Question 1

5616-1918

9118

1) i)

$$E_{REV} = \frac{-\Delta G}{nF} = \frac{-(-224{,}836)\ J\ mol^{-1}}{2(96{,}487)\ coul\ mol^{-1}}$$

$$= 1.17\ V$$

$$\eta_{FC} = \frac{V_{cell}}{E_{REV}} = \frac{0.65}{1.17} = 0.558$$

ii) $$\eta_{CARNOT} = 1 - \frac{T_C}{T_H} = 1 - \frac{273+25}{273+60} = 11\%$$

iii) $$\eta_{CARNOT} = 1 - \frac{T_c}{T_H}$$

$$= 1 - \frac{298}{T_H} = 0.558$$

$$\frac{T_H - 298}{T_H} = 0.558$$

$$T_H - 298 = T_H(0.558)$$

$$T_H(1 - 0.558) = 298 \qquad T_H = \frac{298}{1-0.558} = \frac{298}{0.}$$

$$= 674\ K = 400°C.$$

2.) (i) For a throttle $\Delta H = 0$ (no shaft work)

$P_1 = 4140 kPa$ $P_2 = 139 kPa$

$T_1 = 0°C$ $T_2 = ?$
$= 273.15 K$

$$\Delta H = (C_p^{ig})_H (T_2 - T_1) + H_2^R - H_1^R = 0$$

Assume CH_4 at 139 kPa and T_2 behaves as an ideal gas. $H_2^R = 0$

Properties of CH_4 (methane)

Molar mass = 16 043
ω = 0.012
T_c = 190.6 K $T_R = 1.43$
P_c = 45.99 bar $P_R = 0.90$
Z_c = 0.286
V_c = 98.6 $cm^3\ mol^{-1}$

$$\frac{C_p^{ig}}{R} = 1.702 + 9.081 \times 10^{-3} T - 2.164 \times 10^{-6} T^2$$

(simplest form of Virial equation is sufficient)

$$\frac{C_p^{ig}}{R} = 4.021 \qquad C_{p_{273}}^{ig} = 4.021 \times 8.314 \text{ J/mol K}$$

(2) cont

PS 2

$$\frac{H_1^R}{RT_C} = P_R\left[B^0 - T_R\frac{dB^0}{dT_R} + \omega\left(B^1 - T_R\frac{dB^1}{dT_R}\right)\right]$$

$$B^0 = 0.083 - \frac{0.422}{T_R^{1.6}} = 0.083 - \frac{0.422}{(1.43)^{1.6}}$$

$$= -0.155$$

$$\frac{dB^0}{dT_R} = \frac{0.675}{T_R^{2.6}} = 0.2663$$

$$B^1 = 0.139 - \frac{0.172}{T_R^{4.2}} = 0.139 - \frac{0.172}{(1.43)^{4.2}}$$

$$= 0.1007$$

$$\frac{dB^1}{dT_R} = \frac{0.722}{T_R^{5.2}} = 0.1124$$

$$\frac{H_1^R}{RT_C} = 0.90\left[(-0.155) - 1.43(0.2663) + 0.012\left(0.1007 - 1.43(0.1124)\right)\right]$$

$$= 0.90\left[(-0.5358) - 0.00072\right]$$

$$= 0.90(-0.53653) = -0.48288$$

(2) cont.

$$\frac{H_1^R}{RT_c} = -0.48288$$

$$H_1^R = -0.48288\left(8.314 \frac{J}{mol\ K}\right)(190.6\ K)$$

$$= -765.2 \quad J\ mol^{-1}$$

$$C_p^{ig}(T_2 - T_1) = H_1^R$$

Assume C_p^{ig} does not change for ΔT

$$T_2 = \frac{H_1^R}{C_p^{ig}} + T_1$$

$$= \frac{-765.2\ (J \cdot mol^{-1})}{(8.314)(4.021)(J\ mol^{-1}\ k^{-1})} + 273.15$$

$$= 250.3\ k = -23\ ^\circ C.$$

Check Assump

$$\left(\frac{C_p^{ig}}{R}\right)_{T_2} = 1.702 + 9.081(10^{-3})250.3 - 2.164(10^{-6})(250.3$$

$$= 3.84$$

$$\left(\frac{C_p^{ig}}{R}\right)_{Avg} = \left(\frac{3.84 + 4.02}{2}\right) = 3.93$$

Recalc for new C_p^{ig}

p4

(2)

$$T_2 = \frac{-765.2}{(8.314)(3.93)} + 273.15$$

$$= 249.73\ K \quad = \underline{-23.4\ °C}$$

(ii) Assume reversible adiabatic expansion of methane from 4140 kPa to 138 kPa

$$W = \frac{RT_1}{\gamma - 1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

$$= \frac{(8.314)(273.15)}{(1.3054-1)}\left[\left(\frac{138}{4140}\right)^{\frac{1.3054-1}{1.3054}} - 1\right]$$

$$= 7436.\ (J/mol)\left[0.4513 - 1\right]$$

$$= -4081\ J/mol.$$

$$\dot{n} = \frac{P\dot{V}}{RT} = \frac{(4140)(85\times10^{9})\ [kPa\ L]}{(8.314)(288)}$$

$$= 14.7 \times 10^{9}\ moles/day$$

$$= 1.7 \times 10^{5}\ moles/s.$$

$$\boxed{\dot{W} = \dot{n} \cdot W = -694\ MW}$$

3)

(i)

$$W_s = \Delta H = H_2 - H_1 = 2609.9 - 3515.2 \ (\text{kJ/kg})$$

$$= -905.3 \text{ kJ/kg.}$$

(ii) $T_2 = 60.09°C$, $P_2 = 20$ kPa
$T_1 = 500°C$, $P_1 = 2400$ kPa

$$W = \frac{RT_1}{\gamma - 1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

$$= \frac{(8.314)(798)}{(1.32-1)}\left[\left(\frac{20}{2700}\right)^{\frac{1.32-1}{1.32}} - 1\right]$$

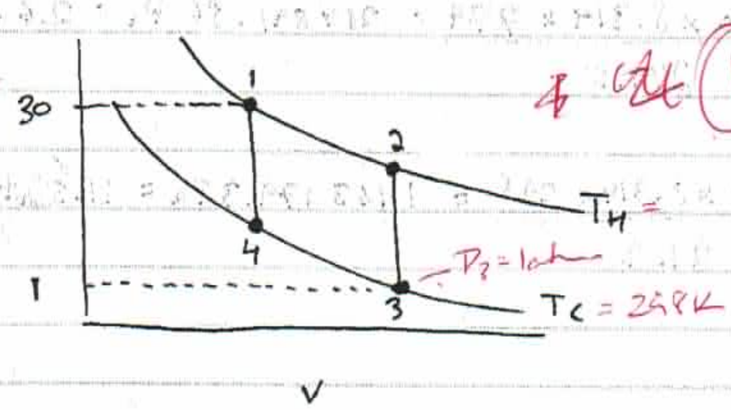
$$= \frac{(8.314)(798)}{(1.32-1)}(-0.6955) = -14,420 \text{ J mol}^{-1}$$

$$= -800 \text{ kJ/kg.}$$

(iii) The ideal enthalpy change and work is 105 kJ/kg less than the real value as predicted by the steam tables

1 3

Q4

① 

4 ✓✓ 1

② a)

Step	T(k)	P(atm)	V (m^3)
1	779	30	21.3 m^3
2	779	2.6	244.5
3	298	1	244.5
4	298	11.5	21.3

Step 3 $\quad P_3V_3 = nRT_3$

$$V_3 = \frac{nRT_3}{P_3} = \frac{10000 \times 8.314 \times 298}{1 \times 101325} = 244.5\,m^3$$ ✓ 1

Step 4→1 $\quad Q_{41} = 60 \times 10^6\ J$

$Q_{41} = C_v(T_1 - T_4)$ 1

$60 \times 10^6 = 1.5 \times 8.314 \times 10000 \times (T_1 - 298)$

$60 \times 10^6 = 124710\,T_1 - 37163580$

$T_1 = 779\ k$ 1

Step 1 $\quad V_1 = \frac{nRT_1}{P_1} = \frac{10000 \times 8.314 \times \boxed{779}}{30 \times 101325} = 21.3\ m^3$ 1

1-2

Step 2 $P_2 = \frac{nRT_2}{V_2} = \frac{10\,000 \times 8.314 \times 779}{244.5} = 264\,891.86$ Pa $= 2.6$ atm
2-3
1

Step 4 $P_4 = \frac{nRT_4}{V_4} = \frac{10000 \times 8.314 \times 298}{21.3} = 1\,163\,179.3$ Pa $= 11.5$ atm
3-4
1

6

(2) b) Step $1 \Rightarrow 2$ $\Delta U = 0$

$Q_{12} = RT_1 \times n \times \ln\left(\frac{V_2}{V_1}\right) = 10\,000 \times 8.314 \times 779 \times \ln\left(\frac{244.5}{21.3}\right)$

$$\boxed{\begin{array}{l} Q_{12} = 158\,062\,102.9\ \text{J} = 158.1\ \text{MJ} \\ W_{12} = -158\,062\,102.9\ \text{J} = -158.1\ \text{MJ} \end{array}}$$ 1

Step $2 \Rightarrow 3$

$Q_{23} = nC_v(T_3 - T_2) = 10000 \times 1.5 \times 8.314 \times (298 - 779)$ 1

$$\boxed{\begin{array}{l} Q_{23} = -59\,985\,510\ \text{J} = -60\ \text{MJ} \\ W_{23} = 0 \end{array}}$$ 1 1

Step $3 \Rightarrow 4$ $\Delta U = 0$

$Q_{34} = nRT \ln\left(\frac{V_4}{V_3}\right) = 10000 \times 8.314 \times 298 \times \ln\left(\frac{21.3}{244.5}\right)$ 1

$$\boxed{\begin{array}{l} Q_{34} = -60\,465\,348.72\ \text{J} = -60.5\ \text{MJ} \\ W_{34} = 60\,465\,348.7\ \text{J} = 60.5\ \text{MJ} \end{array}}$$ 1

Step $4 \Rightarrow 1$

$$\boxed{\begin{array}{l} Q_{41} = 60\ \text{MJ} \\ W_{41} = 0 \end{array}}$$ 1

8

② c)

Total heat supplied by wood-pellet furnace = Q_{in}

$Q_{in} = Q_{12} + Q_{41} = 158.1 + 60 = 218.1\ MJ$ 1

Total heat rejected by engine = Q_{out}

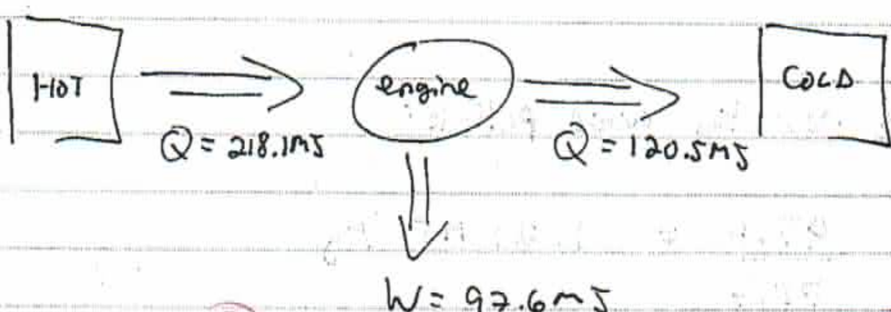
$Q_{out} = Q_{23} + Q_{34} = -60 - 60.5 = -120.5\ MJ$ 1

Net work produced by stirling engine = W_{net}

$W_{net} = W_{12} + W_{23} + W_{34} + W_{41} = -158.1 + 0 + 60.5 + 0$

$W_{net} = -97.6\ MJ$ 1

② d) Stirling engine can be thought of as a "thermodynamic engine" operating between a hot and cold heat reservoir:



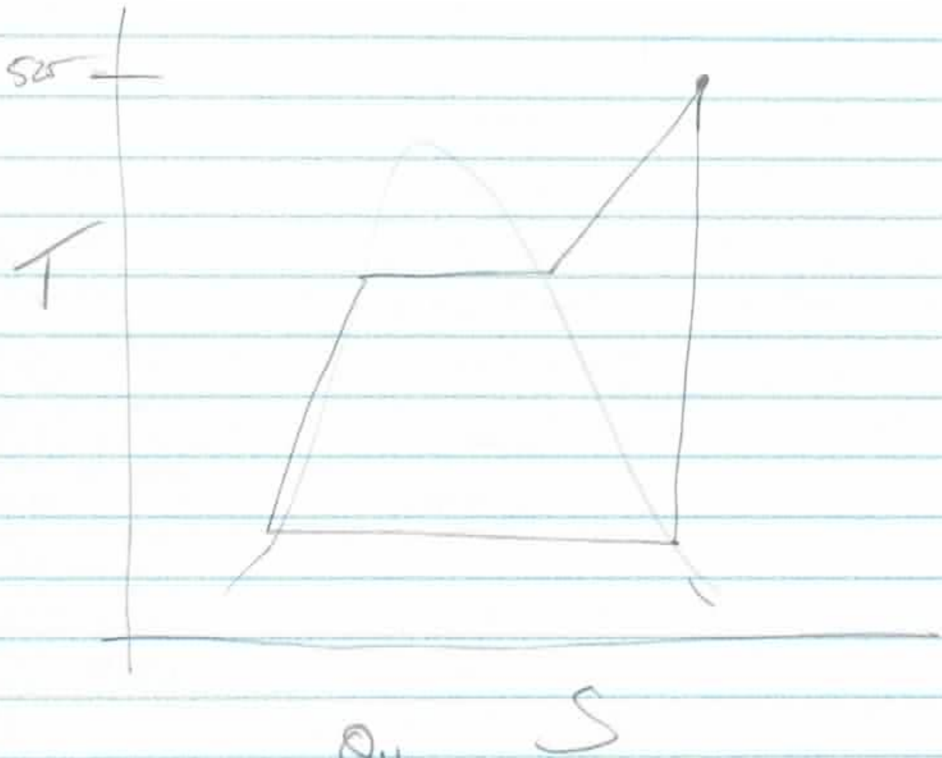
1 1

$$\eta = \frac{W_{out}}{\text{Energy In}} = \frac{97.6}{218.1} = 0.45 = 45\%$$

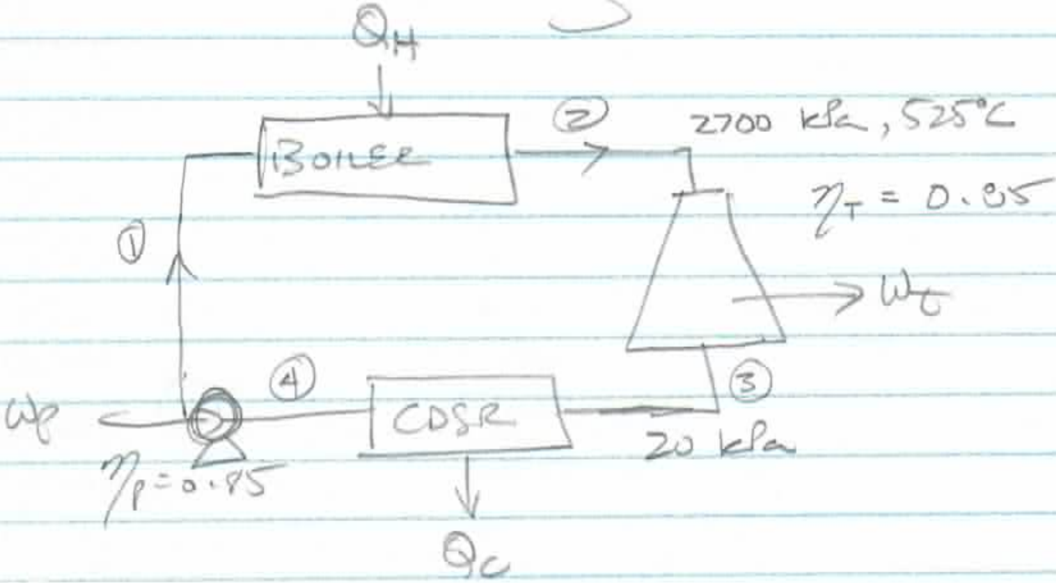
or $$\eta = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{120.5}{218.1} = 0.45 = 45\%$$

Q-5

p1



525
T
S



Q_H
BOILER
②
2700 kPa, 525°C
$\eta_T = 0.85$
W_T
①
④
③
W_P
CDSR
20 kPa
$\eta_P = 0.85$
Q_C

Consider Turbine $\eta_T = 0.85$

		sat liq 1	sat vap 1
$H_2 = 3515.2$ 1	H_3	251.453	2609.9
$S_2 = 7.3571$	S_3	0.8321	7.9094

find $(\Delta H)_s$

find x_3 for $S_2 = S_3 = 7.3571$ kJ/kg K 1

$$x = \frac{7.3571 - 0.8321}{7.9094 - 0.8321} = 0.922 \quad 1$$

$$H_{3_s} = 0.922(2609.9) + (1 - 0.922)(251.453)$$
$$= 2425.9 \text{ kJ/kg} \quad 1$$

$$H_3 = H_2 + \eta_T\left((H_{3_s} - H_2\right) \quad 1$$

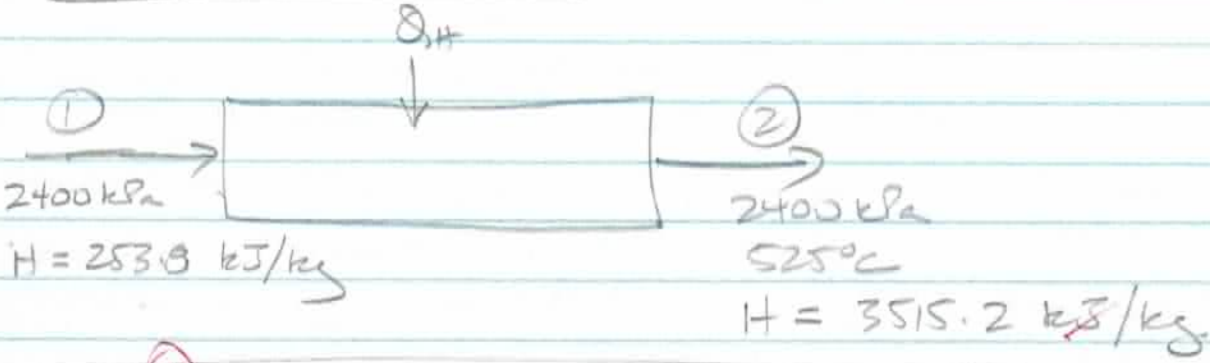
$$= 3515.2 + (0.85)(2425.9 - 3515.2)$$

$$= (3515.2 - 925.9) = 2589.3 \text{ kJ/kg} \quad 1$$

$$\boxed{W_T = -925.9 \text{ kJ/kg}} \quad 2$$

/10

Consider the Boiler.



1

$$\boxed{Q_H = \Delta H_{Boil} = (3515.2 - 253.8) = 3261.4 \text{ kJ/kg}}$$

1

/2

$$\eta_{cycle} = \frac{|W_{Net}|}{(Q_H)} = \frac{|925.9| - |3.21|}{(3261.4)}$$

$$= \frac{922.7}{3261.4} = \boxed{0.283}$$

1

/1

Q6. 10

p 1

(i) Ethanol.

$$\Delta H = C_p \Delta T + V(1 - \beta T)\Delta P$$ ~~2~~ 1

7

$$(W_s)_s = V(P_2 - P_1)$$

$$= (0.790)^{-1} [L/kg] (8600 - 10) \text{ kPa}$$

$$= 10873 \text{ J/kg} = 10.873 \text{ kJ/kg}$$ 1

1 $$\eta = \frac{(W_s)_s}{W_s} \Rightarrow \boxed{W_s = \frac{10.873}{0.75} = 12.79 \text{ kJ/kg} = \Delta H}$$

$$12.79 \text{ [kJ/kg]} = C_p \Delta T + \left(\frac{1}{0.790}\right)\left(1 - (1120 \times 10^{-6})(298)\right)\frac{8590}{1000}$$

[L/kg]

1 $$C_p = \frac{13.444 \times 8.314 \text{ (J/mol K)}}{46.069 \text{ (g/mol)} \times 10^{-3} \text{ kg/g}} = 2789.5 \text{ J/kg K}$$

$$12.79 \left[\text{kJ/kg}\right] = 2.7895 \left(\frac{\text{kJ}}{\text{kg K}}\right)\Delta T + 7.244 \left[\frac{\text{kJ}}{\text{kg}}\right]$$

$$\boxed{\Delta T = 1.99 \text{ K}}$$ 1

$$\boxed{T_{Final} = 27 °C}$$ 1

273.15

300.15

Q6

3 (ii) Water

$$\Delta H = C_p \Delta T + V(1 - \beta T)\Delta P$$

18 g/mol

$$(W_s)_s = 1.0\,(8590) = 8590 \quad J/kg$$
$$= 8.590 \quad kJ/kg$$

$$\boxed{W_s = \frac{8.590}{0.85} = 10.11 \quad kJ/kg. = \Delta H}$$ 1

$$C_p = \frac{(9.069)(8.314)}{(18.02)(10^{-7})} = 4.184 \quad kJ/kg.$$

$$10.11 = 4.184\,\Delta T + 1.0\left(1 - 256(10^{-6})\,298\right)\frac{8590}{1000}$$

$$\boxed{\Delta T = \frac{10.11 - 7.9346}{4.184} = 0.52 \quad K}$$ 1

$$\boxed{T_{FINAL} = 25.5\ °C.}$$ 1

273.15

298

Q-7

① $W = \Delta H$

$$\Delta H = H(2\,bar, 54.5°C) - H(100\,bar, 225°C)$$

$$H(2\,bar, 54.5°C) = H_{ref} + \int_{T_{ref}}^{54.5} C_p\,dT + H^R(2\,bar, 54.5°C)$$

$$H(100\,bar, 225°C) = H_{ref} + \int_{T_{ref}}^{225} C_p\,dT + H^R(100\,bar, 225°C)$$

$$\Delta H = \int_{225°C}^{54.5°C} C_p\,dT + \left[H^R(2\,bar, 54.5°C) - H^R(100\,bar, 225°C)\right]$$

$$\Delta H = \Delta H^{ig} + \Delta H^R$$

$$\Delta H^{ig} = \int_{225+273}^{54.5+273} (0.1562T + 27.9)\,dT$$

$$\Delta H^{ig} = \frac{0.1562}{2}T^2 + 27.9T \Big|_{225+273}^{54.5+273}$$

$$\Delta H^{ig} = \left[\frac{0.1562}{2}(54.5+273)^2 + 27.9(54.5+273)\right] - \left[\frac{0.1562}{2}(225+273)^2 + 27.9(225+273)\right]$$

$$\Delta H^{ig} = 17513.96 - 33263.3 = -15749.3 \text{ J/mol}$$

$$\Delta H^R = H^R(2\text{bar}, 54.5°C) - H^R(100\text{bar}, 225°C)$$

$\underline{H^R(2\text{bar}, 54.5°C)}$

$T_R = 0.89 \qquad P_R = 0.047$

$$\frac{H^R}{RT_c} = P_R\left[B^0 - T_R\frac{dB^0}{dT_R} + \omega\left(B' - T_R\frac{dB'}{dT_R}\right)\right]$$

$$B^0 = 0.083 - \frac{0.422}{T_R^{1.6}} = -0.43$$

$$B' = 0.139 - \frac{0.172}{T_R^{4.2}} = -0.14$$

$$\frac{dB^0}{dT_R} = \frac{0.675}{T_R^{2.6}} = 0.91$$

$$\frac{dB'}{dT_R} = \frac{0.722}{T_R^{5.2}} = 1.32$$

$$\frac{H^R}{RT_c} = 0.047\left[-0.43 - 0.89 \times 0.91 + 0.152\left(-0.14 - 0.89 \times 1.32\right)\right]$$

$$\frac{H^R}{RT_c} = -0.068$$

$$H^R(2\text{bar}, 54.5°C) = -208 \text{ J/mol}$$

Q8

(i) $\eta_{ideal} = 1 - \left(\frac{P_A}{P_B}\right)^{\frac{\gamma-1}{\gamma}} = 1 - \left(\frac{1}{7}\right)^{\frac{1.4-1}{1.4}} = 0.426$ ①

①

(ii) $$\eta_T = \frac{\eta_T \eta_C (T_C/T_A)(1 - 1/\alpha) - (\alpha - 1)}{\eta_C (T_C/T_A - 1) - (\alpha - 1)}$$ ①

① $\alpha = \left(\frac{P_B}{P_A}\right)^{\gamma-1/\gamma} = (7)^{\frac{.4}{1.4}} = 1.744$

$$\eta = \frac{(0.83)(0.83)\left(\frac{1033.15}{298.15}\right)\left(1 - \frac{1}{1.744}\right) - (1.744 - 1)}{(0.83)\left(\frac{1033.15}{298.15} - 1\right) - (1.744 - 1)}$$

$$= \frac{1.01838 - 1.744 + 1}{1.3021} = \frac{0.27438}{1.3021}$$

$$\boxed{\eta = 0.211}$$ ①