REVIEW THERMODYNAMICS I

Conceptual questions properties of pure substances

- Sketch the variation in the saturation pressure of a pure substance as a function of the saturation temperature

- What is difference between saturated vapor and superheated vapor?

- Explain the difference between the critical point and the triple point?

- Consider a pure water in the saturated liquid-vapor mixture phase, is each of the following combinations of properties enough to fulfill the state postulate:

i) Temperature and pressure
ii) Temperature and quality
iii) Pressure and specific volume
iv) Temperature and specific volume
v) Specific volume and quality

Consider 1 kg of compressed liquid water at a pressure lower than 4 MPa (< 5 MPa) and a temperature of 100°C, its thermodynamic properties are obtained using:

i) Superheated vapor table considering the same temperature
ii) Saturated liquid-vapor tables considering the same pressure
iii) Saturated liquid-vapor tables considering the same temperature

- Is it possible to have water vapor at 20°C?

- A renowned chef participates a cooking contest where he needs to cook ratatouille in 15 minutes. Should he use a pan that is a) uncovered, b) covered with a light lid or c) covered with a heavy lid to make sure he can finish his desk within this short period? Why?

-Does the amount of heat absorbed as 2 kg of saturated liquid water boils at 100°C and normal pressure have to be equal to the amount of heat released as 2 kg of saturated vapor condenses at 100°C and normal pressure?

- Does the latent heat of vaporization changes with pressure? Does it take more energy to vaporize 1 kg of saturated liquid water at 100°C than it needs at 150°C?

- What is vapor quality?

- The ___________ is a point in p-v-T space where solid, liquid and gas phases can coexist.

- Given two data point (x_1, y_1) and (x_2, y_2), write down the equation of line y = f(x). Using this equation, perform a linear interpolation to determine u [kJ/kg] at x = 270 K if the two points are given as (250, 2723.5) and (300, 2802.9).

I.1. (Tutorial) Compute the following properties table for: *Note: cells in gray will be used for self-evaluation*

Water

T [°C]	P [kPa]	x	u [kJ/kg]	Phase type
300			1332.0	
150			1595.63	
	250	0.6		
	600		3477.0	
60	200	--		
370	1200	--		

Refrigerant-134a

T [°C]	P [MPa]	v [m^3/kg]	h [kJ/kg]	Phase type
-20	0.30			
40			147.0	
90		0.0046		
30	0.24			
	0.80		292.0	

I.2. A piston-cylinder device initially contains 0.30 kg of Nitrogen at 130 kPa and 190°C, which is now allowed to expand isothermally to a final pressure of 75 kPa. Compute the boundary work, in kJ.

I.3. A piston-cylinder device initially contains 0.20 kg of Air at 2.5 MPa and 350°C. The gas first expanded isothermally to a pressure of 600 kPa, and then compressed polytropically with n = 1.2 back to the initial pressure, and finally compressed at constant pressure to the initial state. Calculate the boundary work, in kJ, for each thermodynamic process and find the net work for the cycle.

I.4. i. A single cylinder in a car engine has a maximum volume of $5\text{x}10^{-4}$ m^3 (before the compression stroke). After the compression process, the gas has been compressed to one-tenth of its initial volume where the temperature is 1500°C and the pressure is 60 atm. What is the mass of gas (approximate as pure air and ideal gas) inside the cylinder? (*Note:* 1 atm = 101 kPa and specific gas constant for air R_s is 0.287 kJ/kg·K)

ii. This hot, compressed gas then expands and does work on the piston until the volume is brought back to its initial value of $5\text{x}10^{-4}$ m^3. The boundary work produced by this expansion is transmitted by the connecting rod from the piston to the crankshalf which converts the up and down motion of the piston into the rotary motion of the crankshalf that eventually turns the wheels of your car.

It is know that the pressure and the volume follow the polytropic relation throughout the expansion process:

$$PV^n = \text{constant}$$

where n is the polytropic coefficient. If n = 1.4, find the pressure after expansion and the total amount of boundary work produced during this expansion process.

iii. What is the final temperature in the cylinder and by how much did the internal energy decrease? Was any heat lost by the hot gases in the cylinder during the expansion? (assume constant specific heat c_v = 0.7175 kJ/ kg·K)

I.5. A cylinder device fitted with a piston contains initially argon gas at 100kPa and 27°C occupying a volume of 0.4 m^3. The argon gas is first compressed while the temperature is held constant until the volume reaches 0.2 m^3. Then the argon is allowed to expand while the pressure is held constant until the volume becomes 0.6 m^3. Determine the total amount of net heat transferred to the argon in kJ.

I.6. Steam is flowing steadily into an adiabatic turbine. The inlet conditions of the steam are 6 MPa, 400 °C and 90 m/s, and the exit conditions are 40 kPa, 90% quality and 55 m/s. The mass flow rate of the steam is 18 kg/s. Determine the change in kinetic energy, the power output and the turbine inlet area.

I.7. Steam flows steadily into a turbine at 10 MPa and 500 °C and leaves at 10 kPa with a quality of 88%. The turbine is assumed to be an adiabatic turbine without losses. Neglecting the changes in kinetic and potential energies, determine the mass flow rate required for a power output of 5.8 MW.

I.8. An adiabatic compressor is used to compress 8 L/s of air at 120kPa and 22 °C to 1000 kPa and 300 °C. Determine the work required by the compressor, in kJ/kg, and the power required to run this air compressor, in kW.

I.9. Argon gas flows steadily with a velocity of 50 m/s into an adiabatic turbine at 1500 kPa and 450°C. The gas leaves the turbine at 140 kPa with a velocity of 140 m/s. The inlet area of the turbine is 55 cm^2. The power output of the turbine is measured to be 180 kW. Determine the exit temperature of the argon.

I.10. A compressor is used to compress Helium gas from 120 kPa and 300K to 750 kPa and 450 K. A heat loss of 18kJ/kg is found during the compression process. Neglecting kinetic energy changes, compute the power input required to maintain a mass flow rate of 88 kg/min.

I.11. Air initially at 1400 kPa and 500°C is expanded through an adiabatic gas turbine to 100 kPa and 127°C. Air enters the turbine at an average velocity of 45 m/s through the 0.18 m^2 opening, and leaves through a 1-m^2 opening. Determine the mass flow rate of air through the turbine and the power produced by the turbine.

I.12. Steam enters a two-stage steady-flow turbine with a mass flow rate of 22 kg/s at 600 °C, 5 MPa. The steam expands in the turbine to a saturated vapor at 500 kPa where 8% of the steam is removed for some other use. The remainder of the steam continues to expand all the way to the turbine exit where the pressure is now 10kPa and quality is 88%. The turbine is assumed to be adiabatic. Compute the rate of work done by the steam during the process. Neglect the change in kinetic energy.

I.13. (Tutorial) Steam expands through a turbine with a mass flow rate of 25 kg/s and a negligible velocity at 6 MPa and 600 °C. The steam leaves the turbine with a velocity of 175 m/s at 0.5 MPa and 200 °C. The rate of work done by the steam in the turbine is measured to be 19 MW. Determine the rate of heat transfer associated with this process.

I.14. Consider the throttling valve shown on Fig. 5.20. The valve is crossed by a gas with an inlet pressure of 1.2 MPa and inlet temperature of 20°C. Assuming that the outlet pressure is 100 kPa and the velocity at the inlet and at the outlet remain the same, determine the exit temperature and the ratio between the inlet and exit areas.

Fig.5.20

I.15. Consider an adiabatic throttling valve with water entering at pressure of 1.6 MPa, a temperature of 250°C and a velocity of 4.5 m/s. If the exit pressure is 300 kPa, determine the velocity at the exit.

I.16. Two kg/s of water are condensed from 50 kPa and 300°C to saturated liquid. For this purpose, cooling water enters the condenser at 20°C and leaves at 35°C. Determine the required mass flow rate of the cooling water.

I.17. (Tutorial) The exhaust gases of a car are to be used to heat up water. 0.5 kg/s of hot gases enter the heat exchanger at a temperature of 250°C and leave at a 150°C. If 0.5 kg/s of water enter the heat exchanger with an inlet temperature of 20°C, determine the temperature of the water at the exit.
Assume Cp for the hot gases and for the water to be 1.08 and 4.186 kJ/kg K, respectively.

I.18. A car engine produces 30 hp while rejecting 35 kW to the atmosphere. Determine its thermal efficiency.

I.19. The average winter low temperature in winter in Montreal is around -13°C. However, far enough below the ground, the temperature can remain above zero and reaches around 10°C. If you want to design a heat engine using this difference in temperature, what will be its maximal efficiency?

I.20. (Tutorial) An inventor was invited to the show `Dragon's Den` on CBC and claims that she/he developed an innovative design for a heat engine capable of receiving 300 KW of heat from a reservoir of 1000 K and rejecting 100 KW to a reservoir of 400 K. The inventor asks for a million dollars investment for 20% of his company. As an engineer you are asked to give your opinion on the invention to one of the Dragons, what will be your advice and why?

I

Refrigerant-134a

T	P	v	h	Phase
-20°C	0.30 MPa	0.0007361 m^3/kg	24.26 kJ/kg	Compressed liquid
40°C	1.0164 MPa	0.005663 m^3/kg	147.0 kJ/kg	Saturated mixture $x = 0.2518$
90°C	3.2455 MPa	0.0046 m^3/kg	276.32 kJ/kg	Saturated vapor
30°C	0.24 MPa	0.09794 m^3/kg	275.95 kJ/kg	superheated vapor
	0.801 MPa		292.0 kJ/kg	superheated vapor

	v	h
at 50°C	0.02846	284.39
70°C	0.03131	294.98

$$\therefore \quad T(292) = \frac{70-50}{294.98-284.39}(292-284.39)+50$$

$$= \underline{\underline{64.37°C}}$$

$$v(292) = \frac{0.03131-0.02846}{294.98-284.39}(292-284.39)+0.02846$$

$$= \underline{\underline{0.03051\ m^3/kg}}$$

2 [redacted]

R_s for nitrogen $= 0.2968 \ kJ/kg \cdot k$

$$V_1 = \frac{m R_s T_1}{P_1} = \frac{0.30 \ kg \ (0.2968 \ kJ/kg \cdot K) \cdot (483 \ K)}{(130 \ kPa)}$$

$$= 0.331 \ m^3$$

isothermal

$$V_2 = \frac{m R_s T_2}{P_2} = \frac{(0.30 \ kg)(0.2968 \ kJ/kg \cdot k)(483 \ K)}{75 \ kPa}$$

$$= 0.5734 \ m^3$$

$$W = \int_1^2 P \, dV = P_1 V_1 \ln\left(\frac{V_2}{V_1}\right)$$ for isothermal process

$$= (130 \ kPa)(0.331 \ m^3) \ln\left(\frac{0.5734}{0.331}\right) = \underline{\underline{23.6 \ kJ}}$$

3 [redacted]

$$V_1 = \frac{m R_s T_1}{P_1} = \frac{0.2 \cdot (0.287)(623)}{2500 \text{ kPa}} = 0.0143 \text{ m}^3$$

$$V_2 = \frac{m R_s T_2}{P_2} = \frac{0.2 (0.287)(623)}{600} = 0.0596 \text{ m}^3$$

for isothermal process:

$$W_{1-2} = P_1 V_1 \ln\left(\frac{V_2}{V_1}\right) = (2500 \text{ kPa})(0.0143 \text{ m}^3) \ln\left(\frac{0.0596}{0.0143}\right)$$

$$= \underline{\underline{51.03 \text{ kJ}}}$$

$$P_2 V_2^{\,n} = P_3 V_3^{\,n}$$

$$(600 \text{ kPa})(0.0596)^{1.2} = (2500 \text{ kPa})(V_3^{\,1.2})$$

$$V_3 = 0.01814 \text{ m}^3$$

$$W_{2-3} = \frac{P_3 V_3 - P_2 V_2}{1-n} = \frac{(2500)(0.01814) - 600(0.0596)}{1-1.2}$$

$$= \underline{\underline{-47.95 \text{ kJ}}}$$

$$W_{3-1} = P_3 (V_1 - V_3)$$

$$= (2500)(0.0143 - 0.01814)$$

$$= \underline{\underline{-9.6 \text{ kJ}}}$$

$$W_{net} = \sum W = 51.03 + (-47.95) + (-9.6)$$

$$= \underline{\underline{-6.52 \text{ kJ}}}$$

4

[redacted]

$P_1 V_1 = m R_s T_1$

$$m = \frac{60 \times 101\,kPa \times 0.00005\,m^3}{0.287\,kPa \cdot m^3/kg\,K \cdot 1773\,K} = 5.955 \times 10^{-4}\,kg$$

$P_1 V_1^n = P_2 V_2^n$

$$P_2 = P_1 \left(\frac{V_1}{V_2}\right)^n = 60\left(\frac{1}{10}\right)^{1.4} = 2.3886\ atm = 241.24\ kPa$$

For polytropic process:

$$W = \int_1^2 P\,dV = \frac{P_2 V_2 - P_1 V_1}{1-n}$$

$10V_1$

$$= \frac{2.3886 \times 101\,kPa \times 0.0005 - (0.00005)(60 \times 101\,kPa)}{1-1.4}$$

$$= \underline{\underline{0.456\ kJ}}$$

$$T_2 = \left(\frac{P_2}{P_1}\right)\left(\frac{V_2}{V_1}\right) T_1 = 705.8\ K$$

$$\Delta U = m C_v \Delta T = (5.955 \times 10^{-4})(0.7175)(705.8 - 1773)$$

$$= -0.456\ kJ$$

1st law: $\Delta U = \delta Q - \delta W$

$-0.456 = \delta Q - (0.456)$ $\quad \therefore \delta Q = 0$ no heat loss

4

[redacted]

5

Argon is contained in a cylinder device fitted with a piston. Initially, the argon is at 100 kPa and 27°C and occupies a volume of 0.4 m^3. The argon is first compressed while the temperature is held constant until the volume is 0.2 m^3. Then the argon expands while the pressure is held constant until the volume is 0.6 m^3

Determine the total amount of net heat transfered to the argon in kJ. Assume constant properties.

Assume: closed system

$\Delta PE = \Delta KE \simeq 0$

$$\left.\begin{aligned} C_v &= 0.3122 \ kJ/kg\,K \ (\text{Table A-2}) \\ R_s &= 0.2081 \ kJ/kg\,K \end{aligned}\right\} \text{argon}$$

ideal gas.

$1 \rightarrow 2$ isothermal

$2 \rightarrow 3$ (isobaric)

$$dU = \delta Q - \delta W$$

Energy balance for this system for the complete process $1 \rightarrow 3$

$$dU = Q_{\substack{net \\ 1\rightarrow 3}} - (\underbrace{W_{1\rightarrow 2} + W_{2\rightarrow 3}}_{W_{net}})$$

$$mC_v(T_3 - T_1) = Q_{net} - W_{net}$$

$$m = \frac{P_1 V_1}{R T_1} = \frac{(100\ kPa)(0.4 m^3)}{(0.2081\ kPa \cdot m^3/kg \cdot K)(300K}$$

$$= 0.6407\ kg$$

$1 \rightarrow 2$ isothermal

$$\left.\begin{array}{l} P_1 V_1 = m R_s T_1 \\ P_2 V_2 = m R_s T_2 \end{array}\right\} \quad P_2 = P_1 \frac{V_1}{V_2} = (100) \frac{0.4}{0.2} = 200\ kPa$$

27+ 273 = 300k

$2 \rightarrow 3$ isobaric

$$\left.\begin{array}{l} P_2 V_2 = m R_s T_2 \\ P_3 V_3 = m R_s T_3 \end{array}\right\} \quad T_3 = T_2 \frac{V_3}{V_2} = (300) \frac{0.6}{0.2} = 900\ K$$

$1 \rightarrow 2$: isothermal

$$W_{12} = P_1 V_1 \ln \frac{V_2}{V_1} = (100)(0.4) \ln\left(\frac{0.2}{0.4}\right)$$

$$= -27.7\ kJ$$

$2 \rightarrow 3$: isobaric

$$W_{23} = P_2 (V_3 - V_2) = 80\ kJ$$

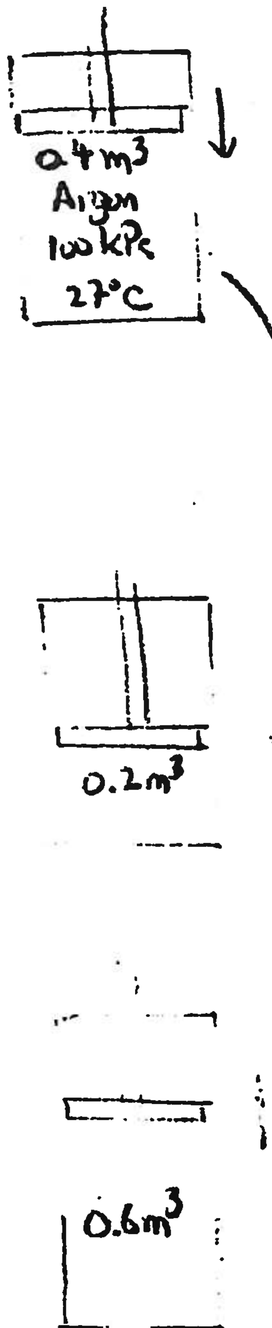
$$m c_v (T_3 - T_1) = Q_{net} - (-27.7\ kJ + 80\ kJ)$$

$$Q_{net} = (0.6407 kg) \cdot (0.3122 \tfrac{kJ}{kg \cdot K})(900 - 300) + (-27.7 + 80)$$

$$= +172.3\ kJ$$

input

①



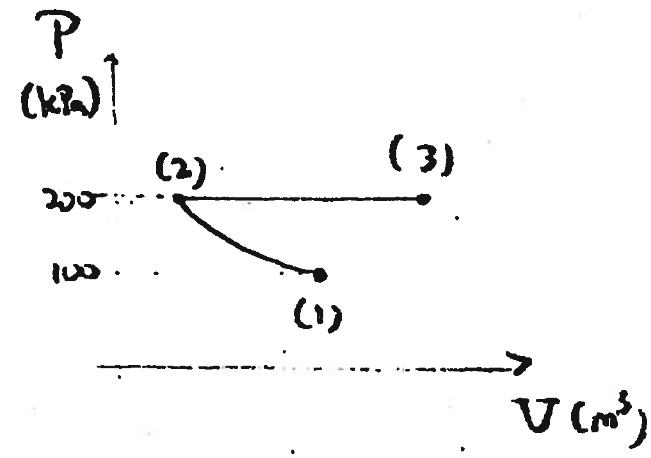
set of stops

$$m = \frac{P_1 V_1}{R T_1} = \frac{(100\ \text{kPa})(0.4\ \text{m}^3)}{(0.2081\ \text{kPa}\cdot\text{m}^3/\text{kg}\,\text{K})(300\ \text{K})}$$

$$= \underline{\underline{0.6407\ \text{kg}}}$$

Isothermal process
$T = $ const.

Isobaric process
$P = $ const.



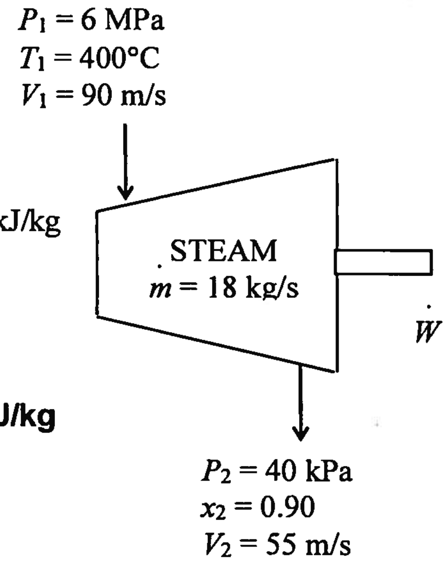
Determine net Q to the argon in kJ

6 [redacted]

This is a steady-flow process. Potential energy changes are negligible. The device is adiabatic and thus heat transfer is negligible.

From the steam tables

$$\left.\begin{array}{l} P_1 = 6 \text{ MPa} \\ T_1 = 400°\text{C} \end{array}\right\} \begin{array}{l} v_1 = 0.047420 \text{ m}^3/\text{kg} \\ h_1 = 3178.3 \text{ kJ/kg} \end{array}$$



and

$$\left.\begin{array}{l} P_2 = 40 \text{ kPa} \\ x_2 = 0.90 \end{array}\right\} h_2 = h_f + x_2 h_{fg} = 317.62 + 0.90 \times 2392.1 = 2470.5 \text{ kJ/kg}$$

(a) The change in kinetic energy is determined from

$$\Delta ke = \frac{V_2^2 - V_1^2}{2} = \frac{(55 \text{ m/s})^2 - (90 \text{ m/s})^2}{2}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right) = \mathbf{-2.54 \text{ kJ/kg}}$$

(*b*) There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the turbine as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as

$$\cancel{\frac{dE_s}{dt}} = \cancel{\dot{Q}} - \dot{W}_s + \dot{m}_i(h_i + V_i^2/2 + \cancel{gZ_i}) - \dot{m}_e(h_e + V_e^2/2 + \cancel{gZ_e}) = 0$$

$$\dot{m}_i = \dot{m}_e = \dot{m}$$

$$\dot{W}_s + \dot{m}(h_2 + V_2^2/2) = \dot{m}(h_1 + V_1^2/2) \quad (\text{since } \dot{Q} \cong \Delta\text{pe} \cong 0 \text{ and adiabatic})$$

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

Then the power output of the turbine is determined by substitution to be

$$\dot{W}_s = -(18 \text{ kg/s})(2470.5 - 3178.3 - 2.54)\text{kJ/kg} = 12{,}786 \text{ kW} = \mathbf{12.79 \text{ MW}}$$

(*c*) The inlet area of the turbine is determined from the mass flow rate relation,

$$\dot{m} = \frac{1}{v_1}A_1V_1 \longrightarrow A_1 = \frac{\dot{m}v_1}{V_1} = \frac{(18 \text{ kg/s})(0.047420 \text{ m}^3/\text{kg})}{90 \text{ m/s}} = \mathbf{0.00948 \text{ m}^2}$$

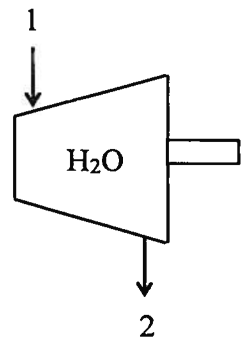
7 [redacted]

This is a steady-flow process. Kinetic and potential energy changes are negligible. The device is adiabatic.

Properties From the steam tables

$$\left.\begin{aligned} P_1 &= 10\ \text{MPa} \\ T_1 &= 500°\text{C} \end{aligned}\right\} h_1 = 3375.1\ \text{kJ/kg}$$

$$\left.\begin{aligned} P_2 &= 10\ \text{kPa} \\ x_2 &= 0.88 \end{aligned}\right\} h_2 = h_f + x_2 h_{fg} = 191.81 + 0.88 \times 2392.1 = 2296.9\ \text{kJ/kg}$$



There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the turbine as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as

$$\cancel{\frac{dE_s}{dt}} = \cancel{\dot{Q}} - \dot{W}_s + \dot{m}_i(h_i + \cancel{V_i^2/2} + \cancel{gZ_i}) - \dot{m}_e(h_e + \cancel{V_e^2/2} + \cancel{gZ_e}) = 0$$

$$\dot{m}_i = \dot{m}_e = \dot{m}$$

$$\dot{W}_s + \dot{m}h_2 = \dot{m}h_1 \quad (\text{since } \Delta ke \cong \Delta pe \cong 0)$$

$$\dot{W}_s = \dot{m}(h_1 - h_2)$$

Substituting, the required mass flow rate of the steam is determined to be

$$+5800\ \text{kJ/s} = \dot{m}(3375.1 - 2296.9)\ \text{kJ/kg} \longrightarrow \dot{m} = \mathbf{5.38\ kg/s}$$

Positive because it is work output from the turbine.

8

Question 14

This is a steady-flow process. Kinetic and potential energy changes are negligible. Air is an ideal gas with constant specific heats.

The constant pressure specific heat of air is determined at the average temperature c_p = 1.018 kJ/kg·K. The gas constant of air is R = 0.287 kPa·m^3/kg·K.

There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the compressor as the system, which is a control volume since mass crosses the boundary.

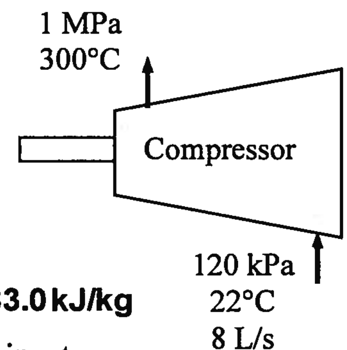
The energy balance for this steady-flow system can be expressed in the rate form as

$$\cancel{\frac{dE_s}{dt}} = \cancel{\dot{Q}} - \dot{W}_s + \dot{m}_i(h_i + \cancel{V_i^2/2} + \cancel{gZ_i}) - \dot{m}_e(h_e + \cancel{V_e^2/2} + \cancel{gZ_e}) = 0$$

$$\dot{m}_i = \dot{m}_e = \dot{m}$$

$$\dot{W}_s + \dot{m}h_2 = \dot{m}h_1 \quad \text{(since } \Delta ke \cong \Delta pe \cong 0\text{)}$$

$$\dot{W}_s = \dot{m}(h_1 - h_2)$$



$$\dot{W}_s = \dot{m}(h_1 - h_2) = \dot{m}c_p(T_1 - T_2)$$

Thus,

$$w_s = c_p(T_1 - T_2) = (1.018\,\text{kJ/kg}\cdot\text{K})(295 - 573)\text{K} = \mathbf{-283.0\,kJ/kg}$$

Negative to denote work input

The specific volume of air at the inlet and the mass flow rate are

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(22+273\,\text{K})}{120\,\text{kPa}} = 0.7055\,\text{m}^3/\text{kg}$$

$$\dot{m} = \frac{\dot{V}_1}{v_1} = \frac{0.008\,\text{m}^3/\text{s}}{0.7055\,\text{m}^3/\text{kg}} = 0.01134\,\text{kg/s}$$

Then the power input is determined from the energy balance equation to be

$$\dot{W}_s = \dot{m}w_s = \mathbf{-3.21\,kW}$$

9

[redacted]

This is a steady-flow process. Potential energy changes are negligible. The device is adiabatic. Argon is an ideal gas with constant specific heats.

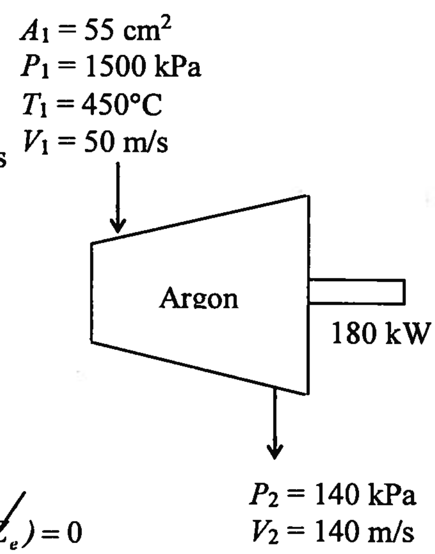
The gas constant of Ar is $R_s = 0.2081$ kPa.m^3/kg.K. The constant pressure specific heat of Ar is $c_p = 0.5203$ kJ/kg·K

There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. The inlet specific volume of argon and its mass flow rate are

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.2081\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(723\ \text{K})}{1500\ \text{kPa}} = 0.1003\ \text{m}^3/\text{kg}$$

Thus,

$$\dot{m} = \frac{1}{v_1}A_1V_1 = \frac{1}{0.1003\ \text{m}^3/\text{kg}}(0.0055\ \text{m}^2)(50\ \text{m/s}) = 2.742\ \text{kg/s}$$



We take the turbine as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as

$$\cancel{\frac{dE_s}{dt}} = \cancel{\dot{Q}} - \dot{W}_s + \dot{m}_i(h_i + V_i^2/2 + \cancel{gZ_i}) - \dot{m}_e(h_e + V_e^2/2 + \cancel{gZ_e}) = 0$$

$$\dot{m}_i = \dot{m}_e = \dot{m}$$

$$\dot{m}(h_1 + V_1^2/2) = \dot{W}_s + \dot{m}(h_2 + V_2^2/2) \quad (\text{since } \dot{Q} \cong \Delta\text{pe} \cong 0)$$

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

Substituting,

$$+180\ \text{kJ/s} = -(2.742\ \text{kg/s})\left[(0.5203\ \text{kJ/kg}\cdot\text{K})(T_2 - 723\text{K}) + \frac{(140\ \text{m/s})^2 - (50\ \text{m/s})^2}{2}\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right)\right]$$

It yields

$T_2 =$ **580.4K**

10 [redacted]

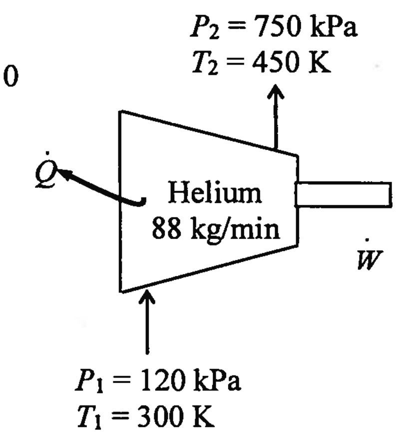
This is a steady-flow process. Kinetic and potential energy changes are negligible. Helium is an ideal gas with constant specific heats.

The constant pressure specific heat of helium is given as $c_p = 5.1926$ kJ/kg·K

There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$.
We take the compressor as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as

$$\cancel{\frac{dE_s}{dt}} = \dot{Q} - \dot{W}_s + \dot{m}_i(h_i + \cancel{V_i^2/2} + gZ_i) - \dot{m}_e(h_e + \cancel{V_e^2/2} + gZ_e) = 0$$

$$\dot{m}_i = \dot{m}_e = \dot{m}$$



$$\dot{W}_s - \dot{Q} = \dot{m}(h_1 - h_2) \quad \text{(since } \Delta\text{ke} \cong \Delta\text{pe} \cong 0\text{)}$$

$$\dot{W}_s = \dot{m}(h_1 - h_2) + \dot{Q} = \dot{m}c_p(T_1 - T_2) + \dot{Q}$$

Thus,

$$\dot{W}_s = \dot{Q} + \dot{m}c_p(T_1 - T_2)$$
$$= (88/60 \text{ kg/s})(-18 \text{ kJ/kg}) + (88/60 \text{ kg/s})(5.1926 \text{ kJ/kg}\cdot\text{K})(300 - 450)\text{K}$$
$$= -1168.8 \textbf{ kW}$$

Work input **Heat loss**

11 [redacted]

This is a steady-flow process. The turbine is well-insulated, and thus adiabatic. Air is an ideal gas with constant specific heats.

The constant pressure specific heat of air at the average temperature of (500+127)/2 = 314°C = 587 K is c_p = 1.048 kJ/kg·K. The gas constant of air is R_s = 0.287 kPa·m^3/kg·K

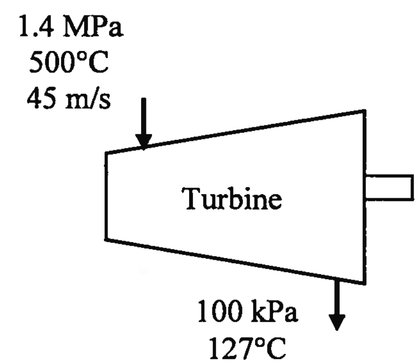
There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the turbine as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as

$$\cancel{\frac{dE_s}{dt}} = \cancel{\dot{Q}} - \dot{W}_s + \dot{m}_i(h_i + V_i^2/2 + \cancel{gZ_i}) - \dot{m}_e(h_e + V_e^2/2 + \cancel{gZ_e}) = 0$$

$$\dot{m}_i = \dot{m}_e = \dot{m}$$

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

$$\dot{W}_s = \dot{m}\left(h_1 - h_2 + \frac{V_1^2 - V_2^2}{2}\right) = \dot{m}\left(c_p(T_1 - T_2) + \frac{V_1^2 - V_2^2}{2}\right)$$



The specific volume of air at the inlet and the mass flow rate are

$$\upsilon_1 = \frac{RT_1}{P_1} = \frac{(0.287\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(500+273\,\text{K})}{1400\,\text{kPa}} = 0.1585\,\text{m}^3/\text{kg}$$

$$\dot{m} = \frac{A_1 V_1}{\upsilon_1} = \frac{(0.18\,\text{m}^2)(45\,\text{m/s})}{0.1585\,\text{m}^3/\text{kg}} = \mathbf{51.1\,kg/s}$$

Similarly at the outlet,

$$\upsilon_2 = \frac{RT_2}{P_2} = \frac{(0.287\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(127+273\,\text{K})}{100\,\text{kPa}} = 1.148\,\text{m}^3/\text{kg}$$

$$V_2 = \frac{\dot{m}\upsilon_2}{A_2} = \frac{(51.1\,\text{kg/s})(1.148\,\text{m}^3/\text{kg})}{1\,\text{m}^2} = 58.66\,\text{m/s}$$

(*b*) Substituting into the energy balance equation gives

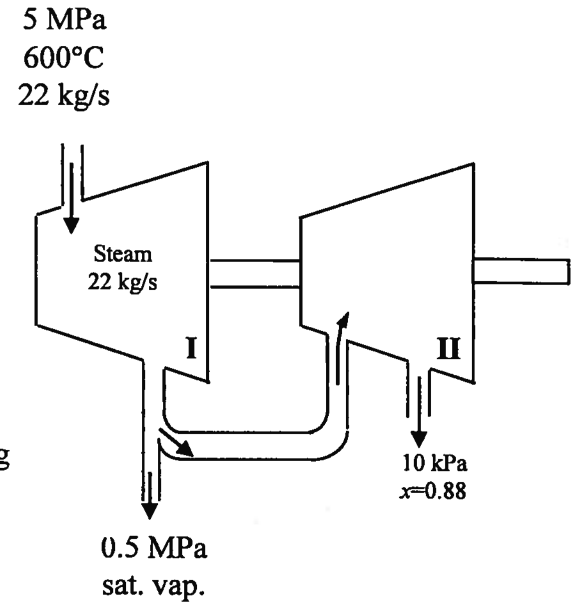
$$\dot{W}_s = \dot{m}\left(c_p(T_1 - T_2) + \frac{V_1^2 - V_2^2}{2}\right)$$

$$= (51.1\,\text{kg/s})\left[(1.048\,\text{kJ/kg}\cdot\text{K})(773-400)\text{K} + \frac{(45\,\text{m/s})^2 - (58.66\,\text{m/s})^2}{2}\left(\frac{1\,\text{kJ/kg}}{1000\,\text{m}^2/\text{s}^2}\right)\right]$$

$$= \mathbf{19{,}939\,kW}$$

12 [redacted]

This is a steady-flow process. Kinetic and potential energy changes are negligible. The turbine is adiabatic.



From the steam tables

$$\left.\begin{array}{l} P_1 = 5\ \text{MPa} \\ T_1 = 600°\text{C} \end{array}\right\} h_1 = 3666.9\ \text{kJ/kg}$$

$$\left.\begin{array}{l} P_2 = 0.5\ \text{MPa} \\ x_2 = 1 \end{array}\right\} h_2 = 2748.1\ \text{kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 10\ \text{kPa} \\ x_2 = 0.88 \end{array}\right\} \begin{array}{l} h_3 = h_f + xh_{fg} \\ \quad = 191.81 + (0.88)(2392.1) = 2296.9\text{kJ/kg} \end{array}$$

We take the entire turbine, including the connection part between the two stages, as the system, which is a control volume since mass crosses the boundary. Noting that one fluid stream enters the turbine and two fluid streams leave, the energy balance for this steady-flow system can be expressed in the rate form as

$$\cancel{\frac{dE_s}{dt}} = \cancel{\dot{Q}} - \dot{W}_s + \sum \dot{m}_i(h_i + \cancel{V_i^2/2 + gZ_i}) - \sum \dot{m}_e(h_e + \cancel{V_e^2/2 + gZ_e}) = 0$$

$\dot{m}_1 = \dot{m}_2 + \dot{m}_3$ (conservation of mass)

$$\dot{m}_1 h_1 = \dot{m}_2 h_2 + \dot{m}_3 h_3 + \dot{W}_s$$

$$\dot{W}_s = \dot{m}_1 (h_1 - 0.08h_2 - 0.92h_3)$$

Substituting, the power output of the turbine is

$$\begin{aligned} \dot{W}_s &= \dot{m}_1 (h_1 - 0.08h_2 - 0.92h_3) \\ &= (22\ \text{kg/s})(3666.9 - 0.08 \times 2748.1 - 0.92 \times 2296.9)\ \text{kJ/kg} \\ &= \mathbf{29{,}346\ kW} \end{aligned}$$

13

Question 19.

Steam expands through a turbine with a mass flow rate of 25 kg/s and a negligible velocity at 6 MPa and 600 °C. The steam leaves the turbine with a velocity of 175 m/s at 0.5 MPa and 200 °C. The rate of work done by the steam in the turbine is measured to be 19 MW. Determine the rate of heat transfer associated with this process.

This is a steady-flow process since there is no change with time. Kinetic and potential energy changes are negligible.

From the steam tables

$$\left.\begin{array}{l} P_1 = 6\text{ MPa} \\ T_1 = 600°\text{C} \end{array}\right\} h_1 = 3658.8\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_2 = 0.5\text{ MPa} \\ T_2 = 200°\text{C} \end{array}\right\} h_2 = 2855.8\text{ kJ/kg}$$

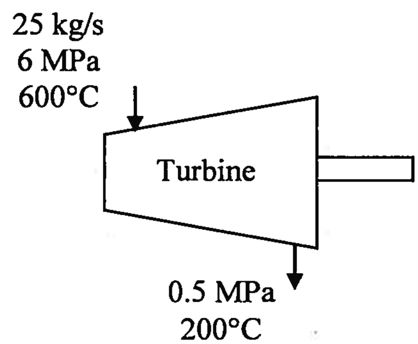
We take the turbine as the system, which is a control volume since mass crosses the boundary. Noting that one fluid stream enters and leaves the compressor, the energy balance for this steady-flow system can be expressed in the rate form as

$$\cancel{dE_s/dt} = \dot{Q} - \dot{W}_s + \sum \dot{m}_i(h_i + V_i^2/2 + \cancel{gZ_i}) - \sum \dot{m}_e(h_e + V_e^2/2 + \cancel{gZ_e}) = 0$$

$$\dot{m}_1 = \dot{m}_2 = \dot{m}$$

$$\dot{m}\left(h_1 + \frac{V_1^2}{2}\right) = \dot{m}\left(h_2 + \frac{V_2^2}{2}\right) + \dot{W}_s - \dot{Q} \quad (\text{since } \Delta\text{pe} \cong 0)$$

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



Substituting,

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

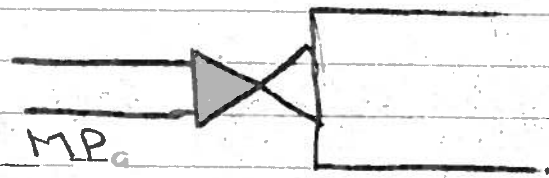
$$= (+19{,}000\text{ kW}) + (25\text{ kg/s})\left[(2855.8 - 3658.8)\text{kJ/kg} + \frac{(175 - 0\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right)\right]$$

$$= -692.2\ \textbf{kW}$$

↑

Negative for heat loss.

Problem [redacted] 14



① $P_1 = 1.2\ MPa$

$T_1 = 20°C$

② $V_1 = V_2$

$T_2 = ?$

$\frac{A_2}{A_1} = ?$

- conservation of mass.

$\dot{m}_1 = \dot{m}_2$

- 1^{st} law of Thermo

$$\cancel{\frac{dE}{dt}\Big|_{cv}} = \cancel{\dot{Q}_{cv}} - \cancel{\dot{W}_{cv}} + \sum_i \dot{m}_i \left(h_i + \tfrac{1}{2}\cancel{V_i^2} + \cancel{g z_i}\right)$$

$$- \sum_e \dot{m}_e \left(h_e + \tfrac{1}{2}\cancel{V_e^2} + \cancel{g z_e}\right)$$

$\cancel{\dot{m}_1} h_1 = \cancel{\dot{m}_2} h_2 \quad \Rightarrow \quad h_1 = h_2$

for an ideal gas this leads to $T_1 = T_2 = 20°C$

Determination of A_2/A_1

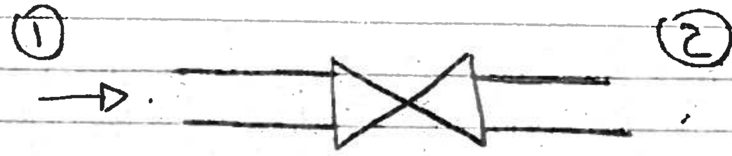
$$\dot{m}_1 = \dot{m}_2 \Leftrightarrow \frac{\cancel{V_1} A_1}{v_1} = \frac{\cancel{V_2} A_2}{v_2}$$

$$\Rightarrow \frac{A_1}{RT_1/P_1} = \frac{A_2}{RT_2/P_2} \Rightarrow A_1 P_1 = A_2 P_2$$

A2/A1=12

Problem [redacted] 15

[redacted]



$P_1 = 1.6\ MPa$ $\qquad$ $P_2 = 300\ kPa$

$T_1 = 250\ °C$

$V_1 = 4.5\ m/s$ $\qquad$ $V_2 = ?$

- conservation of mass

$$\dot{m}_1 = \dot{m}_2$$

Then $\dfrac{V_1 A_1}{v_1} = \dfrac{V_2 A_2}{v_2}$

we have to assume $A_1 = A_2$.

Then $\dfrac{V_1}{v_1} = \dfrac{V_2}{v_2}$

- 1^{st} law of Thermo

$$\cancel{\frac{dE}{dt}}\Big|_{cv} = \cancel{\dot{Q}_{cv}} - \cancel{\dot{W}_{cv}} + \sum_i \dot{m}_i \left(h_i + \frac{1}{2}V_i^2 + \cancel{g z_i}\right)$$
$$0$$

$$- \sum \dot{m}_e \left(h_e + \frac{1}{2}V_e^2 + \cancel{g z_e}\right)$$

$$\dot{m}_1 \left(h_1 + \frac{1}{2}V_1^2\right) = \dot{m}_2 \left(h_2 + \frac{1}{2}V_2^2\right)$$

$$\underset{\checkmark}{h_1} + \frac{1}{2}\underset{\checkmark}{V_1^2} = \underset{?}{h_2} + \frac{1}{2}\underset{?}{V_2^2}$$

we have 1 eq but 2 unknowns.

So, we have to assume ΔE_k negligible compared to Δh and as a consequence

$$h_2 = h_1 = 2919.9 \text{ kJ/kg}$$

we also have:

$$v_1 = v\Big|_{\substack{1.6 MPa \\ 250°C}} = 0.1419 \text{ kg/m}^3$$

know with $\begin{cases} P_2 = 300 \text{ kPa} \\ h_2 = 2919.9 \text{ kJ/kg} \end{cases}$

we have to get v_2? by interpolation

$$v_2 = 0.7588 \text{ kg/m}^3$$

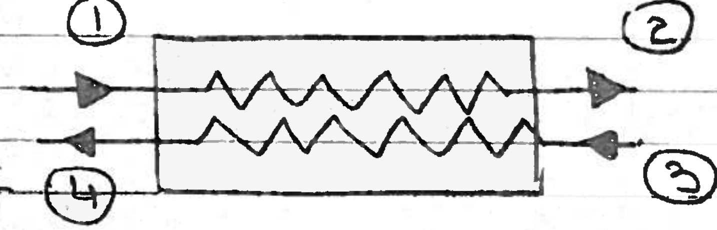
Then $V_2 = v_2 \dfrac{V_1}{v_1} = 0.7588 \dfrac{4.5}{0.1419}$

$$V_2 = 24.06 \text{ m/s}$$

Problem [redacted] 16

$P_1 : 50\,kPa$, $T_1 : 300°C$

$2\,kg/s$



$x_2 = 0$

$T_3 : 20°C$

$T_4 : 35°C$

We have to determine $\dot{m}_3$

Conservation of mass:

$$\begin{cases} \dot{m}_1 = \dot{m}_2 \\ \dot{m}_3 = \dot{m}_4 \end{cases}$$

1^{st} law of Thermodynamics

$$\cancel{\frac{dE}{dt}\Big|_{cv}}^{0} = \cancel{\dot{Q}_{cv}} - \cancel{\dot{W}_{cv}} + \sum_i \dot{m}_i \left(h_i + \cancel{\frac{1}{2}V_i^2} + \cancel{g z_i}\right) - \sum \dot{m}_e \left(h_e + \cancel{\frac{1}{2}V_e^2} + \cancel{g z_e}\right)$$

$$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4$$

but $\dot{m}_1 = \dot{m}_2$ and $\dot{m}_3 = \dot{m}_4$

Then: $\dot{m}_3 = \dot{m}_1 \dfrac{h_2 - h_1}{h_3 - h_4}$

$$h_1 = h\Big|_{\substack{50\,kPa \\ 300°C}} = 3075.8\ kJ/kg$$

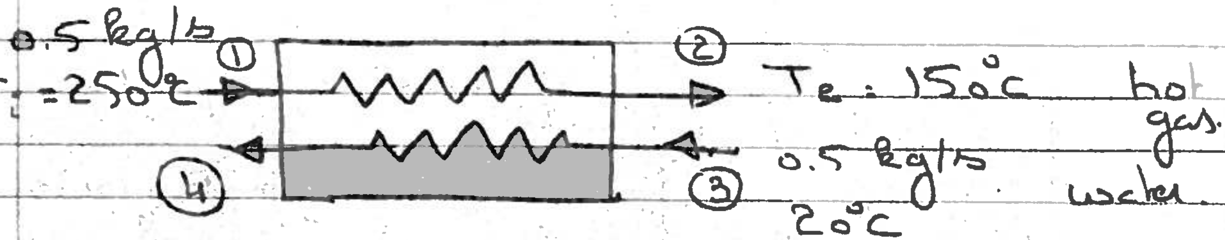
$$h_2 = h\Big|_{\substack{P_2 = 50\ kPa \\ x_2 = 0}} = 340.54\ kJ/kg$$

$$h_3 = h\Big|_{T_3 = 20°C} = h_f\Big|_{T_3 = 20°C} = 83.91\ kJ/kg$$

$$h_4 = h\Big|_{T_4 = 35°C} = h_f\Big|_{T_4 = 35°C} = 146.64\ kJ/kg$$

$$\dot{m}_3 = 87.2\ kg/s$$

Problem [redacted] 17



$Cp_{HG} = 1.08$ kJ/kg K

$Cp_{water} = 4.186$ kJ/kg K

We consider a CV including both substances

1. Conservation of mass

$$\begin{cases} \dot{m}_1 = \dot{m}_2 \\ \dot{m}_3 = \dot{m}_4 \end{cases}$$

2. 1st law of Thermo

$$\cancel{\frac{dE}{dt}}\Big|_{cv} = \cancel{\dot{Q}}_{cv} - \cancel{\dot{W}}_{cv} + \sum \dot{m}_i \left(h_i + \cancel{\tfrac{1}{2}V_i^2} + \cancel{gz_i}\right)$$

$$- \sum \dot{m}_e \left(h_e + \cancel{\tfrac{1}{2}V_e^2} + \cancel{gz_e}\right)$$

$$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4$$

$$\dot{m}_1 (h_1 - h_2) = \dot{m}_3 (h_4 - h_3)$$

$$\dot{m}_1 (h_1 - h_2) = \dot{m}_3 Cp_{water} (T_4 - T_3)$$

$$\dot{m}_1 Cp_{HG} (T_1 - T_2) = \dot{m}_3 Cp_{water} (T_4 - T_3)$$

Then $T_4 = 45.8°C$

Chapter 6

Second law of thermodynamics

18 [redacted]

$1\ hp = 0.7457\ kW$

$W = 30 \times 0.7457 = 22.37\ kW$

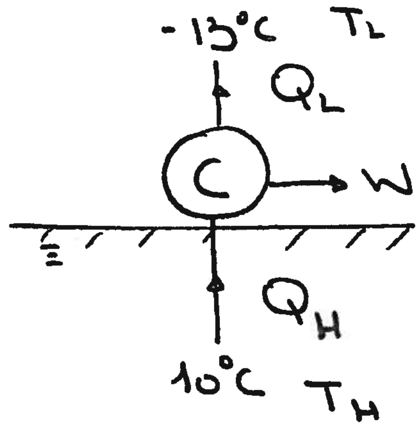
$\eta_{th} = \frac{W}{Q} = \frac{22.37}{\text{[redacted]}} =$ [redacted] 0.39

should be (35 +22.37)

$\eta_{th} =$ [redacted] should be 39%

[redacted]

19



Carnot efficiency will be:

$$\eta_c = 1 - \frac{T_L}{T_H} = 1 - \frac{273.15-13}{273.15+10}$$

$$\eta_c = 0.0812 \quad \text{or} \quad 8\%$$

Hence, the maximal efficiency will be only 8%.

[redacted] . [redacted]

20

Let us compute the thermal efficiency of the inventor's heat engine

$$\eta = \frac{\dot{W}}{\dot{Q}_{in}} = \frac{\dot{Q}_{in} - \dot{Q}_{out}}{\dot{Q}_{in}} = \frac{300 - 100}{300}$$

$$\eta = 66.7\,\%$$

Let us compare this efficiency to a Carnot heat engine working between $T_H = 1000$ K and $400\text{ K} = T_L$

$$\eta_{Carnot} = 1 - \frac{T_L}{T_H} = 1 - \frac{400}{1000} = 0.6$$

$$\eta_{Carnot} = 60\,\%$$

So, $\eta_{inventor} > \eta_{Carnot}$ impossible (so far ....)

STEAM POWER CYCLES: SIMPLE RANKINE CYCLE

II.1. (Tutorial) Determine the thermal efficiency of a simple Rankine cycle operating under the following conditions:
- Condenser exit temperature: 45°C
- Boiler exit pressure: 4 MPa
- Maximal temperature: 500°C

II.2. (Tutorial) Determine the thermal efficiency of the simple Rankine cycle in problem II.1 knowing that the isentropic efficiencies of the pump and the turbine are 85% and 90%, respectively.

II.3. (Tutorial) Consider a simple Rankine cycle with the following operating conditions:
- Condenser exit temperature: 45°C
- Boiler exit pressure: 3 MPa
- Maximal temperature: 600°C
- Mass flow rate: 40 kg/s

a) Determine the power output produced by this cycle.
b) Assuming a cooling water, entering at a temperature of 10°C and leaving at 17°C, is used to condensate the steam in the condenser, determine the required mass flow rate for this cooling water. Cp (cooling water) = 4.18 kJ/kg K.

Simple Rankine cycle

II.1

✓ C.V. pump

$$w_p = \cdot v_1 \, (P_2 - P_1) = 0.00101 \, (4000 - 9.6)$$

$$w_p = 4.03 \text{ kJ/kg}$$

✓ C.V. Boiler

$$q_{in} = q_{23} = h_3 - h_2$$

with $h_3 = h\big|_{\substack{4MPa \\ 500°C}} = 3445.3$ kJ/kg

$$h_2 = h_1 - (w_p) = 188.45 + 4.03$$

$$h_2 = 192,45 \text{ kJ/kg}$$

with $h_1 = h\big|_{\substack{x_1 = 0 \\ T_1 = 45°C}} = 188.45$ kJ/kg

Then $q_{in} = 3445.3 - 192.45$

$$q_{in} = 3252.8 \text{ kJ/kg}$$

CV. Turbine

$w_T = h_3 - h_4$

with $h_3 = 3445.3$ kJ/kg

and $h_4 = h\Big|_{\substack{T_4 = 45°C \\ s_4 = s_3}}$

knowing that $s_3 = s\Big|_{\substack{4MPa \\ 500°C}} = 7.0901$ kJ/kg·

Then $x_4 = 0.8572$

and $h_4 = 2241.3$ kJ/kg

So, $w_T = h_3 - h_4$

$= 3445.3 - 2241.3$

$= 1204$ kJ/kg

finally, $\eta_{th} = \dfrac{w_{net}}{q_{in}}$

$= \dfrac{1204 - 4.03}{3252.0}$

$\eta_{th} = 0.369$ or 36.9%

II.2

The simplest approach is to consider:

$$\eta = \frac{\eta_T w_T - \frac{w_P}{\eta_P}}{q_{in}}$$

$$= \frac{0.9 \times 1204 - \frac{4.03}{0.85}}{3252.8}$$

$$\eta = 0.3316 \text{ or } 33.16\%$$

II.3

$$h_1 = h\Big|_{\substack{x_1=0 \\ T_1=45°C}} = 188.42 \text{ kJ/kg}.$$

This also gives $\vartheta_1 = 0.00101 \text{ m}^3/\text{kg}$
$P_1 = 9.59 \text{ kPa}.$

$$h_3 = h\Big|_{\substack{3 MPa. \\ 600°C}} = 3682.34 \text{ kJ/kg}$$

- Power output

$$\dot{W} = \dot{m}(\omega_T - \omega_P)$$

$$\omega_P = -\vartheta_1(P_2 - P_1) = -0.00101(3000 - 9.6)$$

$$\omega_P = -3.02 \text{ kJ/kg}$$

$$\omega_T = h_3 - h_4$$

$$h_3 = 3682.34 \text{ kJ/kg}$$

$$h_4 = h\Big|_{\substack{T_4=45°C \\ s_4=s_3}} \longrightarrow x_4 = 0.9128$$

$s_3 = 7.5084 \text{ kJ/kg K}.$

$$h_4 = 2374.4 \text{ kJ/kg}$$

Then $\omega_T = h_3 - h_4 = 1307.94$ kJ/kg

and

$$\dot{W} = \dot{m}(\omega_T - \omega_p)$$

$$= 40(1307.94 - 3.02)$$

$$\dot{W} = 52.20 \text{ MW}$$

* Mass flow rate of cooling water.

we have to compute the heat rejected by the condenser.

$$q_L = q_{41} = h_1 - h_4$$

$$= 188.42 - 2374.4$$

$$q_L = -2186 \text{ kJ/kg}$$

but $\dot{Q}_L = \dot{m}_w \, C_{p_{water}} \, \Delta T = \dot{m}_{steam} \, q_L$

Then. $$\dot{m}_w = \frac{\dot{m}_{steam} \, q_L}{C_{p_w} \, \Delta T} = \frac{40 \times 2186}{4.18(17-10)}$$

$$\dot{m}_w = 2988 \text{ kg/s}$$

STEAM POWER CYCLES: SIMPLE RANKINE REHEAT CYCLE

III.1. Consider a simple Rankine cycle with a reheat process. Steam enters the turbine at a temperature of 600°C and a pressure of 3 MPa and leaves at temperature of 45°C. The reheat process is perform at 500 kPa and brings the steam to a temperature of 400°C.

- Sketch the T-s diagram for this cycle.
- Determine the thermal efficiency of this cycle.

III.2. Consider a simple Rankine cycle with a reheat process. Steam enters the turbine at a temperature of 400°C and a pressure of 3 MPa and leaves at a pressure of 10 kPa. The reheat process is perform at 800 kPa and brings the steam to a temperature of 400°C.

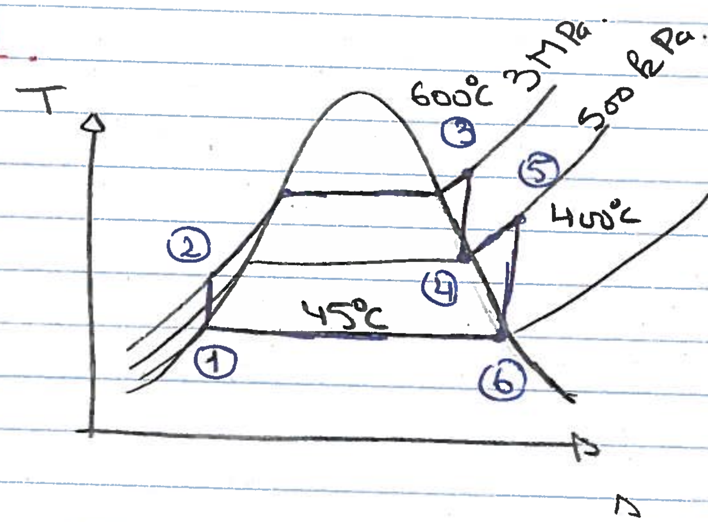
- Sketch the T-s diagram for this cycle.
- Determine the thermal efficiency of this cycle.

III.3. (Tutorial) Consider a simple Rankine cycle with a two reheat processes. Steam enters the turbine at a temperature of 400°C and a pressure of 3 MPa and leaves at a pressure of 10 kPa. A first reheat process is perform at 1200 kPa and brings the steam to a temperature of 400°C. Then a second reheat process is perform at 800 kPa and brings the steam also to a temperature of 400°C

- Sketch the T-s diagram for this cycle.
- Determine the thermal efficiency of this cycle.

Simple Rankine Reheat

III . 1.



- we neglect the work of the pump

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{w_T}{q_{in}}$$

- computation of w_T

$$w_T = (h_3 - h_4) + (h_5 - h_6)$$

$h_3 = 3682.34$ kJ/kg

$h_4 = 3093.26$ kJ/kg

$h_5 = 3271.83$ kJ/kg

$h_6 = 2465.1$ kJ/kg $(x_6 = 0.9507)$

$$w_T = 1395.81 \text{ kJ/kg}$$

- Computation of q_{in}

$$q_{in} = (h_3 - h_2) + (h_5 - h_4)$$

with $h_2 = h_1 = 188.42$ kJ/kg

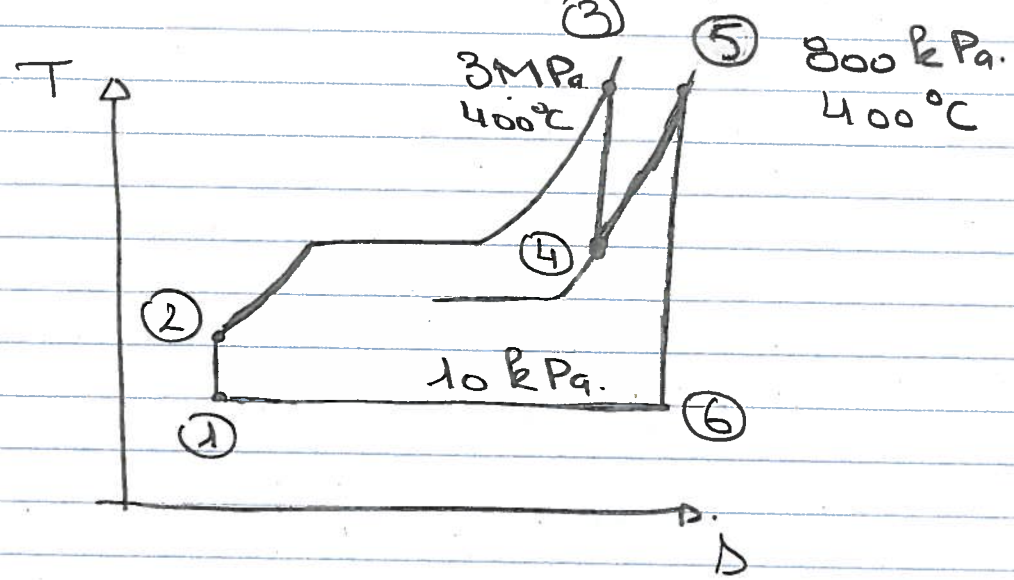
$$q_{in} = 3672.5 \text{ kJ/kg}$$

Then

$$\eta_{th} = \frac{1395.81}{3672.5} = 0.38$$

$$\eta_{th} = 38\ \%$$

II



- We neglect the work of the pump

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{w_T}{q_{in}}$$

$$w_T = (h_3 - h_4) + (h_5 - h_6)$$

$h_3 = 3230.82$ kJ/kg

$h_4 = 2891.6$ kJ/kg

$h_5 = 3267.1$ kJ/kg

$h_6 = 2400$ kJ/kg $(x_6 = 0.923)$

$$w_T = 1237.8 \text{ kJ/kg}$$

- Computation of q_{in}

$$q_{in} = (h_3 - h_2) + (h_5 - h_4)$$

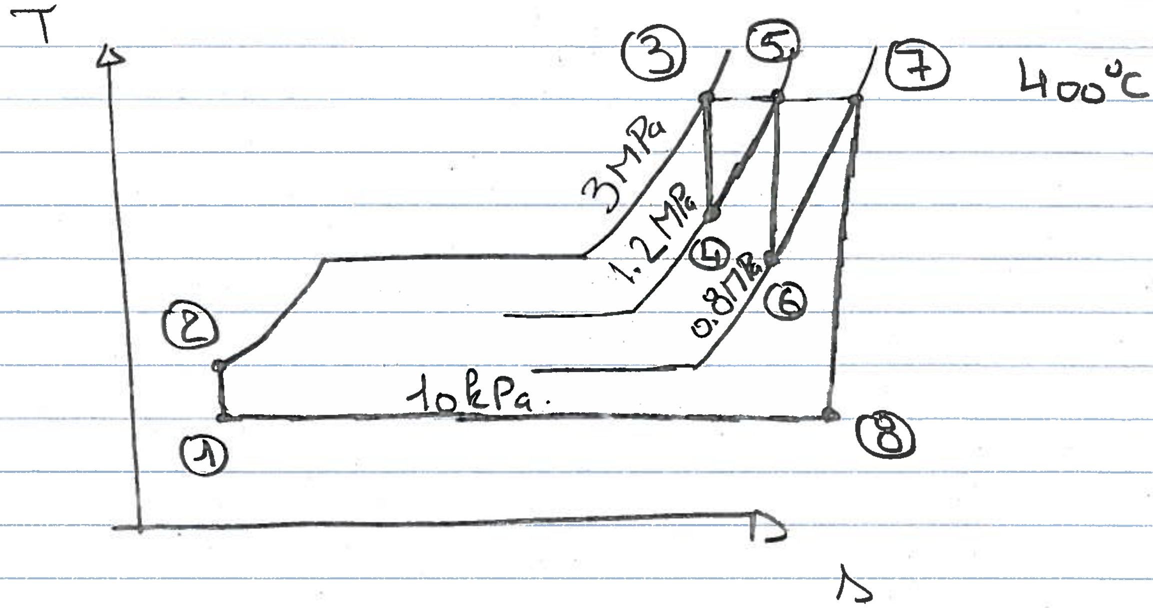
with $h_2 = h_1 = 191.81$ kJ/kg

$$q_{in} = 3414.5 \text{ kJ/kg}$$

$$\eta_{th} = 0.3625$$

$$\eta_{th} = 0.36 \%$$

III



we neglect the work of the pump

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{w_T}{q_{in}}$$

- computation of w_T

$$w_T = (h_3 - h_4) + (h_5 - h_6) + (h_7 - h_8)$$

$h_3 = 3230.82$ kJ/kg

$h_4 = 2985.3$ kJ/kg

$h_5 = 3260.7$ kJ/kg

$h_6 = 2811.2$ kJ/kg

$h_7 = 3276.5$ kJ/kg

$h_8 = 2400$ kJ/kg (superheated vapor)

$w_T = \boxed{1572}$ kJ/kg

- computation of q_{in}

$q_{in} = (h_3 - h_2) + (h_5 - h_4) + (h_7 - h_6)$

with $h_2 = h_1 = 191.81$ kJ/kg

$q_{in} = 3824$ kJ/kg

$\eta_{th} = 0.40$

$\eta_{th} = 40$ %

Note: values may change a bit depending on the tables used.

STEAM POWER CYCLES: REGENRATIVE RANKINE CYCLE

IV.1. (Tutorial) In an ideal regenerative Rankine cycle, the maximal pressure and the maximal temperature reach 10 MPa and 550°C, respectively. Steam is extracted from the turbine at 1 MPa and the condenser operates at a pressure of 10 kPa.

- Determine the cycle efficiency assuming the cycle uses a closed FWH (Fig IV.1).

- Determine the cycle efficiency assuming the cycle uses now an open FWH.

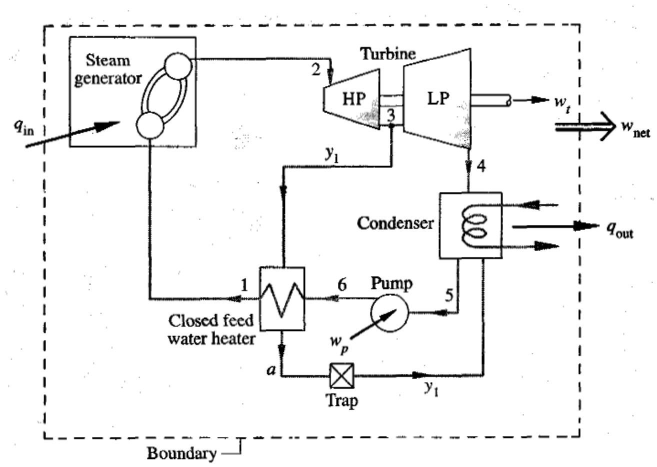


Figure IV.1

h_1	closedFWH: 762.6 kJ/kg openFWH: 772.6 kJ/kg	h_2	3501.9 kJ/kg
h_3	2856.9 kJ/kg	h_4	2139.3 kJ/kg
h_5	191.8 kJ/kg	h_6	closedFWH: 201.9 kJ/kg openFWH: 192.8 kJ/kg
h_7	762.5 kJ/kg		

IV.2. Consider the ideal reheat-regenerative Rankine cycle sketched in Figure (IV.2).

- Write the expression of the work the turbine.

- Use the 1st law of thermodynamics to derive the expression for y_1 and y_2 as a function of enthalpies.

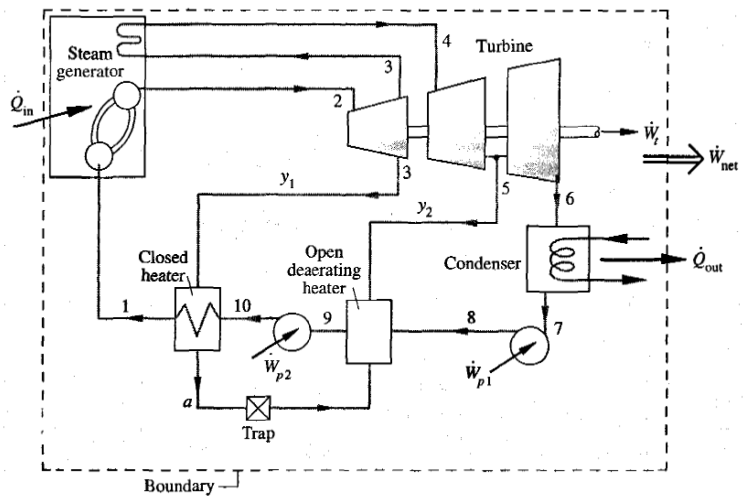


Figure IV.2

IV.3. (Tutorial) Consider the ideal regenerative Rankine cycle sketched in Figure (IV.3).

- Write the expression of the work of the turbine.

- Use the 1st law of thermodynamics to derive the expression for y_1, y_2 and y_3 as a function of enthalpies.

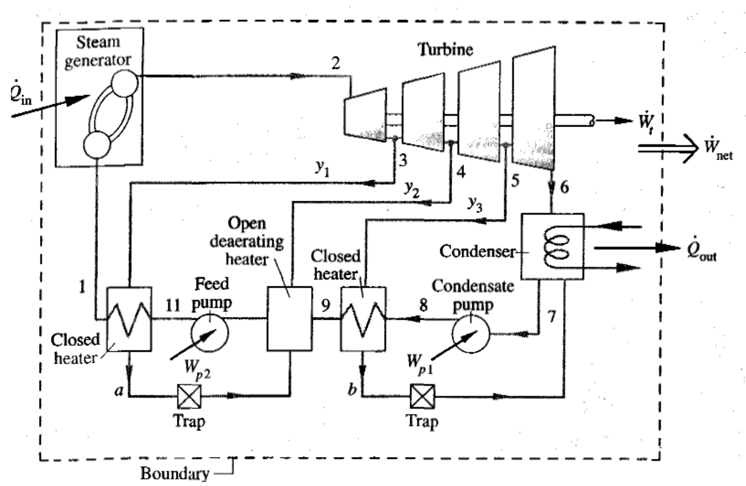
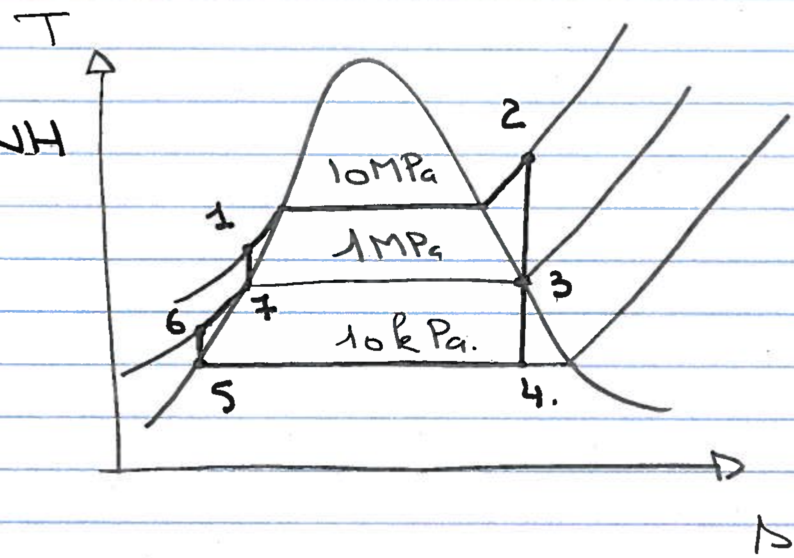


Figure IV.3

Regenerative Rankine

IV.1

open FWH



$$w_T = (h_2 - h_3) + (1-y)(h_3 - h_4)$$

with

$$y = \frac{h_7 - h_6}{h_3 - h_6} = 0.2176$$

Then $w_T = 1206$ kJ/kg

also $q_{in} = h_2 - h_1 = 2729.3$ kJ/kg

So $\eta = \frac{1206}{2729.3} = 0.441$ or 44.1%

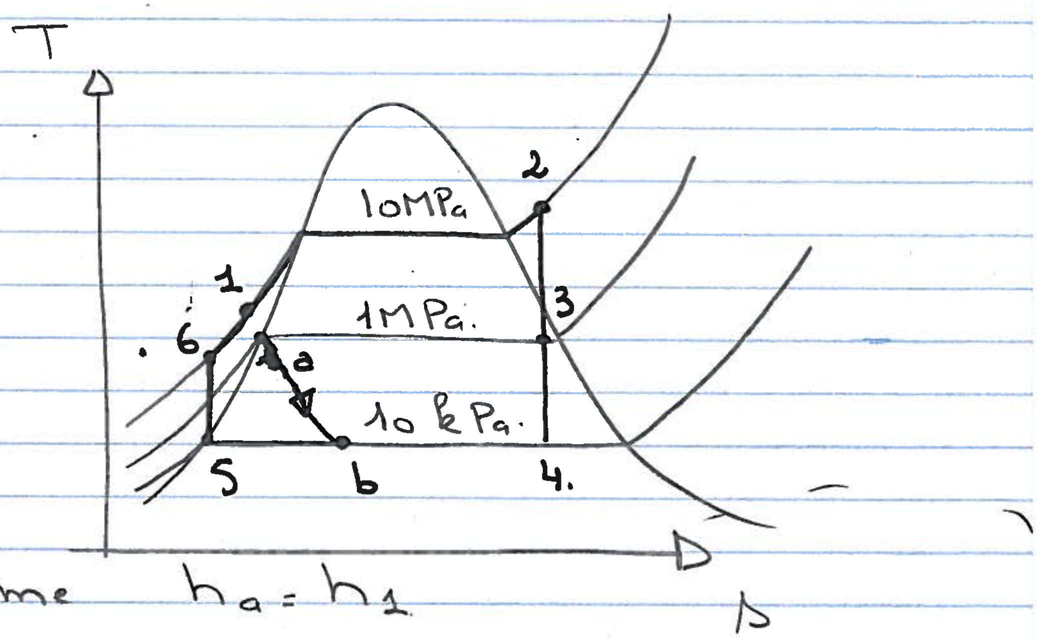
Note: considering $w_p \rightarrow \eta = 43.8\%$

Regenerative Rankine

IV.1

Closed

FWH



✓ assume $h_a = h_1$

$$w_T = (h_2 - h_3) + (1-y)(h_3 - h_4)$$

with $y = \dfrac{h_1 - h_6}{h_3 - h_a} = 0.2677$

Then $w_T = 1170$ kJ/kg

and $q_{in} = h_2 - h_1 = 2739.4$ kJ/kg

So $\eta = \dfrac{1170}{2739.4} = 0.427$ (42.7%)

Note: considering $w_p \rightarrow \eta = 42.3\%$

Regenerative Rankine + Reheat

IV.2

$$w_T = (h_2 - h_3) + (1 - y_1)(h_4 - h_5) + (1 - y_1 - y_2)(h_5 - h_6)$$

- We consider CV ≡ closed FWH

$$y_1 = \frac{h_1 - h_{10}}{h_3 - h_a}$$

- We consider CV ≡ open FWH

$$y_2 = \frac{(h_a - h_8) - y_1 (h_a - h_8)}{h_5 - h_8}$$

Note: $q_{in} = (h_2 - h_1) + (1 - y_1)(h_4 - h_3)$

Regenerative Rankine

IV.3

$$w_T = (h_2 - h_3) + (1 - y_1)(h_3 - h_4) + (1 - y_1 - y_2)(h_4 - h_5) + (1 - y_1 - y_2 - y_3)(h_5 - h_6)$$

WoW!!

- CV ≡ closed FWH (before the Boiler)

$$y_1 h_3 + (1) h_{11} = y_1 h_a + (1) h_1$$

$$y_1 = \frac{h_1 - h_{11}}{h_3 - h_a}$$

- CV ≡ open FWH.

$$y_2 h_4 + y_1 h_a + (1 - y_1 - y_2) h_9 = (1) h_{10}$$

$$y_2 = \frac{(h_{10} - h_9) - y_1 (h_a - h_9)}{h_4 - h_9}$$

- CV = closed FWH

$$y_3 h_5 + (1 - y_1 - y_2) h_8 = y_3 h_6 + (1 - y_1 - y_2) h_9$$

$$y_3 = (1 - y_1 - y_2) \frac{h_9 - h_8}{h_5 - h_6}$$

STEAM POWER CYCLES: COGENERATION CYCLE

V. A client of your engineering consulting company plans to build a cogeneration power plant running under the following conditions:

- Total mass flow rate of 30 kg/s
- Maximal pressure of 7 MPa and a maximal temperature of 500°C.
- Condenser pressure of 7.5 kPa
- 10 kg/s steam extracted from the turbine to the process heat at a pressure 500 kPa. The exit of the process heat is a saturated liquid at a pressure of 100 kPa.
- Determine the power output for the turbine and the process heat transfer.

h_1= 168.79 kJ/kg

h_2= 168.88 kJ/kg

h_5= 3410.3 kJ/kg

h_6= 2738.6 kJ/kg

h_7= 2119 kJ/kg

h_8= 417.6 kJ/kg

GAS POWER CYCLES: OTTO CYCLE

VI.1. In an ideal gasoline engine, the inlet air pressure and temperature are 95 kPa and 300 K. The engine has a compression ratio of 8 and requires 1500 kJ/kg of heat per cycle.

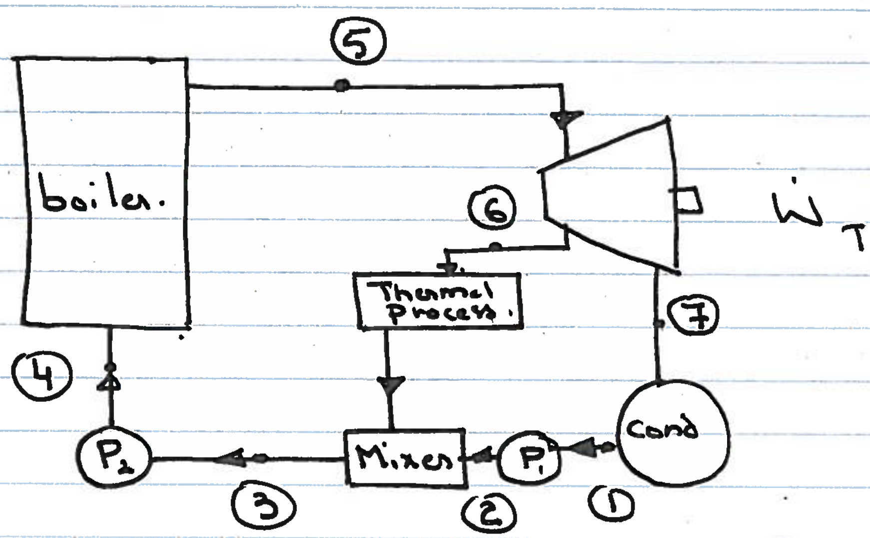
- Determine the maximal temperature for this cycle.
- Determine its thermal efficiency and the corresponding Carnot efficiency.

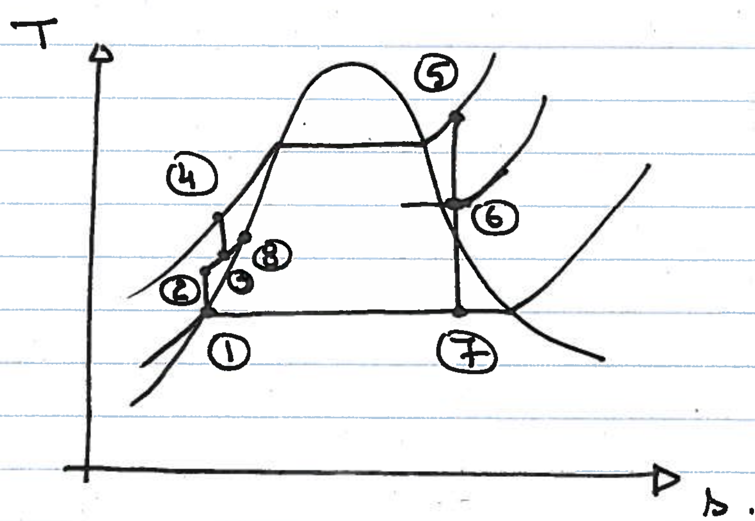
VI.2. A four stroke, four cylinders gasoline engine running at 2000 rpm has a compression ratio of 10. The total displacement volume is 2.5 L. Air enters the engine at a pressure of 70 kPa and a temperature of 280 K. 1800 kJ/kg of heat is added per cycle, through a combustion process.

- Determine the power produced by the engine.

k=1.4; C_v=0.717 kJ/kg K; R= 0.287 kJ/kg K

Cogeneration





$$\dot{W}_T = \dot{m}_5 (h_5 - h_6) + \dot{m}_7 (h_6 - h_7)$$

$$\dot{m}_5 = 30 \text{ kg/s}$$

$$\dot{m}_7 = 20 \text{ kg/s}.$$

$$\dot{W}_T = 30 (3410.3 - 2738.6)$$

$$+ 20 (2738.6 - 2119)$$

$$\dot{W}_T = 32{,}54 \text{ MW}.$$

$$\dot{Q}_P = \dot{m}_6 (h_6 - h_8)$$

$$= 10 (2738.6 - 417.46)$$

$$\dot{Q}_P = 23.21 \text{ MW}$$

Otto cycle

VI . 1

Computation of the maximal T°. (T_3)

$$T_3 = T_2 + \frac{q_{in}}{c_v}$$

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

$$= 300\ (8)^{1.4-1} = 689.2\,K.$$

Then $T_3 = 689.2 + \dfrac{1500}{0.717}$

$$T_3 = 2781\ K$$

Thermal efficiency

$$\eta_{otto} = 1 - \frac{1}{r^{k-1}} = 0.56 \text{ or } 56\%$$

$$\eta_{Carnot} = 1 - \frac{T_1}{T_3} = 0.89 \text{ or } 98\%$$

IV Determination of the power produced by the engine

We have: $\eta_{otto} = 1 - \frac{1}{r^{k-1}} = 1 - \frac{1}{10^{1.4-1}}$

$$\eta_{otto} = 0.602$$

Then, $w_{net} = q_{in} \, \eta_{otto}$

$= 1800 \times 0.602$

$$w_{net} = 1083.6 \text{ kJ/kg}$$

We also have:

$$\dot{W} = P_{eff} \, V_{disp} \, \frac{rpm}{60} \, \frac{1}{2}$$

we have then to compute the mean effective pressure P_{eff}

$$P_{eff} = \frac{w_{net}}{v_1 - v_2} = \frac{w_{net}}{v_1 \left(1 - \frac{1}{r}\right)}$$

with $v_1 = \frac{RT_1}{P_1} = 0.287 \, \frac{280}{70} = 1.148 \, \frac{m^3}{kg}$

Then $P_{eff} = \dfrac{1083.6}{1.148\left(1 - \frac{1}{10}\right)} = 1048.8 \text{ kPa.}$

and

$$\dot{W} = 1048.8 \times 0.0025 \; \frac{2000}{60} \; \frac{1}{2}$$

$$\dot{W} = 43.7 \text{ kW}$$

GAS POWER CYCLES: BRAYTON CYCLE

I. (Tutorial) 15 kg/s of air enters an air-standard Brayton cycle at 100 kPa, 20°C. The pressure ratio is 12 and the maximal temperature in the cycle is 1100°C. , and the pressure ratio across the compressor is 12:1. The maximum temperature in the cycle is 1100°C. Determine the compressor power, the turbine power, and the thermal efficiency of the cycle.

C_p= 1.004 kJ/kg K

II.a. Air enters the compressor of a gas turbine at 27°C and 100 kPa. The pressure ratio is 10, and the maximum temperature at the exit of the combustion chamber is 1350 K.

- Determine the pressure and temperature at each state in the cycle
- Determine the work of the compressor and the work of the turbine.
- Determine the thermal cycle efficiency per kilogram of air.

II.b. Consider the isentropic efficiencies of the compressor and the turbine are 85%.

Determine the new thermal efficiency.

C_p= 1.0047 kJ/kg K

III. (Tutorial) An ideal regenerator is incorporated into the ideal air-standard Brayton cycle of Problem I. determine the new thermal efficiency for the cycle.

Assume now a regenerator with an efficiency of 75%. Determine the new thermal efficiency for the cycle.

Brayton cycle

II. a

- State I

$T_1 = 300\ K$, $P_1 = 100\ kPa$.

- State ②

$r_p = \frac{P_2}{P_1} = 10 \longrightarrow P_2 = 1000\ kPa$.

$T_2 = T_1 (r_p)^{\frac{k-1}{k}} = 579.6\ K$

- State ③

$P_3 = P_2 = 1000\ kPa$

$T_3 = T_{max} = 1350\ K$

- State ④

$P_4 = P_1 = 100\ kPa$

$T_4 = T_3 \left(\frac{P_4}{P_3}\right)^{\frac{k-1}{k}} = 698.8\ K$

- Work of the compressor

$w_c = -c_p(T_2 - T_1) = -280.9$ kJ/kg

- work of the turbine

$w_T = c_p(T_3 - T_4) = 654.3$ kJ/kg

- Heat addition

$q_{in} = c_p(T_3 - T_2) = 774.0$ kJ/kg

- Thermal efficiency

$$\eta = \frac{w_{net}}{q_{in}} = \frac{w_T - w_c}{q_{in}}$$

$\eta = 0.482$ or 48.2%

- Considering η_c and η_T equal to 85%

Then: $$\eta = \frac{\eta_T w_T - \frac{w_c}{\eta_c}}{q_{in}}$$

$\eta = 29\%$

Brayton cycle.

I). • compressor work.

$$T_2 = T_1 (r_p)^{\frac{k-1}{k}} = 596.8\,K.$$

Then $w_c = -c_p (T_2 - T_1)$

$$w_c = 304.8 \text{ kJ/kg}.$$

$$\dot{W}_c = \dot{m}\, w_c = 4572 \text{ kW}$$

• Work of the Turbine

$$T_4 = T_3 \left(\frac{1}{r_p}\right)^{\frac{k-1}{k}} = 674.4\,K.$$

Then $w_T = c_p (T_3 - T_4)$

$$= 701.3 \text{ kJ/kg}$$

$$\dot{W}_T = \dot{m}\, w_T = 10520 \text{ kW}$$

• Thermal efficiency

$$q_{in} = c_p (T_3 - T_2) = 779.5 \text{ kJ/kg}$$

Then $\eta = \dfrac{w_T - w_c}{q_{in}} = 0.509$

or

$\sim 51\%$

Brayton + regeneration

III adding a regenerator does not change w_c and w_T, but reduces q_{in} and q_{out}.

for an ideal regenerator $T_5 = T_4$.
T_5 being the T° exiting the regenerator and entering the combustion chamber

Then, $q_{in} = c_p (T_3 - T_4)$
$= 701.3$ kJ/kg

(compared to 779.5 kJ/kg without regenerator)

Then $\eta = \dfrac{w_T - w_c}{q_{in}} = 0.565$

or 56.5%

compared to 51% without regeneration

- For a regenerator with 75% we have.

$$\eta_{reg} = \frac{T_5 - T_2}{T_4 - T_2} = 0.75$$

then $T_5 = 655\ K$.

and the new q_{in} will be

$$q_{in} = c_p (T_3 - T_5)$$
$$= 721\ kJ/kg$$

and the new thermal efficiency is $\eta \approx 55\%$

GAS POWER CYCLES: JET ENGINES

I. (Tutorial) A jet aircraft is flying at a speed of 280 m/s at an altitude where the atmospheric pressure is 55 kPa and the temperature is -18°C. The compressor pressure ratio is 14 and the maximal temperature at the inlet of the turbine is 1450 K. At the inlet of the jet engine, a diffuser increases the pressure and brings the relative air velocity, relative to the aircraft, to zero.

Determine:

- The temperature and pressure at the inlet of the compressor
- The exit velocity.

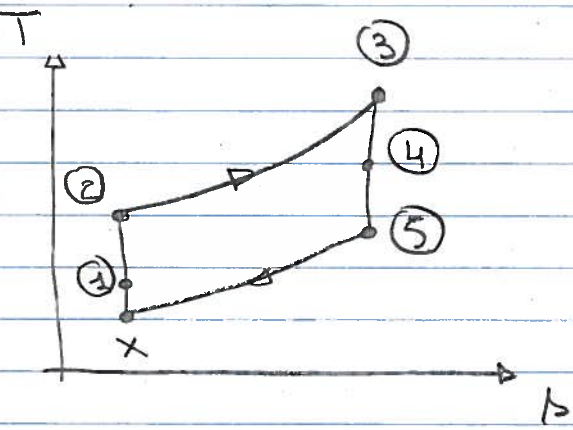
II. An afterburner is used to increase the temperature and pressure after the turbine exit. Assume the pressure and temperature at the exit of the turbine to 250 kPa and 800 K. Assume also that the afterburner increases the pressure while keeping the specific volume constant. Assume the additional combustion resulting from the afterburner adds 450 kJ/kg of energy.

Determine:

- The relative increase in exit velocity due to the afterburner

Jet engine

I.



The conditions at the entrence of the diffuser are:

$V_x = 280$ m/s

$T_x = 255.2$ K , $P_x = 55$ kPa

- Determination of T_1 and P_1

Through the diffuser

$$T_1 = T_x + \frac{V_x^2}{2\,c_p} = 255.2 + \frac{(280)^2}{2 \times 1.004 \times 1000}$$

$$T_1 = 294.3 \text{ K}$$

Then $P_1 = P_x \left(\frac{T_1}{T_x}\right)^{k/k-1} = 55 \left(\frac{294.3}{255.2}\right)^{\frac{k}{k-1}}$

$$P_1 = 90.5 \text{ kPa}$$

- Computation of V_{exit}

we have: $V_5 = \sqrt{2\, c_p\, (T_4 - T_5)}$

we need to get T_4 and T_5

for T_4, we know that

$W_c = W_T \iff c_p (T_2 - T_1) = c_p (T_3 - T_4)$

with $T_1 = 294.3$ K and $T_3 = 1450$ K

and $T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = 626$ K

Then $T_4 = 1118.3$ K

for T_5, we know that

$T_5 = T_4 \left(\frac{P_5}{P_4}\right)^{\frac{k-1}{k}}$

with $P_4 = P_3 \left(\frac{T_4}{T_3}\right)^{k/(k-1)} = 510$ kPa

knowing that $P_3 = P_2 = r_p \times P_1$

Then $T_5 = 591.5$ K

and $V_5 = 1028$ m/s

II

- without afterburner:

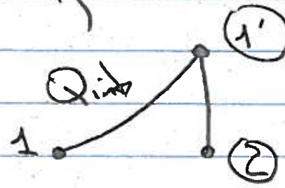
$$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = 800 \left(\frac{95}{250}\right)^{(k-1)/k}$$

$$T_2 = 606.8\ K$$

Then $V_2 = \sqrt{2 c_p (T_1 - T_2)}$

$$V_2 = 622.8\ m/s$$

- with the afterburner.



$$T_{1'} = T_1 + \frac{q_{in}}{c_v} = 800 + \frac{450}{0.717} = 1427.6\ K$$

and

$$v_1 = v_{1'} \Rightarrow P_{1'} = P_1 \left(\frac{T_{1'}}{T_1}\right)$$

$$= 250 \left(\frac{1427.6}{800}\right) = 446.1\ kPa$$

Then $T_2 = T_{1'} \left(\frac{P_2}{P_{1'}}\right)^{\frac{k-1}{k}}$.

$$T_2 = 917.7\ K$$

So $V_2 = \sqrt{2 c_p (T_{1'} - T_2)}$

$$= 1012\ m/s$$

the afterburner increase the speed by $\sim 63\%$

GAS POWER CYCLES: BRAYTON CYCLE WITH INTERCOOLING AND REHEAT

I. (Tutorial) An ideal gas-turbine has two stages of compression and two stages of expansion. The pressure ratio across each stage, for both the compressor and the turbine is 8. The inlet conditions for first compressor are 20°C and 100 kPa. The temperature at the entrance of the second compressor is also 20°C. The temperature entering each turbine is 1100°C. In order to optimize the thermal efficiency of the cycle, an ideal regenerator is installed at the exit of the second turbine.

Determine:

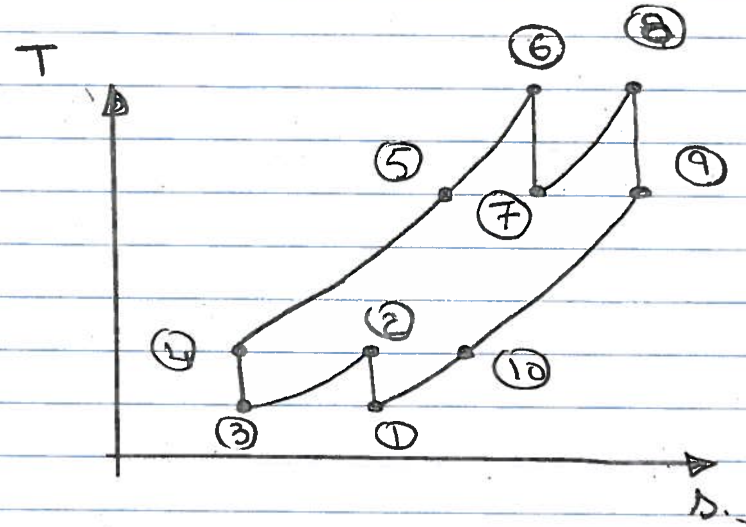
- The compressor work.

- The turbine work.

- The thermal efficiency of the cycle.

C_p= 1.004 kJ/kg K

Brayton cycle with intercooling and reheat



We have:

$$\frac{P_2}{P_1} = \frac{P_4}{P_3} = \frac{P_6}{P_7} = \frac{P_8}{P_9} = 8$$

$P_1 = 100$ kPa.

$T_1 = T_3 = 20°C$ and $T_6 = T_8 = 1100°C$

- Work of the compressor

$$W_c = 2\,W_{12} = 2\,c_p\,(T_2 - T_1)$$

with $T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$

$$= 293.2\,(8)^{\frac{k-1}{k}}$$

$$T_2 = 531.4\ K = T_4$$

Then $w_c = 2\, c_p (T_2 - T_1)$

$= 2\; 1.004\, (531.4 - 293.2)$

$w_c = 478.1$ kJ/kg

- Work of the turbine

$w_T = 2\, w_{67} = 2\, c_p (T_6 - T_7)$

with $T_7 = T_6 \left(\frac{P_7}{P_6}\right)^{\frac{k-1}{k}}$

$= 1373.2 \left(\frac{1}{8}\right)^{\frac{k-1}{k}}$

$T_7 = 757.6\ K = T_9$

Then $w_T = 2\, c_p (T_6 - T_7)$

$= 2\; 1.004\, (1373.2 - 757.6)$

$w_T = 1235.5$ kJ/kg

- Thermal efficiency

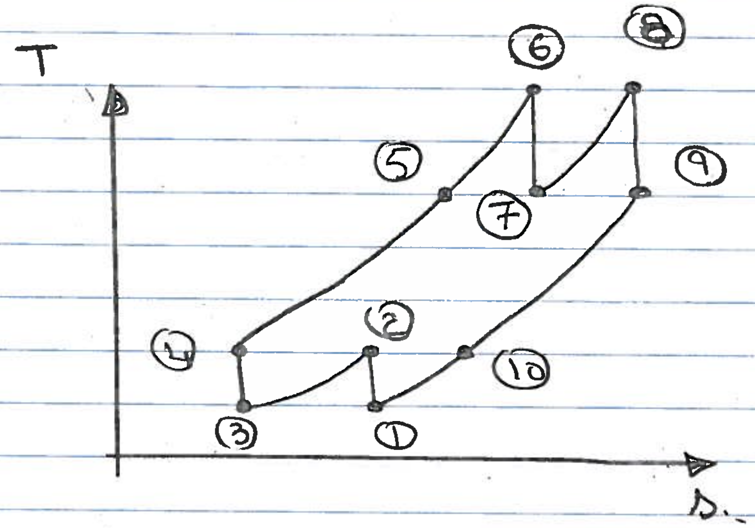
$q_{in} = (h_6 - h_5) + (h_8 - h_7)$

but $T_5 = T_9 = T_7$ and $T_{10} = T_2 = T_4$.

Then $q_{in} = 2\, c_p (T_6 - T_5)$
$= 1235.5$ kJ/kg

$\eta_{th} = 0.613$

Brayton cycle with intercooling and reheat



we have:

$$\frac{P_2}{P_1} = \frac{P_4}{P_3} = \frac{P_6}{P_7} = \frac{P_8}{P_9} = 8$$

$P_1 = 100$ kPa.

$T_1 = T_3 = 20°C$ and $T_6 = T_8 = 1100°C$

- Work of the compressor

$$w_c = 2\, w_{12} = 2\, c_p (T_2 - T_1)$$

with $T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$

$$= 293.2\, (8)^{\frac{k-1}{k}}$$

$$T_2 = 531.4\ K = T_4$$

then $w_c = 2\, c_p (T_2 - T_1)$

$= 2\ 1.004\ (531.4 - 293.2)$

$w_c = 478.1$ kJ/kg

- Work of the turbine

$w_T = 2\ w_{67} = 2\ c_p (T_6 - T_7)$

with $T_7 = T_6 \left(\frac{P_7}{P_6}\right)^{\frac{k-1}{k}}$

$= 1373.2 \left(\frac{1}{8}\right)^{\frac{k-1}{k}}$

$T_7 = 757.6\ K = T_9$

Then $w_T = 2\ c_p (T_6 - T_7)$

$= 2\ 1.004\ (1373.2 - 757.6)$

$w_T = 1235.5$ kJ/kg

- Thermal efficiency

$q_{in} = (h_6 - h_5) + (h_8 - h_7)$

but $T_5 = T_9 = T_7$ and $T_{10} = T_2 = T_4$.

Then $q_{in} = 2\ c_p (T_6 - T_5)$
$= 1235.5$ kJ/kg

$\eta_{th} = 0.613$

REFRIGERATION CYCLES

I. An ideal refrigerator uses R-12 as the working fluid. It is designed to operate between a minimum temperature of −10°C and a highest pressure of 1 MPa. Determine, heat extracted from the cold space; the heat rejected to the surroundings and its coefficient of performance.

II. A commercial refrigerator is designed to keep the temperature as low as -15°C while the outside temperature is on average 20°C. For this purpose it extracts 5 kW from the cold space. Determine the mass flow rate of R-12 refrigerant required.

III. A refrigerator using R-12 as the working fluid is designed to operate between a minimum temperature of −10°C and a maximum pressure of 1 MPa. The actual temperature measured at the exit of the compressor is 60°C. Determine the heat extracted from the cold space, the coefficient of performance and the isentropic efficiency of the compressor.

IV. Consider an air conditioner unit in a car. The compressor power input is 1.5 kW bringing the R-134a from 201.7 kPa to 1200 kPa by compression. The cold space is a heat exchanger that cools atmospheric air from the outside 30°C down to 10°C and blows it into the car. What is the mass flow rate of the R-134a and what is the low temperature heat transfer rate.

V. A small ammonia absorption refrigeration cycle is powered by solar energy. Saturated vapor ammonia leaves the generator at 50°C, and saturated vapor leaves the evaporator at 10°C. Assuming 7000 kJ/kg of heat is required in the generator (solar collector, determine the overall performance of this system.

VI. An ideal regenerator (heat exchanger) is added into an ideal air-standard refrigeration cycle. The working conditions are so that:

At the inlet of the compressor: T_1 = 15°C; P_1 = 100 kPa

At the exit of the compressor: P_2 = 1.4 MPa
At the inlet of the turbine: T_5 = -50°C

Determine the coefficient of performance for the cycle.

Refrigeration cycles

I.

$h_1 = 183.19$ kJ/kg

$h_2 = 210.1$ kJ/kg

$h_3 = h_4 = 76.22$ kJ/kg

- Heat extracted

$$q_L = h_1 - h_4 = 107 \text{ kJ/kg}$$

- Heat rejected

$$q_H = h_3 - h_2 = -133.9 \text{ kJ/kg}$$

- CoP

$$\text{CoP} = \frac{q_L}{w_c} = \frac{q_L}{q_H - q_L} = 3.98$$

II

$h_1 = 180.97$ kJ/kg

$h_3 = h_4 = 54.87$ kJ/kg

$$\dot{Q}_L = \dot{m}\, q_L = \dot{m}(h_1 - h_4)$$

$$\dot{m} = \frac{\dot{Q}_L}{h_1 - h_4} = \frac{5}{(180.97 - 54.87)}$$

$$\dot{m} = 0.03965 \text{ kg/s}$$

III

$h_1 = 183.19$ kJ/kg

$h_3 = h_4 = 76.22$ kJ/kg

$h_{2a} = 217.97$ kJ/kg

- $q_L = h_1 - h_4 = 107$ kJ/kg

- w_c

$w_{c,ideal} = h_{2s} - h_1$

with $h_{2s} = 210.1$ kJ/kg

$w_{c,ideal} = 26.91$ kJ/kg

while

$w_{c\,actual} = h_{2a} - h_1 = 34.78$ kJ/kg

Then $\eta_c = \dfrac{w_{c\,ideal}}{w_{c\,actual}} = 0.774$

- CoP

$$CoP = \frac{q_L}{w_{c\,actual}} = 3.076$$

IV

$h_1 = 392.28$ kJ/kg

$h_3 = h_4 = 266$ kJ/kg

$h_2 = 429.5$ kJ/kg

- $\dot{m}_{R\text{-}134a}$.

$\dot{W}_c = \dot{m}\, w_c$

$$\dot{m} = \frac{\dot{W}_c}{w_c}$$

with $\dot{W}_c = 1.5$ kW

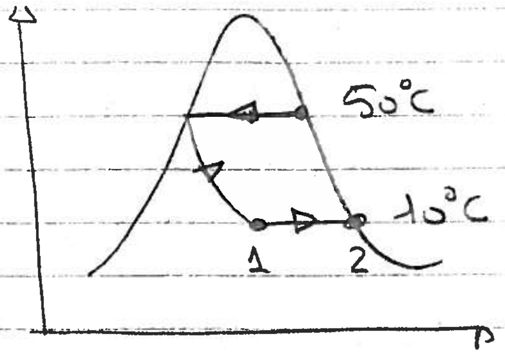
$w_c = h_1 - h_2 = -37.2$ kJ/kg

then $\dot{m} = 0.0403$ kg/s

- $\dot{Q}_L = \dot{m}\,(h_1 - h_4)$

$= 5.21$ kW

V.



$$q_H = 7000 \text{ kJ/kg}_{NH_3}$$

$$q_L = h_2 - h_1$$

with $h_1 = h_f|_{50°C} = 421.6 \text{ kJ/kg}$

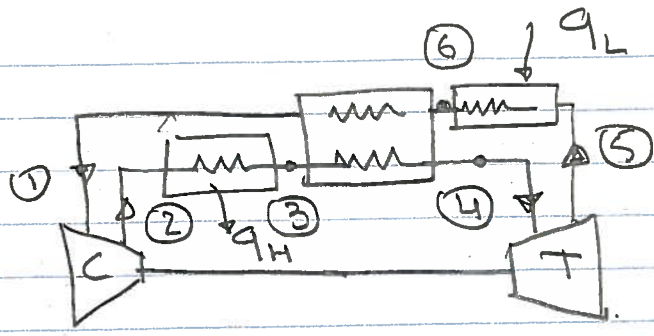
$h_2 = h_g|_{10°C} = 1452.2 \text{ kJ/kg}$

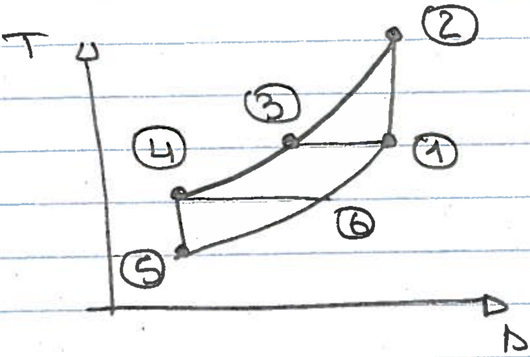
$$q_L = 1030.6 \text{ kJ/kg}$$

- Performance $= \dfrac{q_L}{q_H} = \dfrac{1030.6}{7000}$

$= 0.147$ or 14.7%

IV





$$CoP = \frac{q_L}{w_{net}}$$

- $w_{net} = w_T - w_C$

$w_C = c_p(T_1 - T_2)$

with $T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = 613\ K$

Then $w_C = -326\ kJ/kg$

$w_T = c_p(T_4 - T_5)$

with $T_5 = T_4 \left(\frac{P_5}{P_4}\right)^{\frac{k-1}{k}} = 104.9\ K$

Then $w_T = 118.7\ kJ/kg$

- $q_L = c_p(T_6 - T_5) = w_T = 118.7\ kJ/kg$

- $CoP = \frac{q_L}{w_T - w_C} = 0.573$

GAS MIXTURES AND AIR-VAPOR MIXTURES

GAS-MIXTURES

I. An analysis of the exhaust gases of you engine give the following molar composition:
CO_2 = 10.2%, CO = 0.4%, H_2O = 14.3%, O_2 = 1.9%, and N_2 = 73.2%.
Determine the molecular weight of the products and the mass fraction of each component.

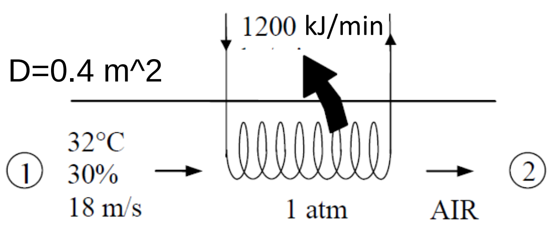
II. (Tutorial) A storage tank at 180 K and 2 MPa includes two kilograms of a mixture of 50% argon and 50% nitrogen by mole. Determine the volume of the storage tank using (a) ideal gas and (b) Kays rule.

AIR-VAPOR MIXTURE

III. An air-vapor mixture at a temperature 38°C is stored in a tank with a volume of 96 m^3. The pressure in the tank is 101 kPa and the relative humidity is 70%. Now, the temperature in the tank is reduced to 10°C at a constant volume.

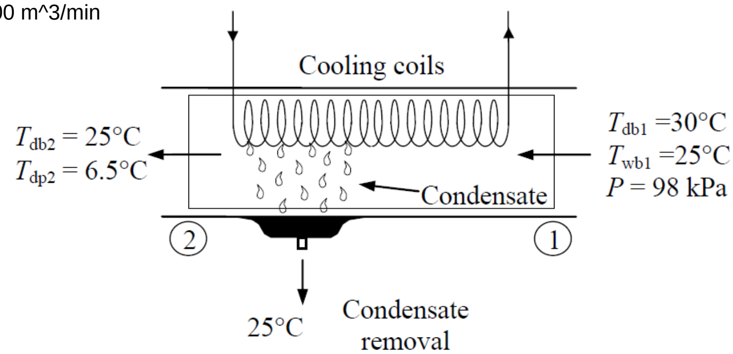
Determine for both the initial and final states: 1) the humidity ratio; 2) the dew point temperature; 3) the mass of the air and the mass of the vapor. Determine also the heat extracted from the tank.

IV. (Tutorial) Determine the exit temperature, the exit relative humidity and the exit velocity of the cooling section sketched below



V. (Tutorial) Determine the rate of heat transfer and the mass flow rate of condensate water in the air conditioner unit sketched below.

Volumetric flow rate: 1000 m^3/min



Gas mixtures

I) $M = \sum y_i M_i$

Then :

$$M = y_{CO_2} M_{CO_2} + y_{CO} M_{CO} + y_{H_2O} M_{H_2O}$$

$$+ y_{O_2} M_{O_2} + y_{N_2} M_{N_2}$$

$$M = 0.102\,(44.01) + 0.004\,(28.01)$$

$$+ 0.143\,(18.016) + 0.019\,(32.0)$$

$$+ 0.732\,(28.016)$$

$$M = 28.29 \ kg/kmol$$

- Mass fractions

$$x_i = y_i \frac{M_i}{M_m}$$

$$x_{CO_2} = 0.102 \ \frac{44.01}{28.29} = 0.159 \ kg_{CO_2}/kg_{mix}$$

$x_{CO} = 0.004 \ kg_{CO}/kg_{mix}$

$x_{H_2O} = 0.091 \ kg_{H_2O}/kg_{mix}$

$x_{O_2} = 0.021 \ kg_{O_2}/kg_{mix}$

$x_{N_2} = 0.725 \ kg_{N_2}/kg_{mix}$

II

a) ideal gas law

$$M_m = \sum y_i M_i$$

$$= 0.5 \; 39.948 + 0.5 \; 28.013$$

$$= 33.981 \text{ kg/kmol}$$

Then $$V = \frac{m R_u T}{M_m P} = \frac{2 \; 8.314 \; 180}{33.981 \; 2000}$$

$$V = 0.044 \text{ m}^3$$

b) Kay's rule

$$P_{c\,mix} = \sum y_i P_{c_i}$$

$$= y_{Ar} P_c|_{Ar} + y_{N_2} P_c|_{N_2}$$

$$= 0.5 \; 4.87 + 0.5 \; 3.39$$

$$P_{c_m} = 4.13 \text{ MPa}$$

$$T_{c\,mix} = \sum y_i T_{c_i} = y_{Ar} T_c|_{Ar} + y_{N_2} T_c|_{N_2}$$

$$= 0.5 \; 150.8 + 0.5 \; 126.2$$

$$T_{c_m} = 138.5 \text{ K}$$

Then, the pseudo-reduced properties

$$P_r = \frac{P}{P_{c_m}} = \frac{2}{4.13} = 0.484$$

$$T_r = \frac{T}{T_{c_m}} = \frac{180}{138.5} = 1.30$$

Then from the chart $Z = 0.925$

So, $$V = Z \frac{m R_u T}{M_m P} = 0.925 \times 0.044$$

$$V = 0.0407 \; m^3$$

$\underline{III}$

$$\boxed{\begin{array}{c} \text{air : vapor} \\ 96\ m^3 \\ 38°C \quad 101\ kPa \\ \phi = 70\% \end{array}}$$

from water tables at 38°C

$P_g : 6.687\ kPa$

and $P_v : \phi P_g : 0.70 \times 6.687$

$P_v : 4.681\ kPa$

• dew point T°"

$$T_{dew} = T_{sat}\Big|_{P=4.681} = 31.5°C$$

• $\omega_1 = 0.622\ \dfrac{\phi P_g}{P - P_v}$

$$= 0.622\ \frac{0.7\ 6.687}{101 - 4.681} = 0.032\ \frac{kg_{vap}}{kg_{air}}$$

• $m_a = \dfrac{P_a V}{R_a T} = \dfrac{96.3 \times 96}{0.287\ 311} = 103.6\ kg$

Since $\omega = \dfrac{m_v}{m_a}$

Then $m_v = \omega\ m_a$

$= 3.13\ kg_{vap}$

(a) 10°C

at 10°C the mixture is saturated because it is lower then the dew point T°"

then $P_{v_2} = P_{g_2} = 1.2287 \text{ kPa}$.

also the pressure of dry air

$$P_{a_2} = \frac{m_a R_a T}{V} = \frac{103.6 \; 0.287 \; 283}{96}$$

$$P_{a_2} = 87.6 \text{ kPa}$$

The total pressure is then.

$$P = P_{a_2} + P_{v_2} = 87.6 + 1.2$$

$$P = 88.8 \text{ kPa}$$

The amount of water condenso is

$$m_f = m_a(\omega_1 - \omega_2)$$

with $\omega_2 = 0.622 \dfrac{P_{v_2}}{P_{a_2}}$

$$\omega_2 = 0.622 \frac{1.2}{87.6} = 0.0085 \; kg_v / kg_{air}$$

Then $m_f = m_a(\omega_1 - \omega_2)$

$$m_f = 103.6(0.0302 - 0.0085)$$

$$m_f = 2.25 \; kg_{water}$$

The mass of the vapor at state 2

is then $m_{v_2} = m_{v_1} - m_f$

$$= 3.13 - 2.25 = 0.88\ kg_{vap}$$

- The amount of heat extracted

$$Q = U_2 - U_1$$

$$U_1 = m_a u_a|_1 + m_v u_v|_1$$

$$U_2 = m_a u_a|_2 + m_v u_v|_2 + m_f u_f$$

Then $Q = U_2 - U_1$

$$Q = m_a (u_a|_2 - u_a|_1)$$

$$+ m_v|_2 u_v|_2 + m_f u_f - m_v|_1 u_v|_1$$

$$Q = 103.6 (0.7176) (283 - 311)$$

$$+ 0.88 \ 2389.3 + 2.25 \ 41.4$$

$$- 3.13 \ 2427.7$$

$$Q = -7484.5\ kJ$$

Tutorial 8

[redacted]

[redacted] = [redacted]0148[redacted]O [redacted]kg dry[redacted]air

[redacted]

[redacted]wb = [redacted]C

[redacted]dp = [redacted]C

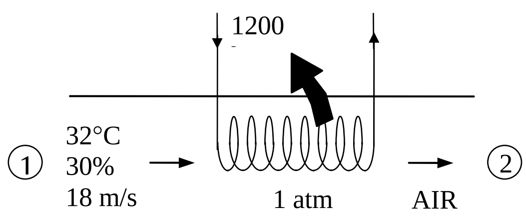
[redacted] $v = 0.868\ \text{m}^3/\text{kg}$[redacted]

14-69 Air enters a cooling section at a specified pressure, temperature, velocity, and relative humidity. The exit temperature, the exit relative humidity of the air, and the exit velocity are to be determined.

Assumptions **1** This is a steady-flow process and thus the mass flow rate of dry air remains constant during the entire process $(\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a)$. **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible.

Analysis (*a*) The amount of moisture in the air remains constant ($\omega_1 = \omega_2$) as it flows through the cooling section since the process involves no humidification or dehumidification. The inlet state of the air is completely specified, and the total pressure is 1 atm. The properties of the air at the inlet state are determined from the psychrometric chart (Figure A-31) to be

$$h_1 = 55.0 \text{ kJ/kg dry air}$$
$$\omega_1 = 0.0089 \text{ kg H}_2\text{O/kg dry air } (= \omega_2)$$
$$v_1 = 0.877 \text{ m}^3/\text{kg dry air}$$



The mass flow rate of dry air through the cooling section is

$$\dot{m}_a = \frac{1}{v_1} V_1 A_1$$
$$= \frac{1}{(0.877 \text{ m}^3/\text{kg})}(18 \text{ m/s})(\pi \times 0.4^2/4 \text{ m}^2)$$
$$= 2.58 \text{ kg/s}$$

From the energy balance on air in the cooling section,

$$-\dot{Q}_{\text{out}} = \dot{m}_a (h_2 - h_1)$$
$$-1200/60 \text{ kJ/s} = (2.58 \text{ kg/s})(h_2 - 55.0) \text{ kJ/kg}$$
$$h_2 = 47.2 \text{ kJ/kg dry air}$$

The exit state of the air is fixed now since we know both h_2 and ω_2. From the psychrometric chart at this state we read

$$T_2 = \mathbf{24.4°C}$$

(*b*) $\phi_2 = \mathbf{46.6\%}$

$$v_2 = 0.856 \text{ m}^3/\text{kg dry air}$$

(*c*) The exit velocity is determined from the conservation of mass of dry air,

$$\dot{m}_{a1} = \dot{m}_{a2} \longrightarrow \frac{\dot{V}_1}{v_1} = \frac{\dot{V}_2}{v_2} \longrightarrow \frac{V_1 A}{v_1} = \frac{V_2 A}{v_2}$$

$$V_2 = \frac{v_2}{v_1} V_1 = \frac{0.856}{0.877}(18 \text{ m/s}) = \mathbf{17.6 \text{ m/s}}$$

14-91 Air flows through an air conditioner unit. The inlet and exit states are specified. The rate of heat transfer and the mass flow rate of condensate water are to be determined.

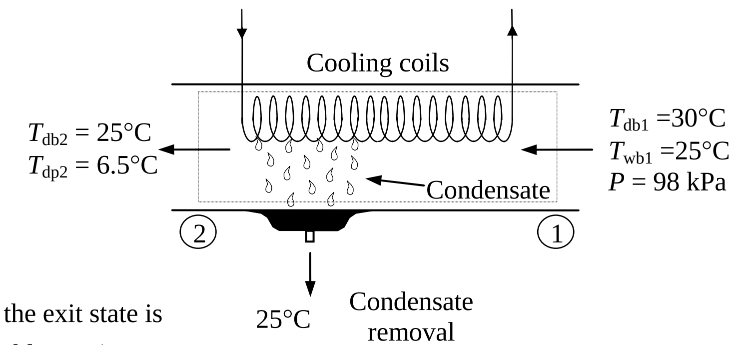
Assumptions **1** This is a steady-flow process and thus the mass flow rate of dry air remains constant during the entire process $(\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a)$. **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible.

Analysis The inlet state of the air is completely specified, and the total pressure is 98 kPa. The properties of the air at the inlet state may be determined from (Fig. A-31) or using EES psychrometric functions to be (we used EES)

$$h_1 = 77.88 \text{ kJ/kg dry air}$$

$$\omega_1 = 0.01866 \text{ kg H}_2\text{O/kg dry air}$$

$$\phi_1 = 0.6721$$



The partial pressure of water vapor at the exit state is

$$P_{v2} = P_{\text{sat@ 6.5°C}} = 0.9682 \text{ kPa} \quad \text{(Table A-4)}$$

The saturation pressure at the exit state is

$$P_{g2} = P_{\text{sat@ 25°C}} = 3.17 \text{ kPa} \quad \text{(Table A-4)}$$

Then, the relative humidity at the exit state becomes

$$\phi_2 = \frac{P_{v2}}{P_{g2}} = \frac{0.9682}{3.17} = 0.3054$$

Now, the exit state is also fixed. The properties are obtained from EES to be

$$h_2 = 40.97 \text{ kJ/kg dry air}$$

$$\omega_2 = 0.006206 \text{ kg H}_2\text{O/kg dry air}$$

$$v_2 = 0.8820 \text{ m}^3\text{/kg}$$

The mass flow rate of dry air is

$$\dot{m}_a = \frac{\dot{V}_2}{v_2} = \frac{1000 \text{ m}^3\text{/min}}{0.8820 \text{ m}^3\text{/kg}} = 1133.8 \text{ kg/min}$$

The mass flow rate of condensate water is

$$\dot{m}_w = \dot{m}_a(\omega_1 - \omega_2) = (1133.8 \text{ kg/min})(0.01866 - 0.006206) = 14.12 \text{ kg/min} = \mathbf{847.2 \text{ kg/h}}$$

The enthalpy of condensate water is

$$h_{w2} = h_{f@ 25°C} = 104.83 \text{ kJ/kg} \quad \text{(Table A-4)}$$

An energy balance on the control volume gives

$$\dot{m}_a h_1 = \dot{Q}_{\text{out}} + \dot{m}_a h_2 + \dot{m}_w h_{w2}$$

$$(1133.8 \text{ kg/min})(77.88 \text{ kJ/kg}) = \dot{Q}_{\text{out}} + (1133.8 \text{ kg/min})(40.97 \text{ kJ/kg}) + (14.12 \text{ kg/min})(104.83 \text{ kJ/kg})$$

$$\dot{Q}_{\text{out}} = 40{,}377 \text{ kJ/min} = \mathbf{672.9 \text{ kW}}$$

CHEMICAL REACTIONS AND COMBUSTION

I. (Tutorial) A fuel oil is burned with 50% excess air, and the combustion characteristics of the fuel are similar to $C_{12}H_{26}$.
Determine the air/fuel ratio, the molar analysis of the products of combustion and the dew point temperature of the products.

II. An unknown hydrocarbon fuel, burned in air, has the following molar analysis: 12.5% CO_2, 0.3% CO, 3.1 O_2, and 84.1% N_2.
Determine the mass air/fuel ratio and the percentage of theoretical air.

III. Propane, C_3H_8, undergoes a steady-state, steady-flow reaction with atmospheric air. Determine the heat transfer per mole of fuel entering the combustion chamber. The reactants and products are at 25°C and 1 atm pressure and the water in the products is in a liquid phase.

IV. (Tutorial) A diesel engine uses dodecane, $C_{12}H_{26\ (V)}$, for fuel. The fuel and air enter the engine at 25°C. The products of combustion leave at 600°K, and 200% theoretical air is used. The heat loss from the engine is measured at 232 000 kJ /kgmol fuel.
Determine the work for a fuel flow rate per kmol/h.

V. (Tutorial) Propane at 25°C and 1 atm is burned with 400% theoretical air at 25°C and 1 atm. The reaction takes place adiabatically, and all the products leave at 1 atm and 942 K. The temperature of the surroundings is 25°C.
Compute the entropy change and the irreversibility.

Chemical Reactions and combustion

I.

$$C_{12}H_{26} + 27.75(O_2 + 3.76N_2)$$

$$\longrightarrow 12CO_2 + 13H_2O + 9.25O_2$$

$$+ 104.34N_2$$

$$AF = \frac{27.75 \times 4.76 \times 29}{(1)\ 170} = 22.53 \frac{kg\ air}{kg\ fuel}$$

- Total number of moles in the products

$$N_m = 12 + 13 + 9.25 + 104.34$$

$$N_m = 138.59$$

Then,

$$y_{CO_2} = \frac{12}{138.59} = 0.0866$$

$$y_{H_2O} = 13/138.59 = 0.0938$$

$$y_{N_2} = 104.34/138.59 = 0.7529$$

$$y_{O_2} = 9.25/138.59 = 0.0667$$

• Dew point Temperature.

$$P_{H_2O} = y_{H_2O} P_{atm}$$

$$= 0.0938 \; 101.3 = 9.5 \text{ kPa}$$

Then $T_{dew} = T_{sat}\Big|_{9.5 \text{ kPa}}$

$$= 45°C$$

II.

$$C_aH_b + c\,O_2 + d\,N_2$$

$$\longrightarrow 12.5\,CO_2 + 0.3\,CO + 3.1\,O_2$$

$$+ 84.1\,N_2 + e\,H_2O$$

C balance : $a = 12.5 + 0.3 = 12.8$

N_2 balance : $d = 84.1$, $\frac{d}{c} = 3.76$

$$c = 22.36$$

O_2 balance:

$$22.36 = 12.5 + \frac{0.3}{2} + 3.1 + \frac{e}{2}$$

$$e = 13.2$$

H_2 balance : $b = 2e = 26.4$

Then (you can round off the number of atoms, of continue the analysis with decimal numbers

$$C_{12.8}H_{26.4} + 22.35(O_2 + 3.76\,N_2)$$

$$\longrightarrow 12.5\,CO_2 + 0.3\,CO + 3.1\,O_2 + 84.1\,N_2$$

$$+ 13.2\,H_2O$$

$$AF = \frac{22.35 \times 4.76 \; 29}{(1) \quad 180} = 17.13$$

Now the reaction with 100%
Theoretical air gives

$$C_{12.8}H_{26.4} + 19.4(O_2 + 3.76 N_2)$$

$$\longrightarrow 12.8 CO_2 + 13.2 H_2O + 73 N_2$$

and

$$AF_{Th} = 14.87$$

The percentage of theoretical air

is then : $100 \dfrac{17.13}{14.87} = 115.2\%$

III.

$$C_3H_8 + 5(O_2 + 3.76 N_2)$$

$$\longrightarrow 3CO_2 + 4H_2O_{(\ell)} + 18.8 N_2$$

1st law:

$$Q = \sum_P n\left(\bar{h}^\circ_f + (\bar{h} - \bar{h}^\circ)\right)$$

$$- \sum_R n\left(\bar{h}^\circ_f + (\bar{h} - \bar{h}^\circ)\right)$$

$$\sum_R n\left(\bar{h}^\circ_f + (\bar{h} - \bar{h}^\circ)\right) = \bar{h}^\circ_f\Big|_{C_3H_8}$$

$$= 103909 \text{ kJ/kmol}$$

$$\sum_P n\left(\bar{h}^\circ_f + (\bar{h} - \bar{h}^\circ)\right) = 3\,\bar{h}^\circ_f\Big|_{CO_2}$$

$$+ 4\,\bar{h}^\circ_f\Big|_{H_2O}$$

$$= -2325311 \text{ kJ/kmol}$$

The $Q = -2221402$ kJ/kmol fuel

IV.

$$C_{12}H_{26(\ell)} + 18.5 \times 2 \times (O_2 + 3.76\,N_2)$$

$$\rightarrow 12\,CO_2 + 13\,H_2O + 18.5\,O_2$$

$$+ 139.1\,N_2$$

1st law

$$Q + \sum_R n_R(\bar{h}^\circ_f + \bar{h} - \bar{h}^\circ)$$

$$= W + \sum n_p(\bar{h}^\circ_f + \bar{h} - \bar{h}^\circ)$$

with

$$\sum n_R(\bar{h}^\circ_f + \bar{h} - \bar{h}^\circ) = -290\,971 \text{ kJ/km.}$$

$$\sum n_p(\bar{h}^\circ_f + \bar{h} - \bar{h}^\circ) = -6171255 \text{ kJ/kms}$$

Then

$$W = 5648\,284 \text{ kJ/kmol fuel}$$

and $\dot{W} = \dot{N}_f W = \dfrac{(1)\ 5648284}{3600}$

$$\dot{W} = 1568.9 \text{ kW}$$

V

$$C_3H_8 + 5 \times 4 \times (O_2 + 3.76 N_2)$$

$$\longrightarrow 3 CO_2 + 4 H_2O + 15 O_2 + 75.2 N_2$$

$$S_R = \sum_R n\bar{S}^\circ = \bar{S}^\circ_{C_3H_8} + 20\bar{S}^\circ_{O_2} + 75.2\bar{S}^\circ_{N_2}$$

$$= 18782 \text{ kJ/kmol K}$$

$$S_P = \sum_P n\bar{S}^\circ = \left(3\bar{S}^\circ_{CO_2} + 4\bar{S}^\circ_{H_2O} + 15\bar{S}^\circ_{O_2} + 75.2\bar{S}^\circ_{N_2}\right) @ 942K$$

$$= 3(266.04) + 4(230.22) + 15(241.47) + 75.2(226.19)$$

$$= 22351 \text{ kJ/kmol K}$$

The irreversibility

$$I = T_0(\bar{S}_P - \bar{S}_R)$$

$$= 298(22351 - 18782)$$

$$= 1063562 \text{ kJ/kmol K}$$