K\ \Rightarrow\ inside\ \ the\ dome$$

$$\frac{s_f - 2.1396}{184-180} = \frac{2.2359-2.1396}{190-180} \Rightarrow s_f = 2.178\ KJ/Kg.K$$

$$x_9 = \frac{s_9 - s_f}{s_g - s_f} \qquad\qquad with\ s_8 = s_9$$

$$x_9 = \frac{6.5386-2.178}{6.5572-2.178} \Rightarrow x_9 = 0.996$$

$$x_9 = \frac{h_9 - h_f}{h_{fg}} \qquad with\ \frac{h_f - 763.22}{184-180} = \frac{807.62-763.22}{190-180} \Rightarrow h_f = 780.98KJ/Kg$$

And $\frac{h_f g - 72015}{184-180} = \frac{1978.8-2015}{190-180} \Rightarrow h_{fg} = 2000.52KJ/Kg$

$$\frac{h_9 - 780.98}{2000.52} = 0.996 \quad \Rightarrow h_9 = 2773.5\ KJ/Kg$$

State 16:

$$TTD = T_{opt,9} - T_{16} \Rightarrow T_{16} = T_{opt,9} - TTD$$

$$\left.\begin{array}{l}\Rightarrow T_{16} = 184 + 7 = 191℃ \\ \quad P_{16} = P_8 = 50\ bar\end{array}\right\} \Rightarrow compressed\ liquid\ water$$

$$\frac{h_{16} - 765.25}{191 - 180} = \frac{853.9 - 765.25}{200 - 180} \quad \Rightarrow h_{16} = 814\ KJ/Kg$$

State 10:

$$T_{10(opt)} = T_9 - \Delta T_{opt} = 184 - 80 = 104\ ℃$$

From table A-2:

$$\frac{P_{10} - 1.014}{104 - 100} = \frac{1.433 - 1.014}{110 - 100} \quad \Rightarrow P_{10} = 1.182\ bar$$

$$\frac{s_g - 7.3549}{104 - 100} = \frac{7.2387 - 7.3549}{110 - 100} \quad \Rightarrow s_g = 7.308\ KJ/Kg\ .K$$

$$s_g > s_8 = s_{10} \quad \Rightarrow inside\ the\ dome$$

$$\frac{s_f - 1.3069}{104 - 100} = \frac{1.4185 - 1.3069}{110 - 100} \quad \Rightarrow s_f = 1.352\ KJ/Kg.K$$

$$x_{10} = \frac{s_{10} - s_f}{s_g - s_f} = \frac{6.5386 - 1.352}{7.308 - 1.352} = 0.871$$

$$\frac{h_f - 419.04}{104 - 100} = \frac{461.3 - 419.04}{110 - 100} \quad \Rightarrow h_f = 435.944\ KJ/Kg$$

$$\frac{h_{fg} - 2257}{104 - 100} = \frac{2230.2 - 2257}{110 - 100} \quad \Rightarrow h_{fg} = 2246.28\ KJ/Kg$$

$$x_{10} = \frac{h_{10} - h_f}{h_{fg}} = 0.871 \Rightarrow \frac{h_{10} - 435.944}{2246.28} = 0.871 \Rightarrow h_{10} = 2392.454\ KJ/Kg$$

For the pump 2:

$$P_{14} = P_{10} = 1.182\ bar$$

State 14: (Saturated liquid)

By interpolation from table A-3:

$$\frac{T_{14} - 99.63}{1.182 - 1} = \frac{111.4 - 99.63}{1.5 - 1} \quad \Rightarrow T_{14} = 103.914\ K$$

$$\frac{h_{14} - 417.46}{1.182 - 1} = \frac{467.11 - 417.46}{1.5 - 1} \quad \Rightarrow h_{14} = 435.53\ KJ/Kg$$

$$\frac{v_{14} - 1.0432 * 10^{-3}}{1.182 - 1} = \frac{(1.0528 - 1.0432) * 10^{-3}}{1.5 - 1}$$

$\Rightarrow v_{14} = 1.047 * 10^{-3}\ m^3/s$

The pump is an adiabatic pump so its work is expressed by:

$$v_{14}(P_{15} - P_{14}) = h_{15} - h_{14}$$

With $P_{15} = P_{16} = 50\ bar$

$\Rightarrow h_{15} = h_{14} + v_{14}(P_{15} - P_{14}) = 435.53 + 1.047 * 10^{-3} * (50 - 1.182) * 10^2$

$\Rightarrow h_{15} = 440.64 \frac{KJ}{Kg} < h_{f_{P=50bar}} = 1154.2 \frac{KJ}{Kg} \Rightarrow compressed\ liquid$

From table A-5:

$$\frac{T_{15} - 100}{440.64} = \frac{140 - 100}{592.15 - 422.72} \quad \Rightarrow T_{15} = 104.23\ K$$

State 17:

$DC = T_{17} - T_{15} \Rightarrow T_{17} = 7 + 104.23 \Rightarrow T_{17} = 111.23\ ℃$

$$P_{17} = P_9 = 11.028\ bar\ \rightarrow Subcooled\ water$$

From table A-2:

$$\frac{h_{17} - 461.3}{111.23 - 110} = \frac{503.71 - 461.3}{120 - 110} \quad \Rightarrow h_{17} = h_{f_{P=11.028bar}} = 466.52\ KJ/Kg$$

$$\Rightarrow h_{17} = h_{18} = 466.52\ KJ/Kg$$

$$T_{cond} = T_{12} = 24℃\ \rightarrow from\ table\ A-2: P_{12} = 0.02985\ bar$$

$$h_{12} = h_f = 100.7\ KJ/Kg$$

$$v_{12} = v_f = 1.0027 * 10^{-3}\ m^3/s$$

$$s_{11} = s_8 = 6.5386\ \ KJ/Kg.K$$

$$P_{11} = P_{12} \rightarrow \begin{cases} s_g = 8.5794\ KJ/Kg.K \\ s_f = 0.3534\ KJ/Kg.K \end{cases} \rightarrow inside\ the\ dome$$

$$h_f = 100.7\ KJ/Kg \qquad\qquad h_{fg} = 2444.7\ KJ/Kg$$

$$x_{11} = \frac{s_{11} - s_f}{s_g - s_f} = \frac{6.5386 - 0.3534}{8.5794 - 0.3534} = 0.752$$

$$x_{11} = \frac{h_{11} - h_f}{h_{fg}} = 0.752 \Rightarrow \frac{h_{11} - 100.7}{2444.7} = 0.752 \Rightarrow h_{11} = 1939.11\ KJ/Kg$$

For the pump 1:

$$v_{12}(P_{13} - P_{12}) = h_{13} - h_{12} \Rightarrow h_{13} = h_{12} + v_{12}(P_{13} - P_{12})$$
$$= 100.7 + 1.0027 * 10^{-3} * (1.182 - 0.02985) * 10^2$$

$$\Rightarrow h_{13} = 100.82\ KJ/Kg$$

Closed feedwater heater:

$$x(h_9 - h_{17}) = h_{16} - h_{15} \Rightarrow x = \frac{h_{16} - h_{15}}{h_9 - h_{17}} = \frac{814 - 440.64}{2773.5 - 466.52} \Rightarrow x = 0.1618$$

open feedwater heater:

$$(1 - x - y) * h_{13} + y * h_{10} + x * h_{18} = h_{14}$$

$$\Rightarrow y * (h_{10} - h_{13}) + (1 - x) * h_{13} + x * h_{18} = h_{14}$$

$$\Rightarrow y * (2392.454 - 100.82) + (1 - 0.1618) * 100.82 + 0.1618 * 466.52$$
$$= 435.53$$

$$\Rightarrow y = 0.1202$$

$$\eta_{boiler} = \frac{\dot{m}_{st}(h_8 - h_{16})}{\dot{m}_{fg} Cp_{fg}(T_6 - T_7)} = 0.86$$

With $T_7 = 170\ ℃$

$$\Rightarrow \dot{m}_{st}(3119.46 - 814) = 0.86 * 2002.7 * 1.234 * (640.124 - (170 + 273))$$

$$\Rightarrow 2305.46 * \dot{m}_{st} = 418956.57 \Rightarrow \dot{m}_{st} = 181.72\ Kg/s$$

$$\dot{W}_{vap,net} = \dot{W}_T - \dot{W}_{pump}$$

$$\dot{W}_T = \dot{W}_{T1} + \dot{W}_{T2} + \dot{W}_{T3}$$
$$= \dot{m}_{st}[(h_8 - h_9) + (1 - x)(h_9 - h_{10}) + (1 - x - y)(h_{10} - h_{11)}]$$

$$= 181.72[(3119.46 - 2773.5) + (1 - 0.1618)(2773.5 - 2392.454)$$
$$+ (1 - 0.1618 - 0.1202)(2392.454 - 1939.11)]$$

$$\Rightarrow \dot{W}_T = 180.06\ MW$$

$$\dot{W}_{pump} = \dot{W}_{P1} + \dot{W}_{P2} = \dot{m}_{st}[(1 - x - y)(h_{13} - h_{12}) + (h_{15} - h_{14})]$$

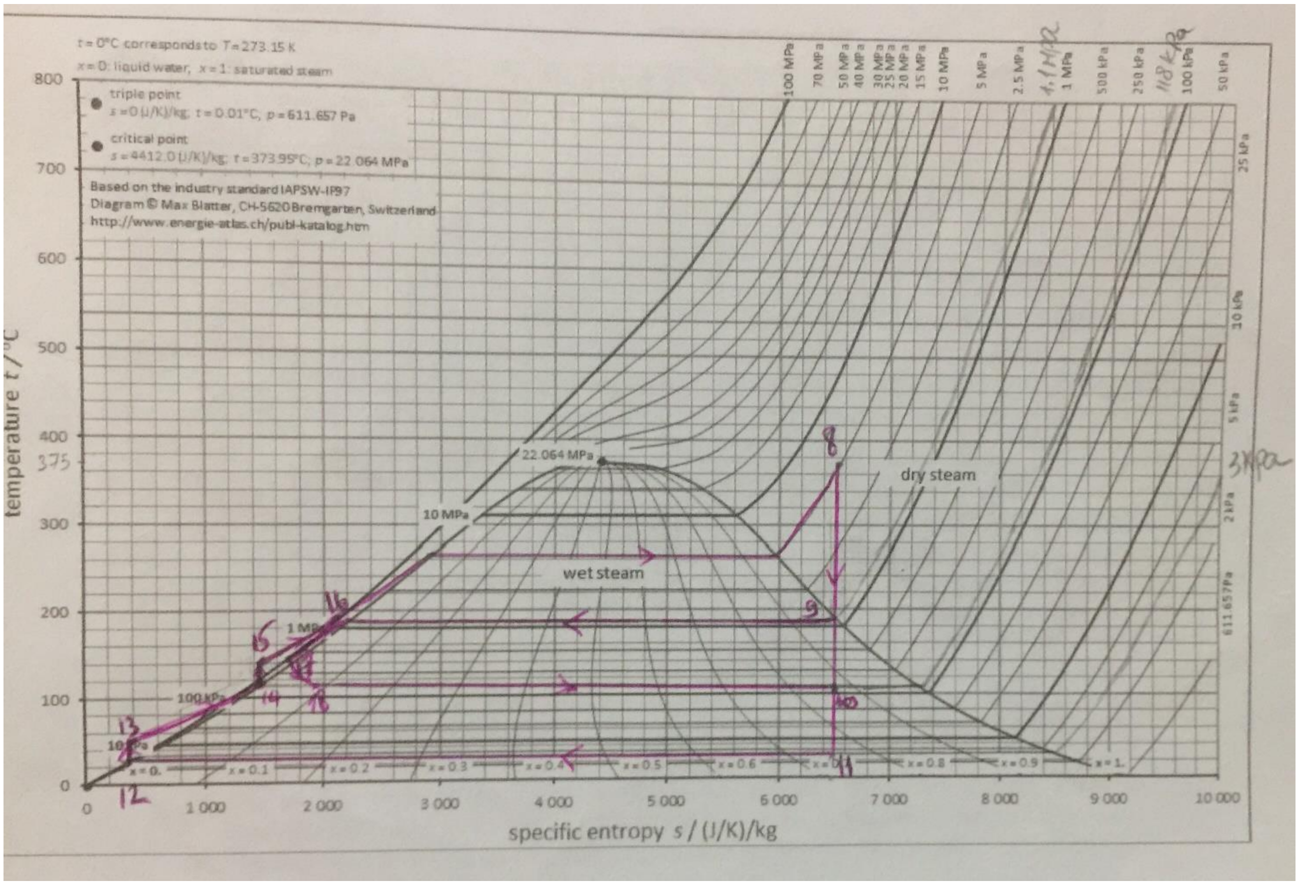
$$= 181.72[(1 - 0.1618 - 0.1202)(100.82 - 100.72) + (440.64 - 435.53)]$$

$$\Rightarrow \dot{W}_{pump} = 0.94\ MW$$

$$\Rightarrow \dot{W}_{vap,net} = 180.06 - 0.94 = 179.12\ MW$$

The efficiency of the combined cycle:

$$\eta_{C.C} = \frac{\dot{W}_{vap,net} + \dot{W}_{gas}}{\dot{Q}_{in}} = \frac{179.12 + 210.526}{787.7} = 49.5\%$$



1. Calculation on EES:

a) For the Brayton cycle:

"Gas composition on mass: C=61% , H=31% , O=6.7% , S=1.3%"

"The complete combustion(stoe)"

"[0.61/12 C+ 0.31H +0.067/16 O +0.013/32 S]+A[O_2 +3.762N_2] ---> B CO_2+D H_2O +EN_2 +F SO_2"

"Balance:"

"C" 0.61/12=B

"H" 0.31=2*D

"S" 0.013/32=F

"O" 0.067/16 +2*A=2*B+D+2*F

"N_2" A*3.762=E

"Air/Fuel stoe"

f_stoe=(A*MOLARMASS(O2))/0.23

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"Excess of air(%):" E_air=140


"Air/Fuel real"

f_real=f_stoe+(E_air*f_stoe)/100


"the mass of flue gases per 1Kg of fuel:"

m_fg=1+f_real


"The real reaction:"

"[0.61/12 C+ 0.31H +0.067/16 O +0.013/32 S] +A1[O_2 +3.762N_2] ---> B CO_2+D H_2O +E1 N_2 +F
SO_2+G O_2"

"Balance:"

A_1=2.4*A

"O" 0.067/16 +2*A_1=2*B+D+2*F+2*G

"N_2" A_1*3.762=E_1

P[1]=1

P[2]=P[1]*9.2

P_flueGases=P[2]

P_H2O=P_flueGases*(D/(B+D+E_1+F+G))

h_f=ENTHALPY(Steam,x=0,P=P_H2O)

h_g=ENTHALPY(Steam,x=1,P=P_H2O)

h_fg=(h_g)-(h_f)


"Calculation of the adiabatic flame T:"

HHV=44400

m_H2O=D*MOLARMASS(Water)

Cp_fg=1.234

T[1]=300
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m_fg*Cp_fg*(T[4]-T[1])=38085.951

"state2:"
r_c=9.2
T_2s/T[1]=(r_c)^(0.4/1.4)
n_isComp=0.83
T[2]=T[1]+(T_2s-T[1])/n_isComp

"state 5:"
r_tur=8.6
P[4]=P[2]
P[5]=P[4]/r_tur
T_5s/T[4]=(1/r_tur)^(0.4/1.4)
n_isTur=0.73
T[5]=T[4]-n_isTur*(T[4]-T_5s)

"state 3:"
"the effectiveness of the regenerator:"
n_reg=0.78
n_reg=(T[3]-T[2])/(T[5]-T[2])

"state 6:"
f_airFlueGases=1+1/f_real
T[5]-T[6]=((CP(Air,T=T[1])*1/f_airFlueGases)*1/Cp_fg)*(T[3]-T[2])
"efficiency of Brayton cycle:"
eff_Brayton=W_dot_net/Q_dot_in

"net work of the cycle:"
P_elec=200*10^3
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n_gen=0.95

W_dot_net=P_elec/n_gen

Q_dot_in=(m_dot_air+m_dot_fuel)*Cp_fg*(T[4]-T[3])


W_dot_net=m_dot_fg*Cp_fg*(T[4]-T[5])-m_dot_air*(CP(Air,T=T[1])*(T[2]-T[1]))

m_dot_air+m_dot_fuel=m_dot_fg

m_dot_fg/m_dot_air=f_airFlueGases
```

	1 P_i	2 T_i
[1]	1	300
[2]	9.2	620
[3]		661.6
[4]	9.2	1013
[5]	1.07	673.4
[6]		640.2

Unit Settings: [kJ]/[K]/[bar]/[kg]/[degrees]

$A = 0.1266$	$A_1 = 0.304$	$B = 0.05083$	$Cp_{fg} = 1.234$	$D = 0.155$	$E = 0.4764$	$eff_{Brayton} = 0.2408$
$E_1 = 1.143$	$E_{air} = 140$	$F = 0.0004063$	$f_{airFlueGases} = 1.024$	$f_{real} = 42.29$	$f_{stoe} = 17.62$	$G = 0.1773$
$HHV = 44400$	$h_f = 409.4$ [kJ/kg]	$h_{fg} = 2263$	$h_g = 2672$ [kJ/kg]	$\dot{m}_{air} = 1970$	$\dot{m}_{fg} = 2016$	$\dot{m}_{fuel} = 46.58$
$m_{fg} = 43.29$	$m_{H20} = 2.792$	$n_{gen} = 0.95$	$n_{isComp} = 0.83$	$n_{isTur} = 0.73$	$n_{reg} = 0.78$	$P_{elec} = 200000$
$P_{flueGases} = 9.2$	$P_{H20} = 0.9339$	$\dot{Q}_{in} = 874279$	$r_c = 9.2$	$r_{tur} = 8.6$	$T_{2s} = 565.6$	$T_{5s} = 547.8$
$\dot{W}_{net} = 210526$						

b) For the Rankine cycle:

```
TTD=-7
DC=7

"State 8:"
p[8]=50
T[8]=370
s[8]=ENTROPY(Steam,T=T[8],P=p[8])
h[8]=ENTHALPY(Steam,T=T[8],P=p[8])

"delta T optimum:"
T_boilerSat=T_SAT(Steam,P=p[8])
dt_optimum=(T_boilerSat-T[12])/3
s[9]=s[8]
T[9]=T_boilerSat-dt_optimum
P[9]=P_SAT(Steam,T=T[9])
x[9]=QUALITY(Steam,s=s[9],P=P[9])
h[9]=ENTHALPY(Steam,s=s[9],P=P[9])

"state 16:"
T[16]=T[9]-TTD
P[16]=P[8]
```

```
h[16]=ENTHALPY(Steam,T=T[16],P=P[16])

"State 10:"
T[10]=T[9]-dt_optimum
P[10]=P_SAT(Steam,T=T[10])
s[10]=s[8]
x[10]=QUALITY(Steam,s=s[10],P=P[10])
h[10]=ENTHALPY(Steam,s=s[10],P=P[10])

"for the pump 2 (state 14):"
P[14]=P[10]
T[14]=T_SAT(Steam,P=P[14])
h[14]=ENTHALPY(Steam,T=T[14],P=P[14])
v[14]=VOLUME(Steam,T=T[14],P=P[14])

"state 15:"
P[15]=P[16]
h[15]=h[14]+v[14]*(P[15]-P[14])*100
T[15]=TEMPERATURE(Steam,h=h[15],P=P[15])

"state 17:"
T[17]=DC+T[15]
P[17]=P[9]
h[17]=ENTHALPY(Steam,T=T[17],P=P[17])

"state 18:"
h[18]=h[17]

"state 12:"
T[12]=24
P[12]=P_SAT(Steam,T=T[12])
h[12]=ENTHALPY(Steam,x=0,P=P[12])
v[12]=VOLUME(Steam,x=0,P=P[12])

"state 11:"
s[11]=s[8]
P[11]=P[12]
x[11]=QUALITY(Steam,s=s[11],P=P[11])
h[11]=ENTHALPY(Steam,x=x[11],P=P[11])

"state 13:"
P[13]=P[10]
h[13]=h[12]+v[12]*(P[13]-P[12])*100
"the mass fraction:"
x*(h[9]-h[17])=h[16]-h[15]
(1-x-y)*h[13]+y*h[10]+x*h[18]=h[14]
"calculation of the mass of steam:"
eff_boiler=0.86
T[7]=170
T[6]=640.124-273
m_dot_fg=2002.7
Cp_fg=1.234
eff_boiler=(m_dot_steam*(h[8]-h[16]))/(m_dot_fg*Cp_fg*(T[6]-T[7]))
w_dot_net=W_dot_tur-W_dot_pump
W_dot_tur=m_dot_steam*((h[8]-h[9])+(1-x)*(h[9]-h[10])+(1-x-y)*(h[10]-h[11]))
W_dot_pump=m_dot_steam*((1-x-y)*(h[13]-h[12])+(h[15]-h[14]))
W_dot_gas=210.526*10^3
```

Q_dot_in=787.7*10^3
eff_combined=(W_dot_gas+W_dot_net)/Q_dot_in

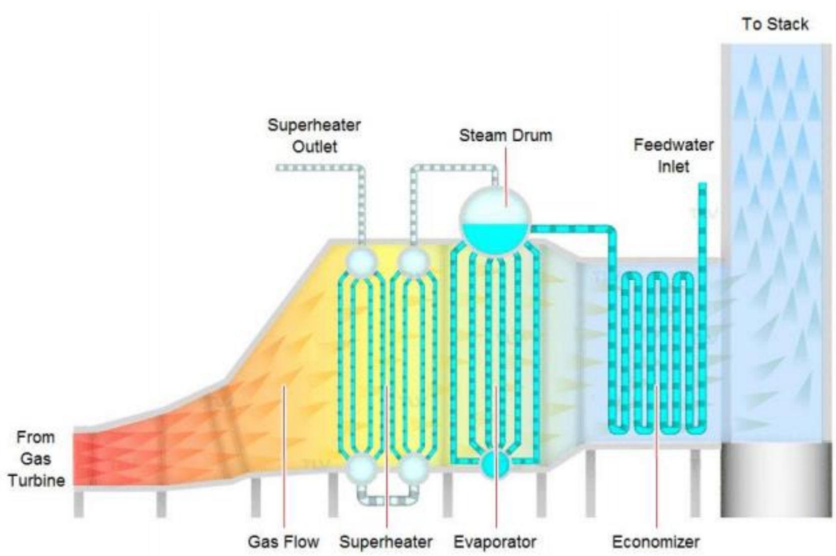
	1 h_i [kJ/kg]	2 p_i	3 s_i [kJ/kg-K]	4 T_i	5 x_i	6 v_i [m3/kg]
[6]				367.1		
[7]				170		
[8]	3120	50	6.531	370		
[9]	2771	10.97	6.531	184	0.9947	
[10]	2389	1.166	6.531	104	0.8696	
[11]	1936	0.02985	6.531		0.7512	
[12]	100.6	0.02985		24		0.001003
[13]	100.7	1.166				
[14]	435.8	1.166		104		0.001047
[15]	440.9	50		104.3		
[16]	813.7	50		191		

Unit Settings: [kJ]/[C]/[bar]/[kg]/[degrees]

Cp_{fg} = 1.234	DC = 7	$dt_{optimum}$ = 79.99	eff_{boiler} = 0.86	$eff_{combined}$ = 0.4953	$\dot{m}_{fg}$ = 2003	$\dot{m}_{steam}$ = 181.7	$\dot{Q}_{in}$ = 787700
TTD = -7	$T_{boilerSat}$ = 264 [C]	$\dot{W}_{gas}$ = 210526	$\dot{w}_{net}$ = 179638	$\dot{W}_{pump}$ = 943.2	$\dot{W}_{tur}$ = 180581	x = 0.1619	y = 0.1205

III. Part B:

1. Given:



The boiler bas the following specifications:
- Boiler efficiency (based on flue gases energy): η_{boiler}
- Evaporator steam exit is 100% dry.
- gas temperature at exit of economizer is minimum 170°C.

2. The steam cycle electric power and Tubes length:

$$P_{elec,steam} = \dot{W}_{vap,net}.\eta_{gen} = 179.12 * 0.95 = 170.16\ MW$$

$$10\% * \eta_{boiler} * \dot{m}_{fg} Cp_{fg}(T_6 - T_7) = \sigma.\varepsilon.A_r * \left(T_6{}^4 - T_w{}^4\right)$$

$$\Rightarrow 0.1 * 0.86 * 2002.7 * 1.234 * \big(640.124 - (170 + 273)\big) * 10^3$$
$$= 5.67 * 10^{-8} * 0.64 * A_r(640.124^4 - (310 + 273)^4)$$

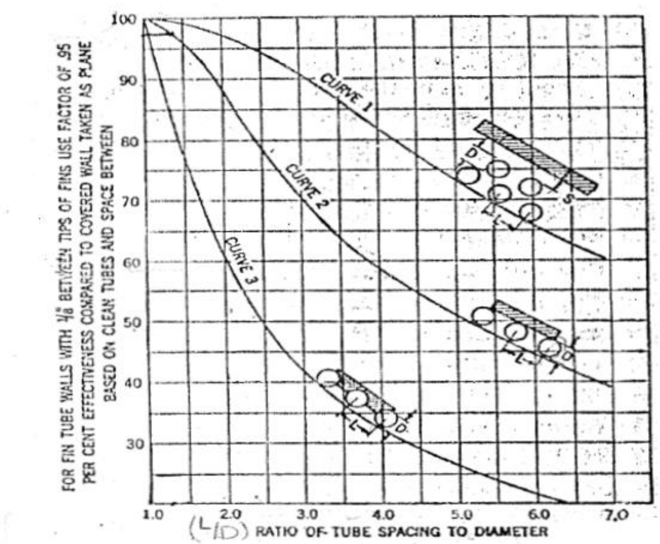
$$\Rightarrow A_r = 22042.5\ m^2$$

$$A_r = A_p * F_{comp}$$

With L/D=60/50=1.2 → $F_{comp} = 100\%\ (for\ the\ 1^{st} type\ tube)$

$A_p = D * L * N = L * 50 * 10^{-3} * 100 = 5L$

$$\Rightarrow L = 4.41\ Km$$



"Effectiveness" factors of bare-tube water walls.

- **Curve 1: Spaced tubes arrangement**
- **Curve 2: Tangent tubes arrangement**
- **Curve 3: Half-radiant tubes cast in refractory**

3. Gas temperature at the exit of each component:

$$T_7 = T_{g4}\ (T^{\circ}_{=}\ at\ the\ exit\ of\ the\ steam\ generator\ for\ the\ flue\ gases)$$

$$h_s = h_8 = 3119.46\ KJ/Kg \qquad T_{g1} = T_6 = 640.124\ K$$

$$h'' = h_{g_{p=50\ bar}} = 2794.3\ KJ/Kg$$

$$h_{eco} = h_{f_{p=50\ bar}} = 1154.2\ KJ/Kg$$

$$h_{fw} = h_{16} = 814\ KJ/Kg$$

Temperature of flue gases leaving the economizer (T_{g4}):

$$T_{g4} = T_{g3} - \frac{\dot{m}_s(h_{eco} - h_{fw})}{\dot{m}_{fg}cp_{fg}}$$

With $\dot{m}_s = \dot{m}_{SR} + \dot{m}_{SC}$ $\quad$ *and* $\quad \dot{m}_{SR} = 0.1\dot{m}_s$

$$\Rightarrow T_{g3} = (170 + 273) + \frac{\dot{m}_{SC}}{0.9} * \frac{1154.2 - 814}{2002.7 * 1.234}$$

$$\Rightarrow T_{g3} = 0.153 * \dot{m}_{SC} + 443$$

$$T_{g3} = T_{g2} - \frac{\dot{m}_{sc}(h_s - h'')}{\dot{m}_{fg}cp_{fg}} = T_{g2} - \frac{\dot{m}_{sc}(3119.46 - 2794.3)}{2002.7 * 1.234}$$

$$\Rightarrow T_{g3} = T_{g2} - 0.1316 * \dot{m}_{sc}$$

With

$$T_{g2} = T_{g1} - \frac{\dot{m}_{sc}(h'' - h_{eco})}{\dot{m}_{fg}cp_{fg}} = 640.124 - \frac{\dot{m}_{sc}(2794.3 - 1154.2)}{2002.7 * 1.234}$$

$$\Rightarrow T_{g2} = 640.124 - 0.664 * \dot{m}_{sc}$$

$$\Rightarrow T_{g3} = 640.124 - 0.664 * \dot{m}_{sc} - 0.1316 * \dot{m}_{sc} = 640.124 - 0.796 * \dot{m}_{sc}$$

$$\begin{cases} T_{g3} = 0.153 * \dot{m}_{SC} + 443 \\ T_{g3} = 640.124 - 0.796 * \dot{m}_{sc} \end{cases} \Rightarrow \begin{cases} \dot{m}_{SC} = 207.72\ Kg/s \\ T_{g3} = 474.78\ K \end{cases}$$

$$\Rightarrow T_{g2} = 640.124 - 0.664 * 207.72 \Rightarrow T_{g2} = 502.2\ K$$

4. Heat loss of flue gases in the chimney:

The heat loss of the flue gases in the chimney:

$$Heat\ loss = \dot{m}_{fg}Cp_{fg}\left(T_{g4} - T_{amb}\right) = \dot{m}_{fg}Cp_{fg}(T_7 - T_{amb})$$

And T_{amb} is to be assumed as 20 °C

$$\Rightarrow Heat\ loss = 2002.7 * 1.234(170 - 20) = 370700\ KW$$

- *What could be done to reduce it?*

Flue gas heat loss is due to the temperature of the gas leaving the furnace. The hotter the gas is in the stack, the less efficiently the boiler can perform.

The gas temperature can become too high if the burner generates more heat than is necessary for the load. That in turn, can damage parts of the machine. Gas can also overheat if heat transfer surfaces aren't working correctly. Most likely in this case, heat-transferring surfaces will need to be cleaned.

Flue gases shouldn't become too cool, though 'if they fall below the dew point, it could cause corrosion in the boiler. Arrange for a professional to check the flue gas outlet on a regular basis in order to avoid flue gas energy loss.

So, to reduce the heat loss of flue gases in the boiler we add a preheater between the economizer and chimney and it increase the thermal efficiency of the boiler by reducing the useful heat lost in the flue gas.

As a consequence, the flue gases are also conveyed to the flue gas stack (or chimney) at a lower temperature, allowing simplified design of the conveyance system and the flue gas stack. It also allows control over the temperature of gases leaving the stack (to meet emissions regulations, for example)

5. Power Plant efficiency:

The power plant efficiency:

$$\eta_{power\ plant} = \eta_{C.C} * \eta_{gen} = 49.5\% * 95\% = 47.03\%$$

- *What could be done to increase the power plant efficiency?*

The Heat Recovery Chimney can be recovered, and the air can be heated through a water-air heat exchanger and further accelerated through a converging thermal chimney to drive wind turbines which are coupled to a generator. The system produces little impacts of the environment. The implementation and use of the Heat Recovery Chimney will make the conventional steam power cycles more effective without adding much to the pollution of the original system.