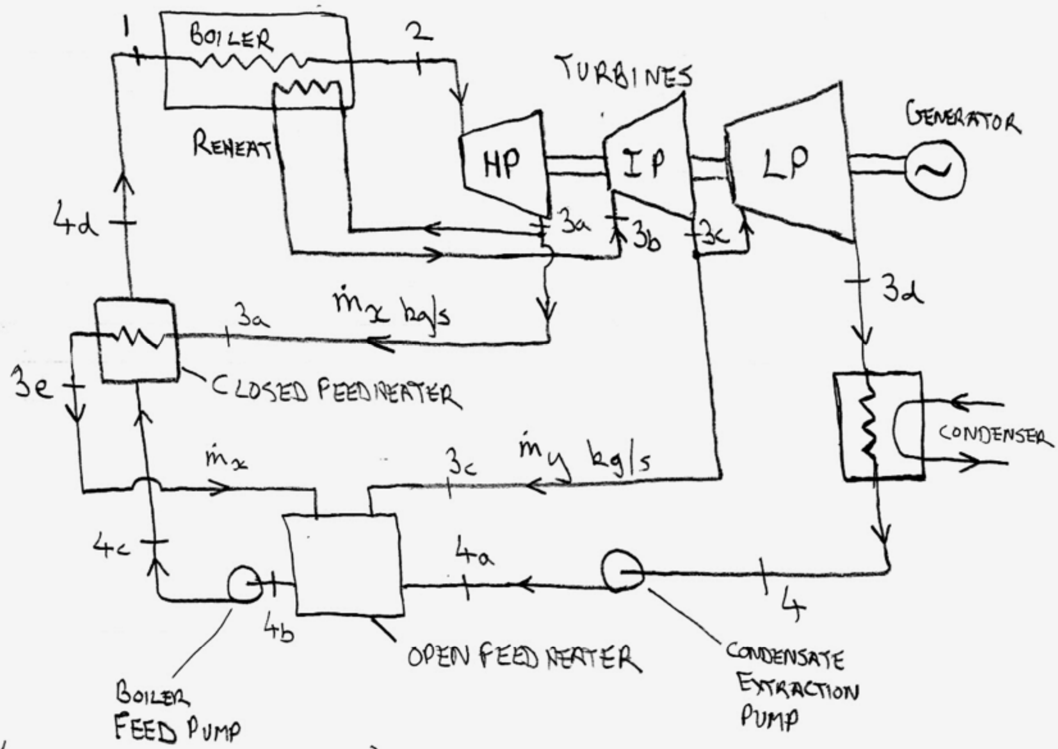
Steam Cycles Exercise Sheet

1. (All enthalpy/entropy values taken from Excel add-in – these are within 0.1% of Steam Tables



(Ignore feed pump work)

Analyse in terms of unit mass flow of steam through the boiler
$\dot{m}_1 = \dot{m}_2 = 1$ kg/s

Let mass flow of steam bled to Closed Feedheater $m_{3a} = x$ kg/s
" " " " " " " Open Feedheater $m_{3c} = y$ kg/s

<u>Boiler</u>
Water at inlet h_{4d} assume saturated at 259°C = 1129 kJ/kg

(water is pressurised at 250 bar, but enthalpy is within 1 kJ/kg of enthalpy of saturated enthalpy at 259°C

Steam at outlet $h_2 = 3493$ kJ/kg
$s_2 = 6.363$ kJ/kgK

<u>HP Turbine</u> (Outlet pressure = 50 bar)
If turbine were isentropic ($s'_{3a} = 6.3633$) $h'_{3a} = 3015$ kJ/kg

$\Delta h_{2-3a'} = 3493 - 3015 = 478$ kJ/kg

Isentropic efficiency is 90% $\therefore$ $\Delta h_{2-3a} = 0.9 \times 478 = 430.2$ kJ/kg

$\therefore$ $h_{3a} = \underline{\underline{3063}}$ kJ/kg

Closed Feed Heater

Feedwater enters at 148°C $h_{4c} = h_{4b} = 623$ kJ/kg
(ignore feedpump work)

Feedwater leaves with enthalpy 4_d of 1129 kJ/kg
Bled steam leaves (3e) at 250°C, enthalpy of 1085 kJ/kg

Enthalpy balance of closed feed heater

$$\dot{m}_{boiler}(h_{4d} - h_{4c}) = \dot{m}_x(h_{3a} - h_{3e})$$

$$1\,(1129 - 623) = x\,(3063 - 1085)$$

$$x = 0.2558 \text{ kg/s}.$$

Reheater

Steam to reheater $= (1 - x) = 0.7442$ kg/s

Outlet enthalpy h_{3b} (50 bar, 600°C) $= 3667$ kJ/kg
" entropy s_{3b} $= 7.260$ kJ/kg

IP Turbine (Outlet pressure = 5 bar)

For an isentropic turbine ($s_{3c'} = 7.260$) $h'_{3c} = 2955$ kJ/kg

$\Delta h_{3b-3c'} = (3667 - 2955) = 712$ kg/kg

Isentropic efficiency is 91% so $\Delta h_{3b-3c} = 0.91 \times 712 = 647.9$ kJ/kg

$\therefore$ $h_{3c} = (3667 - 647.9) = 3019$ kJ/kg

Need entropy at 3c as this is input to LP Turbine

At pressure of 5 bar and enthalpy of 3019 kJ/kg steam is superheated at a temperature 278°C and entropy is 7.380 kJ/kgK

LP Turbine (Outlet pressure = 0.07 bar)

If turbine were isentropic ($s_{3d'} = 7.38$ kJ/kgK) $h'_{3d} = 2293$ kJ/kg

Dryness = 88.4 %

$$\Delta h'_{3c-3d} = (3019 - 2293) = 726 \text{ kJ/kg}$$

Isentropic efficiency is 92%

$$\therefore h_{3d} = 3019 - 0.92(726) = \underline{\underline{2351}} \text{ kJ/kg}$$

Open Feed Heater

Condenser extract water is saturated at 0.07 bar (39°C)

$$h_4 (= h_{4a}) = 163 \text{ kJ/kg}$$

To calculate mass flow of bled steam (y) do enthalpy balance on feed heater

Enthalpy input = Enthalpy output

$$(1 - x - y) h_{4a} + y h_{3c} + x h_{3e} = 1 \times h_{4c}$$

Mass flow at outlet (4c) = 1 kg/s, same as boiler feed.

$$x = 0.2558 \text{ kg/s}$$

$$(1 - 0.2558 - y) 163 + y\, 3019 + 0.2558 \times 1085 = 623$$

$$y(3019 - 163) = 623 - 277.5 - 121.3$$

$$\underline{y = 0.0785} \text{ kg/s}$$

Boiler Heat Input – input to feedwater & reheater

$$Q_{in} = 1(h_2 - h_1) + (1-x)(h_{3b} - h_{3a})$$

$$= 3493 - 1129 + 0.7442(3667 - 3063)$$

$$Q_{in} = 2813 \text{ kJ/kg of boiler feedwater}$$

Total Turbine Work Output (sum of output from 3 turbines)

$$W_T = 1 \times (h_2 - h_{3a}) + (1-x)(h_{3b} - h_{3c}) + (1-x-y)(h_{3c} - h_{3d})$$

$$= (3493 - 3063) + (1 - 0.2558)(3667 - 3019) + (1 - 0.2558 - 0.0785) \times (3019 - 2351)$$

$$= 430 + 482.2 + 444.7$$

(4)

) Cycle thermal efficiency = 1356.9 / 2813

= **48.2 %**

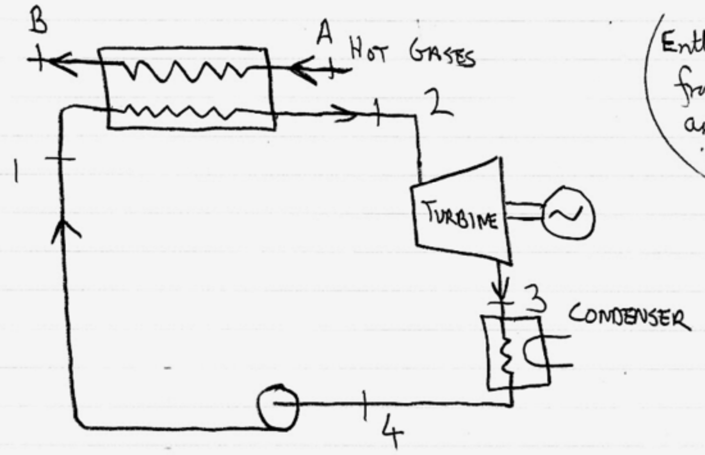
) Specific steam consumption $\frac{1}{W_T}$ = **0.74** kg/MJ

(kg of boiler feed water per MJ of work output from turbines.)

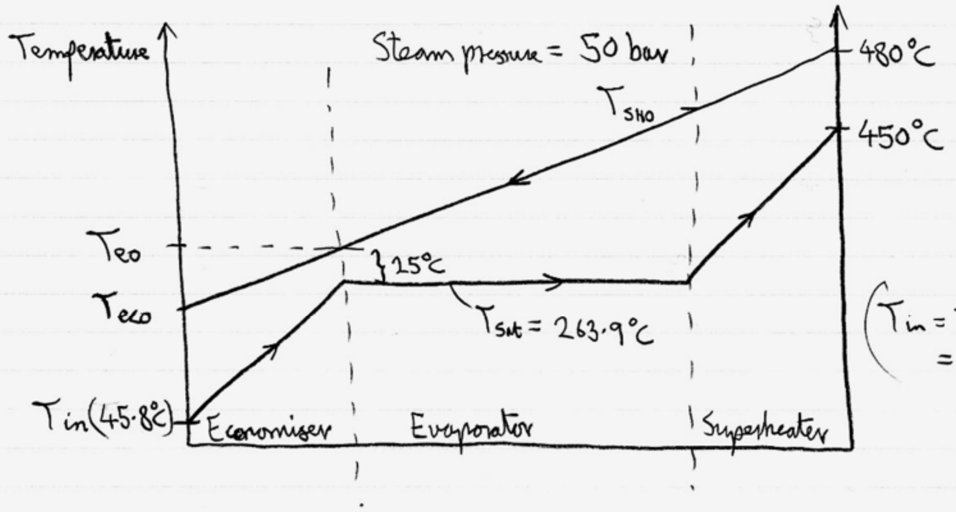
) Electricity generation = 1000 × 0.482 × 0.96

= **463 MW_e**.

2.



(Enthalpy & entropy values taken from Excel Add-in, – these are within 0.1% of values in Tables)



($T_{in} = T_{sat}$ at 0.1 bar $= 45.8°C$)

At evaporator outlet exhaust gas $T_{eo} = 263.9 + 25 = 288.9°C$

To calculate steam mass flow rate do enthalpy balance on Evaporator and Superheater

Enthalpy at superheater outlet (h_2) = 3317 kJ/kg

Enthalpy of feedwater at economiser outlet (assume saturated) = 1155 kJ/kg

In evap & superheater $\dot{m}_{gas}\, c_p (480 - T_{eo}) = \dot{m}_s (3317 - 1155)$

$$\dot{m}_s = \frac{32 \times 1.07 (480 - 288.9)}{(3317 - 1155)} = 3.03 \text{ kg/s}$$

Entropy at superheater outlet = 6.82 kJ/kgK (s_2)

For isentropic turbine $s_3' = s_2$, then $h_3' = 2160$ kJ/kg
dryness = 0.823

(6)

So $\Delta h'_{2-3} = 3317 - 2160 = 1157$ kJ/kg

But isentropic efficiency is 89%

$\therefore \Delta h_{23} = 0.89 \times 1157 = 1030$ kJ/kg

electricity output from turbine $= \dot{m}_s \times 1030 \times 0.94$

(generator effy) ↑

$$W_e = 2.93 \ MW_e$$

<u>Electricity output is 2.9 MW_e</u>

ii) If pinch temperature were reduced to 5°C then Teo would reduce by 20°C to 268.9°C.

The steam mass flow rate would increase

$$\dot{m}_s = \frac{32 \times 1.07(480 - 268.9)}{(3317 - 1155)} = 3.34 \ kg/s$$

The steam conditions around the cycle would remain the same and so the electricity output would increase in proportion to increased steam mass flow.

$$W_e = \frac{3.34}{3.03} \times 2.93 = \underline{\underline{3.23 \ MW_e}}$$

The relative size of heat exchangers can be determined from heat transfer equation

$$Q = UA(LMTD) \qquad LMTD = \text{Log mean temperature difference.}$$

Determine gas temperatures T_{eco} & T_{SHO} from enthalpy balance on economiser and superheater.

	T_{SHO}	T_{eco}
25°C Pinch Temp	434	202
5°C Pinch Temp	429	173

For a heat exchanger $LMTD = \dfrac{\Delta T_{IN} - \Delta T_{OUT}}{\ln \dfrac{\Delta T_{IN}}{\Delta T_{OUT}}}$

Evaporator UA – 25°C Pinch ΔT

$$LMTD = \frac{(434-264)-(289-264)}{Ln\frac{(434-264)}{(289-264)}} = 75.6\ °C$$

$$UA_{EVAP} = \frac{Q}{LMTD} = \frac{32\times1.07\times(434-289)}{75.6} = \underline{65.7\ K/W}$$

Evaporator UA – 5°C Pinch ΔT

$$LMTD = \frac{(429-264)-(269-264)}{Ln\frac{(429-264)}{(289-264)}} = 45.8\ °C$$

$$UA_{EVAP} = \frac{Q}{LMTD} = \frac{32\times1.07\times(429-269)}{45.8} = \underline{\underline{119.6\ K/W}}$$

So reducing Pinch ΔT from 25°C to 5°C requires an increase in evaporator UA from 65.7 to 119.6 assuming U remains the same this represents an increase in Area of ×1.8

Similar analysis for economiser shows an increase in Area of ×2.1.