Basic integration problems

1) $$\int (5x^2 - 8x + 5)\,dx = \frac{5x^3}{3} - \frac{8}{2}x^2 + 5x + C$$

2) $$\int (-6x^3 + 9x^2 + 4x - 3)\,dx$$

$$= \frac{-6x^4}{4} + \frac{9}{3}x^3 + \frac{4}{2}x^2 - 3x + C$$

3) $$\int \frac{x^2+4}{x^2}\,dx = \int (1 + 4x^{-2})\,dx$$

$$= x - \frac{4}{x} + C$$

4) $$\int 3e^x\,dx = 3\int e^x\,dx = 3e^x + C$$

5) $$\int x(x+1)^2\,dx = \frac{1}{4}x^4 + \frac{2}{3}x^3 + \frac{1}{2}x^2 + C$$

6) $$\int \left(\frac{4}{x^2} + 2 - \frac{1}{8x^3}\right)dx$$

$$= \int \left(4x^{-2} + 2 - \frac{1}{8}x^{-3}\right)dx$$

$$= -4x^{-1} + 2x + \frac{1}{16}x^{-2} + C$$

7) $$\int \frac{3}{x}\,dx = 3\int \frac{dx}{x} = 3\ln(x) + C$$

8) $\int_0^2 (x^2+3)\,dx = \left[\frac{x^3}{3} + 3x\right]_0^2$

$= \left(\frac{2^3}{3} + 3\times 2\right) - \left(\frac{0^3}{3} + 3\times 0\right)$

$= \frac{8}{3} + 6 = 8.666$

9) $\int \frac{PV}{T}\,dV = ?$; $\int \frac{PV}{T}\,dP = ?$; $\int \frac{PV}{T}\,dV = ?$

$\int \frac{PV}{T}\,dV = \frac{P}{T}\int V\,dV = \frac{P}{T}\left(\frac{V^2}{2} + C\right)$

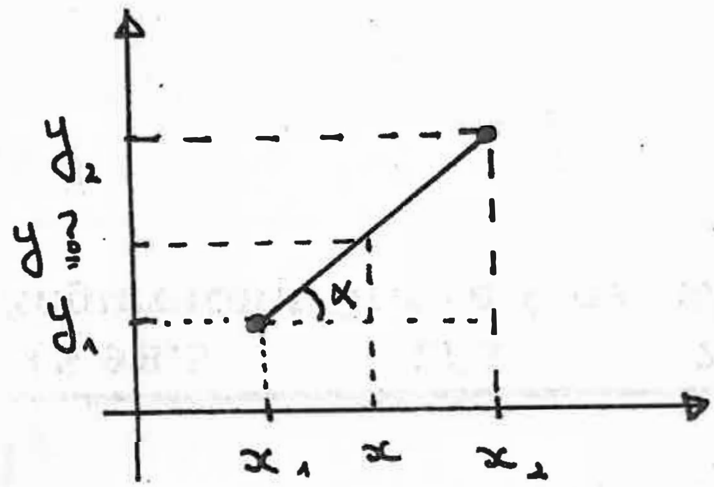
$\int \frac{PV}{T}\,dP = \frac{V}{T}\left(\frac{P^2}{2} + C\right)$

$\int \frac{PV}{T}\,dT = PV\int \frac{1}{T}\,dT = PV\left(\ln(T) + C\right)$

Linear interpolation

Knowing (x_1, y_1) and (x_2, y_2), we try to get the value of (y) at a specific (x).

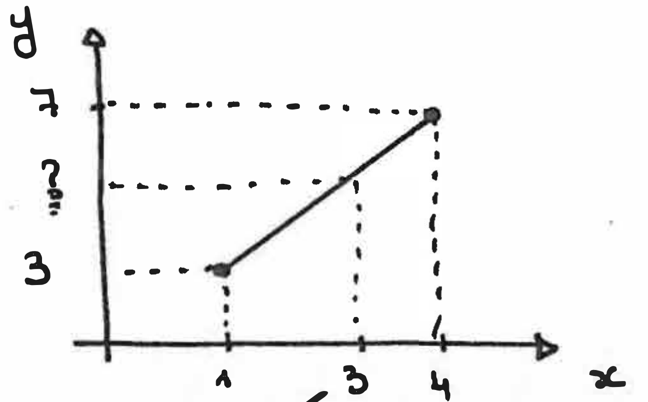
We assume a linear behavior between (x_1, y_1) and (x_2, y_2).



$$tg\,\alpha = \frac{y - y_1}{x - x_1} = \frac{y_2 - y_1}{x_2 - x_1}$$

then,
$$y = y_1 + (x - x_1)\frac{y_2 - y_1}{x_2 - x_1}$$

1) Given $(1,3)$ and $(4,7)$ get the value at $x = 3$.



$$y(3) = y_1 + (x - x_1)\,\frac{y_2 - y_1}{x_2 - x_1}$$

$$= 3 + (3 - 1)\,\frac{7-3}{4-1}$$

$$= 5.66$$

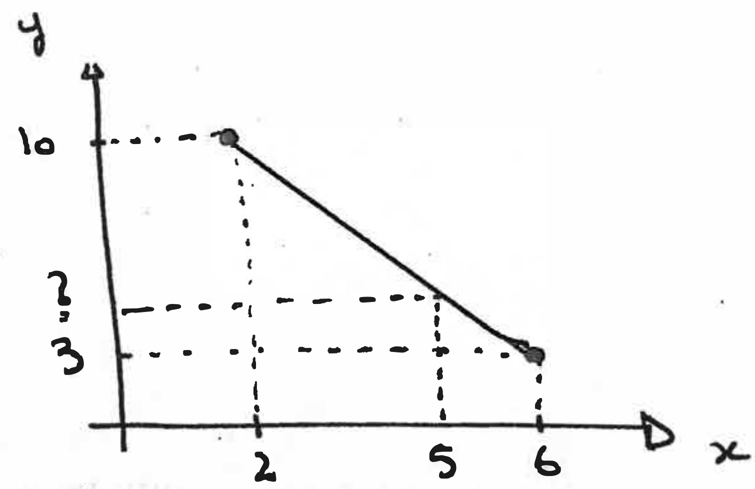
(note that $y(1) < y(3) < y(4)$)

2) Given $\overset{x_1,\,y_1}{(3,8)}$ and $\overset{x_2,\,y_2}{(6,10)}$ get the value at $x = 5$

$$y(5) = 8 + (5-3)\,\frac{10-8}{6-3}$$

$$= 9.33$$

3) Given (2,10) and (6,3) get the value at $x = 5$



x	y
2	10
5	$? = y$
6	3

$$y = y_1 + (x - x_1)\,\frac{y_2 - y_1}{x_2 - x_1}$$

$$y = 10 + (5-2)\,\frac{3-10}{6-2}$$

$$y = 4.75$$

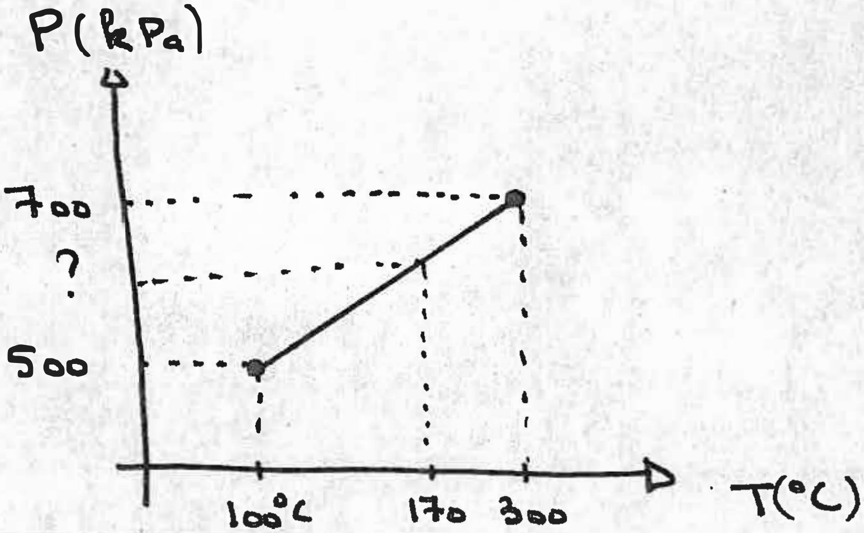
4) Given Temperature and pressure at two differents states:

State 1 : $T_1 : 100°C$, $P_1 : 500$ kPa

State 2 : $T_2 : 300°C$, $P_2 : 700$ kPa

what is the value for the pressure at

$T = 170°C$.



T (°C)	P(kPa)
100	500
170	?
300	700

$$P = P_1 + (T - T_1)\,\frac{P_2 - P_1}{T_2 - T_1)}$$

$$P = 500 + (170 - 100)\left(\frac{700 - 500}{300 - 100}\right)$$

$$P(170) = 570 \text{ kPa}.$$

CHAPTER 1
INTRODUCTION AND BASIC PRINCIPLES

1.1 (Tutorial). Determine if the following properties of the system are intensive or extensive properties:

Property	Intensive	Extensive
Volume		
Density		
Conductivity		
Color		
Boiling point (for a liquid)		
Number of moles		

1.2. State and discuss whether each of the following systems could be analyzed as a closed or open system.
- A lecture room
- Human body
- A car engine
- The sun
- The universe

1.3. State if the following processes could be considered as quasi-static processes
- A compressed gas escaping from a narrow hole in a reservoir
- Combustion in internal combustion engines
- The cooling process of a cup of coffee at 70°C in an environment with a constant temperature of 69.9999°C.

1.4. The state postulate is completely satisfied by:
- Two extensive properties
- One intensive property
- Two intensive, independent properties
- One extensive and one intensive property

1.5. Which thermodynamic property is introduced using the zeroth law of thermodynamics?

1.6. The temperature of a cup of coffee is 23°C. Determine the temperature in K, °F and R? How does it taste? Investigate the reason why?

1.7 (Tutorial). The temperature of a cup of water drops by 40°F when placed in a refrigerator. How much did the temperature of the water change in °C and in K.

1.8 (Tutorial). Find the pressure at the bottom the tank including mercury shown in Fig.1.8. What will be the height if water is used instead of mercury to get the same pressure at the bottom of the tank? Comment on the solution.

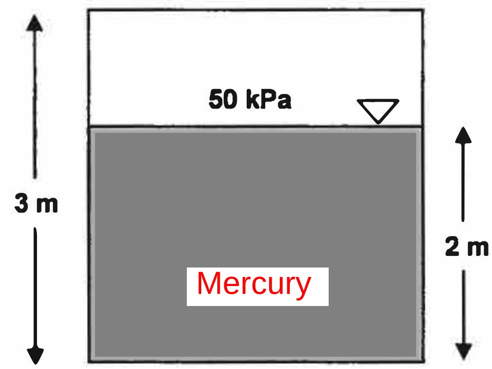


Figure 1.8

1.9. A manometer is used to determine the pressure in a pressurized vessel containing water. If the reading shows an elevation of 50 cm. Determine the gage pressure in the vessel? If the surrounding atmospheric pressure is 101 kPa, determine the absolute pressure in the vessel.

1.10 (Tutorial). The tank shown in Fig. 1.10 contains two different immiscible liquids. Determine the elevation reading obtained using manometer (1). Determine the elevation reading obtained using manometer (2). Determine the total pressure at the bottom of the tank.

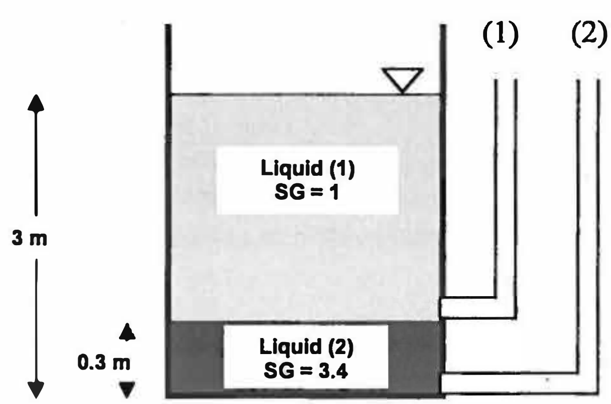


Figure 1.10

1.11 (Tutorial). Determine the gage pressure at A as read by the U-tube manometer. Density of water is ρ =1000 kg/m^3 and the specific gravity of mercury is $SG_{mercury}$ 13.6.

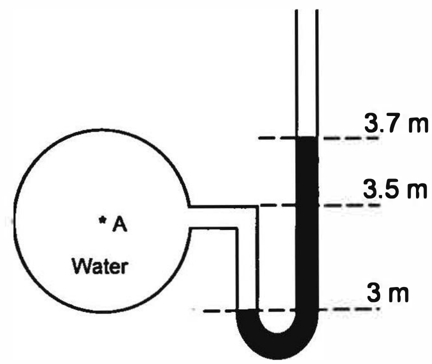


Figure 1.11

1.12. A first-time 1.82-m tall scuba diver submerged himself into the deep sea in a vertical position and immediately he can feel the difference in pressure level acting on his body and also the difficulty in manipulating himself in the water. Compute the difference between the pressure acting at the head and at the toes of the man, in kPa.

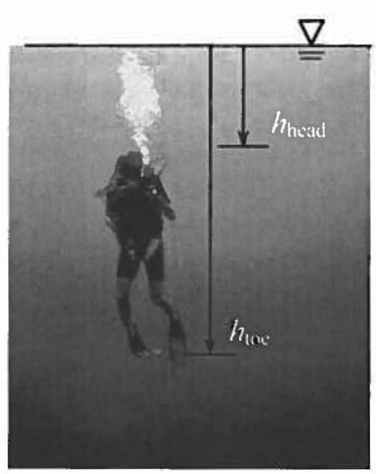


Figure 1.12

1.13. The following simple experimental setup is often used in the laboratory to determine the density of a given unknown fluid. It consists of a tank filled with water (ρ_{water} = 1000 kg/m^3), divided into two column compartments (see the Figure below). The tested fluid is poured into one side, immediately resulting in a rise of the water level to a certain height on the other side due to the density difference between the two liquids. Given the final fluid heights shown on the figure, compute the density of the tested fluid. Assume the liquid does not mix with water and P_{atm} = 101 kPa.

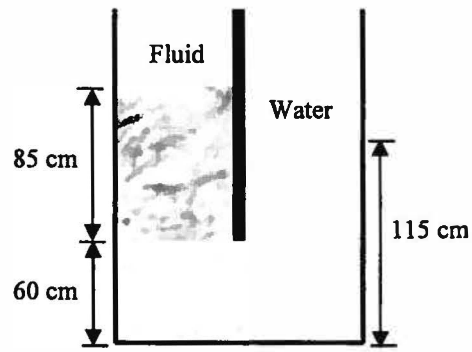


Figure 1.13

1.14. The water in a tank is pressurized by air, and the gage pressure of the air in the tank measured by a meter shown in the figure is found to be 78 kPa. Determine the differential height h_3 of the mercury column if h_1 = 0.4 m and h_2 = 0.70 m. (note: ρ_{water} = 1000 kg/m^3, SG$_{oil}$ = 0.72, SG$_{mercury}$ 13.6 and P_{atm} = 101 kPa).

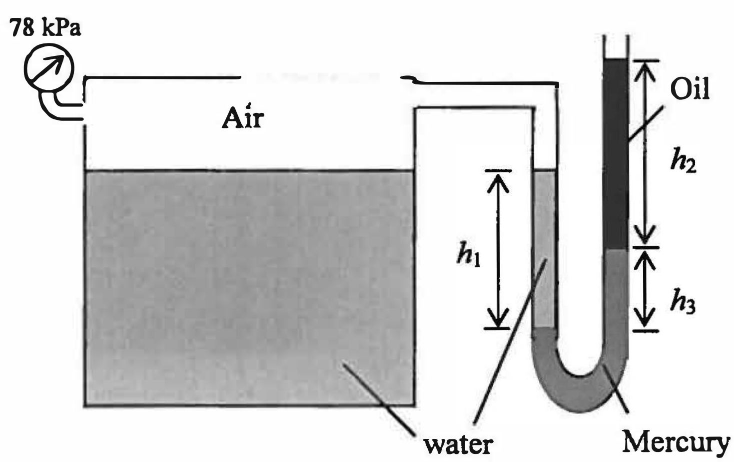


Figure 1.14

1.15. A multi-fluid container opened to the atmosphere contains 3 different liquids, i.e., oil ρ_{oil} = 900 kg/m^3, salted water ρ_{water} = 1035 kg/m^3.and glycerin $\rho_{glycerol}$ = 1260 kg/m^3. Determine the gage pressure at point **C** if h_1 = 80 cm, h_2 = 28 cm and h_3 = 16 cm.

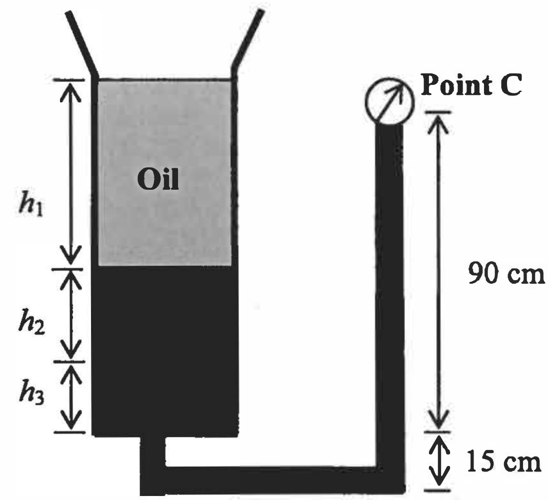


Figure 1.15

1.16 (Tutorial). A large gas chamber is separated into compartments 1 and 2, as shown, which are kept at different pressures. Pressure gauge A reads 280 kPa (gauge pressure of compartment 1) and the mercury manometer installed between the chambers indicates a level difference of 880 mm. If the local barometer reads 101 kPa, **i)** determine the absolute pressures existing in each compartment, and **ii)** the reading of gauge C in kPa (gauge pressure).

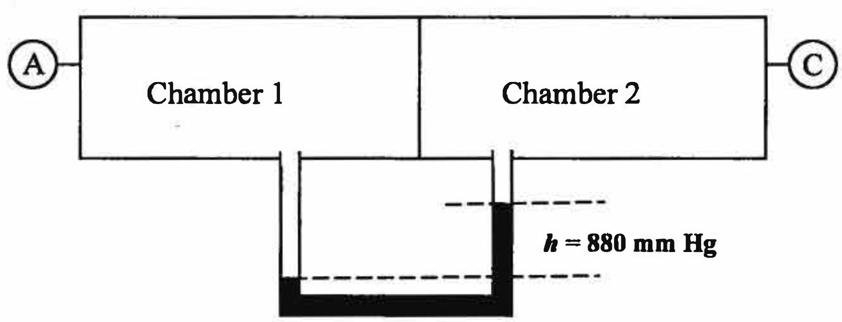


Figure 1.16

Chapter 1

Introduction and Basic Principles (Tutorial)

Problem 1.1)

Property	Intensive	Extensive	
Volume		X	
Density	X		
Conductivity	X		
Color	X		
Boiling Point (for a Liquid)	X		
Number of Moles		X	

Chapter 1
Introduction and Basic Principles (Assigned)

Problem 1.2)

- A lecture room is generally an open system since mass continuously enters and exits the room (air circulates from the vents and doors). In a more general sense, people are also entering and leaving the room.

- The human body is an open system. We consume food and breathe air.

- A car engine is also an open system. Fuel is injected and burned in the engine, while the exhaust gases are released by the engine. Certain stages of the cycle can be considered a closed system however (in the cylinders during the power stroke).

- The sun is an open system since it ejects mass in the form of solar winds and loses mass from the hydrogen fusion in its core (i.e. matter is being turned into energy; $E = mc^2$:)).

- The universe is the ultimate closed system. Nothing can ever leave it or enter it, not matter and not energy. It is essentially an isolated system.

Problem 1.3)

- A compressed gas escaping from a very small hole could be considered as a quasi-static process.

- Combustion in internal combustion engines cannot be considered as a quasi-static process.

- The cooling process of a cup of coffee at 70°C in an environment with a constant temperature of 69.9999°C could be considered as a quasi-static process.

Problem 1.4)

- The state postulate is completely satisfied by two independent intensive properties.

Problem 1.5)

- Temperature is introduced using the zeroth law of thermodynamics.

Problem 1.6)

i) $23°C = ?\ K$

$T(K) = T(°C) + 273.15$

$T(K) = \underline{296.15\,K}$

ii) $23°C = ?\ °F$

$T(°F) = 1.8\,T(°C) + 32$

$T(°F) = \underline{73.4\,°F}$

iii) $23°C = ?\ R$

$T(R) = T(°F) + 459.67$

$T(R) = \underline{533.07\,R}$

Question 1.7

Conversion: $T(^{\circ}F) = 1.8 \times T(^{\circ}C) + 32$

$$T_2 - T_1 = 40^{\circ}F$$

$$(1.8\,T_2 + \cancel{32}) - (1.8\,T_1 + \cancel{32}) = 40$$

$$1.8\,(T_2 - T_1) = 40$$

$$(T_2 - T_1) = 40/1.8 = \underline{\underline{22.22}}\ ^{\circ}C$$

$$\Delta[^{\circ}C] = \Delta[K] = \underline{\underline{22.22}}\ K$$

Problem 1.8)

i) Pressure at the bottom (P_b)

$$P_b = P_s + \rho_{Hg}\, g\, h_{Hg} \qquad (g = 9.81\ m/s^2)$$

$$= P_s + [SG_{Hg}\rho_{ref}]\, g\, h \qquad (\rho_{ref} = \rho_{H_2O} = 1000\ kg/m^3)$$

$$= 50\,kPa + (13.57)(1000\,kg/m^3)(9.81\,m/s^2)(2m)(10^{-3}\,kPa/Pa)$$

$$P_b = \underline{\underline{316.24\,kPa}}$$

ii) Height of water (h_{H_2O}) required for same pressure (P_b)

$$P_b = P_s + \rho_{H_2O}\, g\, h_{H_2O}$$

$$h_{H_2O} = \frac{P_b - P_s}{\rho_{H_2O}\, g} = \frac{\rho_{Hg}\, \cancel{g}\, h_{Hg}}{\rho_{H_2O}\, \cancel{g}} = \frac{\rho_{Hg}}{\rho_{H_2O}} h_{Hg} = SG_{Hg}\, h_{Hg}$$

$$= (13.57)(2m)$$

$$h_{H_2O} = \underline{\underline{27.14\,m}}$$

iii) Comment

- Since water is 13.57 times less dense than mercury, we should require 13.57 times more water to have the same weight acting on the bottom of the tank (and hence the same pressure).

Question 1.8

$$\underbrace{50 \times 10^3 \text{ Pa}} + \underbrace{13.57 \cdot (1000)}_{\rho_{Hg}} \cdot \underbrace{9.81}_{g} \underbrace{(2 \text{ m})}_{h} = P_{bottom}$$

$P_{bottom} = 316.24 \text{ kPa}$

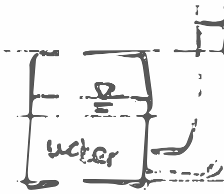
if mercury is replaced by water:

$P_{bottom} - \rho_{water} \cdot g \cdot h = 50 \times 10^3 \text{ Pa}$

$h = \underline{27.14 \text{ m}}$

$\therefore$ Tank is too small

Problem 1.9)



i) Determine the gauge pressure (P_g)

$P_g = \rho_{H_2O}\, g\, h_{H_2O}$

$= (1000\,kg/m^3)(9.81\,m/s^2)(0.5\,m)(10^{-3}\,kPa/Pa)$

$P_g = \underline{4.91\ kPa}$

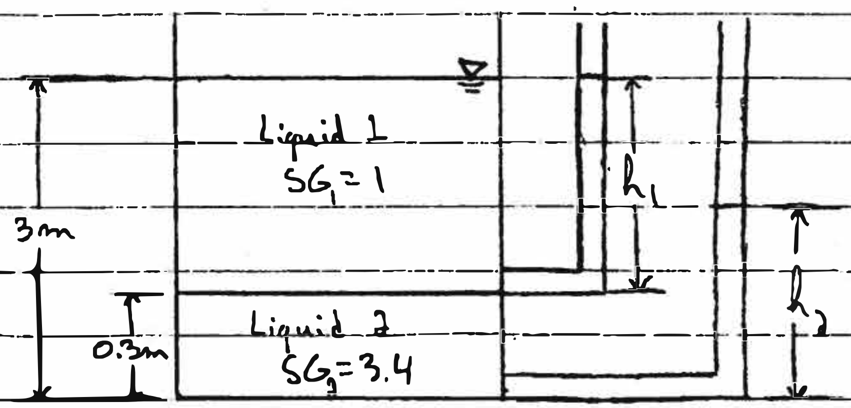
ii) Determine the absolute pressure (P)

$P = P_g + P_{atm}$

$= 4.91\ kPa + 101\ kPa$

$P = \underline{105.91\ kPa}$

Problem 1.10)



i) Determine h_1

$P_{atm} + \rho_1 g d_1 - \rho_1 g h_1 = P_{atm}$

$h_1 = d_1$

$h_1 = \underline{\underline{2.7m}}$

ii) Determine h_2

$P_{atm} + \rho_1 g d_1 + \rho_2 g d_2 - \rho_2 g h_2 = P_{atm}$

$h_2 = d_2 + \frac{\rho_1}{\rho_2} d_1 = d_2 + \frac{1}{SG_2} d_1$

$h_2 = (0.3m) + \frac{1}{3.4}(2.7m)$

$h_2 = \underline{\underline{1.09m}}$

Problem 1.11)

$P_A = P_{atm} + \rho_{Hg}\, g\, h_{Hg} - \rho_{H_2O}\, g\, h_{H_2O}$

$P_{A,g} = P_A - P_{atm}$

$P_{A,g} = \rho_{H_2O}\, g\, (SG_{Hg}\, h_{Hg} - h_{H_2O})$

$= (1000\ kg/m^3)(9.81\ m/s^2)[(13.57)(0.7m) - 0.5m](10^{-3}\ kPa/Pa)$

$P_{A,g} = \underline{\underline{88.28\ kPa}}$

(at book)

1.11

$$P_{atm} + \rho_{Hg} \cdot g \cdot (3.7 - 3.5)\,m \pm \rho_{Hg} \cdot g \cdot (3.5-3)\,m$$
$$- \rho_{water}\, g \cdot (3.5-3)\,m = P_A$$

$$P_A - P_{atm} = P_{A_{gage}} = 26683.2 + 66708 - 4905$$
$$= \underline{\underline{88.49\ kPa}}$$

Problem 1.12)

$$\Delta P = \rho_{H_2O}\, g\, \Delta h$$
$$= (1000\ kg/m^3)(9.81\ m/s^2)(1.82\ m)(10^{-3}\ kPa/Pa)$$
$$\Delta P = \underline{\underline{17.85\ kPa}}$$

Problem 1.13)

$$P_{atm} + \rho_F\, g\, h_F - \rho_{H_2O}\, g\, h_{H_2O} = P_{atm}$$
$$\rho_F = \frac{\rho_{H_2O}\, h_{H_2O}}{h_F}$$
$$= \frac{(1000\ kg/m^3)(0.55\ m)}{0.85\ m}$$
$$\rho_F = \underline{\underline{647.06\ kg/m^3}}$$

Problem 1.14)

$$P_{atm} + P_{Air} + \rho_{H_2O}\, g\, h_1 - \rho_{Hg}\, g\, h_3 - \rho_{oil}\, g\, h_2 = P_{atm}$$
$$h_3 = \frac{P_{Air}}{\rho_{Hg}\, g} + \frac{h_1}{SG_{Hg}} - \frac{SG_{oil}}{SG_{Hg}} h_2$$
$$h_3 = \frac{(78\ kPa)(10^3\ Pa/kPa)}{(13600\ kg/m^3)(9.81\ m/s^2)} + \frac{0.4\ m}{13.6} - \frac{0.72}{13.6}(0.7\ m)$$
$$h_3 = \underline{\underline{0.58\ m}}$$

Question # 1.12

Taking $\rho_{water} = 1000 \ kg/m^3$

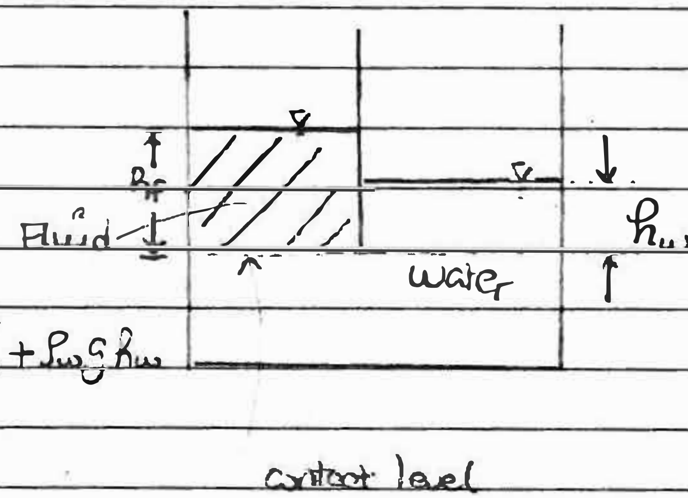
$$P_{head} = P_{atm} + \rho_{water} \, g \, h_{head}$$

$$P_{toe} = P_{atm} + \rho_{water} \, g \, h_{toe}$$

$$\therefore \quad P_{toe} - P_{head} = \rho_{water} \, g \, (h_{toe} - h_{head})$$
$$= 1000 \ kg/m^3 \cdot 9.81 \ m/s^2 \cdot (1.82 \, m)$$
$$= 17854.2 \ N/m^2$$
$$= \underline{\underline{17.85 \ kPa}}$$

Question # 1.13

$\rho_{water} = 1000\ kg/m^3$



$P_{atm} + \rho_f g h_f = P_{contact} = P_{atm} + \rho_w g h_w$

$\rho_f g h_f = \rho_w g h_w$

$\therefore \quad \rho_f = \frac{h_w}{h_f} \rho_w = \frac{(1.15 - 0.60)\,m}{0.85\,m} (1000\ kg/m^3)$

$= \underline{\underline{647.1\ kg/m^3}}$

Question #1.14

$$P_1 + \rho_{water}\, g\, h_1 - \rho_{Hg}\, g\, h_3 - \rho_{oil}\, g\, h_2 = P_{atm}$$

$$P_1 - P_{atm} = 78\,000\ \text{Pa} = \rho_{oil}\, g\, h_2 + \rho_{Hg}\, g\, h_3 - \rho_{water}\, g\, h_1$$

$$78\,000\ \text{Pa} = \rho_{water}\, g\, (SG_{oil} \cdot 0.70\,\text{m} + SG_{Hg}\, h_3 - 0.40\,\text{m})$$

$$= 1000\ \text{kg/m}^3 \cdot 9.81\ \text{m/s}^2 \cdot (0.72 \cdot 0.70\,\text{m} + 13.6 \cdot h_3 - 0.4)$$

$$h_3 = \underline{\underline{0.577\ \text{m}}}$$

Problem 1.15)

$$P_{c,g} = \rho_{oil} g h_1 + \rho_{sw} g h_2 + \rho_G g (h_3 - h)$$

$$= \cancel{(10^3 \text{ kPa}/\text{kPa})}(9.81 \text{ m/s}^2)\left[(900 \text{ kg/m}^3)(0.8 \text{ m}) + (1035 \text{ kg/m}^3)(0.28 \text{ m}) + (1260 \text{ kg/m}^3)(0.16 \text{ m} - 0.9 \text{ m})\right]$$

$$P_{c,g} = 759.29 \text{ Pa}$$

Question # 1.15

$$P_{atm} + \rho_{oil}\, g\, h_1 + \rho_{sw}\, g\, h_2 + \rho_{gly.}\, g\, h_3 + \cancel{\rho_{gly}\, g\, (0.15m)}$$

$$- \cancel{\rho_{gly}\, g\, (0.15m)} - \rho_{gly.}\, g \cdot (0.90m) = P_C$$

$$P_C - P_{atm} = P_{C_{gage}} = \rho_{oil}\, g\, h_1 + \rho_{sw}\, g\, h_2 + \rho_{gly.}\, g\, h_3 - \rho_{gly.}\, g\ 0.9m$$

$$= 7063.2 + 2842.94 + 977.696 - 11124.54$$

$$= 759\ Pa = \underline{\underline{0.759\ kPa}}$$

Problem 1.16)

i) Absolute pressures in chambers 1 and 2 (P_1 and P_2)

$$P_1 = P_{1g} + P_{atm}$$
$$= 280\,kPa + 101\,kPa$$
$$P_1 = \underline{381\,kPa}$$

$$P_2 = P_1 - \rho_{Hg}\, g\, h_{Hg}$$
$$= 381\,kPa - (13.6 \cdot 10^3\,kg/m^3)(9.81\,m/s^2)(0.88\,m)(10^{-3}\,kPa/Pa)$$
$$P_2 = \underline{263.59\,kPa}$$

ii) Reading of gauge C (P_{2g})

$$P_{2g} = P_2 - P_{atm}$$
$$= 263.59\,kPa - 101\,kPa$$
$$P_{2g} = \underline{162.59\,kPa}$$

Question #1.16

$P_{atm} = 101\ KPa$

$P_g = P_{abs} - P_{atm}$

$P_A = 280\ KPa$

$P_1 = P_{A(g)} + P_{atm} = 280\ kPa + 101\ KPa = 381\ KPa$ (absolute)

$P_1 - \rho_{Hg}\, g\, h = P_2$

$\therefore\quad P_2 = 381 \times 10^3\ Pa - (13.6 \times 10^3\ kg/m^3)(9.81\ m/s^2)(0.88\ m)$

$= 263.6\ KPa$ (absolute)

$P_{C\,(gage)} = P_{2\,(abs)} - P_{atm} = (263.6 - 101)\ kPa = 162.6\ kPa$

PROPERTIES OF PURE SUBSTANCE

2.1 Conceptual questions

- 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, which 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).

2.2 (Tutorial) Compute the following properties table for:

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	

2.3 (Tutorial) A 12-L sealed rigid tank contains 8 kg of refrigerant R-134a initially at 320 kPa. The tank is heated until the pressure reaches 600 kPa. Determine a) temperature and b) total enthalpy at both initial and final states.

2.4 (Tutorial) A stainless steel, cooking pan without lid, with an inner diameter of 22 cm is used to boil water on an electric heater. During boiling, the water drops by 8 cm in 40 mins. What is the rate of heat transfer to the cooking pan? What would be the boiling temperature and the water level after 40 mins while keeping the electric power input if a heavy lid is used initially to double the pressure inside the cooking pan?

2.5 A rigid vessel, volume 2.0 m^3, contains 16 kg of saturated liquid-vapor water mixture at 85°C. The vessel is heated until all water liquid is completely vaporized. Show the process in a T-v diagram and determine the final state temperature and pressure.

2.6 (Tutorial) A rigid tank with a volume of 83 m^3 contains 97.7 kg of water at 100°C. Now the tank is slowly heated until the temperature inside reaches 120°C. Determine the pressure inside the tank at both the beginning and the end of the heating process. What would be the final pressure if the tank's temperature increased to 125°C?

2.7 A rigid tank with a volume contains superheated steam at 1200 kPa and 250°C. The tank is now cooled until the temperature decreases to 120 °C. What is the pressure, quality and the enthalpy at the final state after the cooling?

2.8 (Tutorial) A 140-L rigid tank initially filled with 1-kg of superheated vapor at 2 MPa is cooled until the temperature drops to 50 °C. What are the initial temperature and final mixture pressure and quality?

2.9 A 0.5-m^3 rigid tank initially contained a saturated liquid-vapor mixture of water at 140 °C is now heated until the mixture reaches the critical state. Determine the mass and the volume of liquid before the heating process.

2.10 Heat is supplied to a piston-cylinder device that contains initially 1.5 kg of saturated liquid water at 190°C until the volume quadruples and the liquid is completely vaporized. Determine the tank's total volume, temperature and pressure at the final state, as well as the change in total internal energy.

2.11 (Tutorial) A piston-cylinder device contains a 0.90-kg saturated mixture of R-134a at -10°C. The piston weights 10 kg with a diameter of 22 cm. It is free to move without any frictional losses. Heat is then supplied slowly using an electric heater to this device until the temperature reaches 20°C. Determine the pressure, the volume change of the cylinder and the enthalpy change after the heating process. Assume the local atmospheric pressure of 97.5 kPa.

2.12 A piston-cylinder device contains 0.6 kg of steam at 350°C and 1.0 MPa. The steam is cooled at constant pressure until half of the mass condenses. Determine the final temperature and volume.

2.13 (Tutorial) A piston-cylinder device initially contains a saturated liquid-vapor mixture of water at 800 kPa, with the liquid and vapor volumes equal to 0.004 m^3 and 0.95 m^3, respectively. The mixture is then heated at constant pressure until the temperature rises to 250°C. Determine the initial temperature, total mass of water, final volume and pressure.

2.14 (Tutorial) A piston-cylinder device is initially filled with 100 kg of R-134a at 200 kPa with a volume of 12.3 m^3. The system is then cooled at constant pressure until the volume is one-half its original size. Determine the final temperature and the change of total internal energy.

2.2

- Water

T	P	x	u	Phase
300°C	8.581 MPa	0	1332.0 kJ/kg	saturated liquid
150°C	0.4758 MPa	0.5	1595.63 kJ/kg	saturated mixture
127.44°C	250 kPa	0.6	1736.36 kJ/kg	saturated mixture
700°C	600 kPa	—	3477.0 kJ/kg	superheated vapor
60°C	200 kPa	—	251.11 kJ/kg $\approx u_f$	compressed liquid
370°C	1200 kPa	—		superheated vapor

at 350°C $u = 2872.2$ kJ/kg

400°C 2954.9 kJ/kg

$$\therefore u(370°C) = \frac{2954.9 - 2872.2}{400 - 350} \cdot (370 - 350) + 2872.2$$

$$= \underline{\underline{2905.28 \text{ kJ/kg}}}$$

Refrigerant-134a

T	P	v	h	Phase
−20°C	0.30 MPa	0.0007361 m³/kg	24.26 kJ/kg	Compressed liquid
40°C	1.0164 MPa	0.005663 m³/kg	147.0 kJ/kg	saturated mixture $x = 0.2518$
90°C	3.2455 MPa	0.0046 m³/kg	276.32 kJ/kg	saturated vapor
30°C	0.24 MPa	0.09794 m³/kg	275.95 kJ/kg	superheated vapor
	0.80 MPa		292.0 kJ/kg	superheated vapor

		v	h
at	50°C	0.02846	284.39
	60°C	0.02992	294.98

$$\therefore \quad T(292) = \frac{60-50}{294.98-284.39}(292-284.39)+50$$

$$= \underline{\underline{57.186\,^\circ C}}$$

$$v(292) = \frac{0.02992-0.02846}{294.98-284.39}(292-284.39)+0.02846$$

$$= \underline{\underline{0.02951\ m^3/kg}}$$

2.3

$12\text{-L} = 0.012\ m^3$

R-134a
300 kPa
8 kg
12 L

$$v_1 = v_2 = \frac{0.012\ m^3}{8\ kg} = 0.0015\ m^3/kg$$

$$T_{@320kPa} = 2.48\ °C \qquad v_f = 0.000777\ m^3/kg$$
$$v_g = 0.0632\ m^3/kg$$

since $v_f < v_1 < v_g$ ∴ saturated mixture

$$T_1 = T_{@320kPa} = 2.48\ °C$$

$$x = \frac{v_1 - v_f}{v_g - v_f} = \underline{\underline{0.01158}}$$

$$h_1 = h_f + x h_{fg} = 53.31 + 0.01168(195.35)$$
$$= 55.572\ kJ/kg$$

total enthalpy
$$H_1 = m h_1 = \underline{\underline{444.58\ kJ}}$$

$$T_2 = T_{sat @600kPa} = 21.58\ °C \qquad v_f = 0.0008196\ m^3/kg$$
$$v_g = 0.0341\ m^3/kg$$

$v_f < v_2 < v_g$ ∴ remains as saturated mixture

$$x_2 = \frac{0.0015 - 0.0008196}{0.0341 - 0.0008196} = \underline{\underline{0.0204}}$$

$$h_2 = h_{f_2} + x h_{fg_2} = 79.48 + 0.0204(179.71) = 83.146\ kJ/kg$$

$$H_2 = m h_2 = 665.17\ kJ$$

2.34

$$m_{evaporated} = \frac{V_{evaporated}}{v_f} = \frac{\frac{\pi D^2}{4} \cdot L}{v_f}$$

a) without lid, the pressure is 1 atm or 0.10135 MPa

$T = 100°C$ and $v_f = 0.001044\ m^3/kg$ saturated liquid

$$m_{evap.} = \frac{\pi \cdot (0.22)^2/4 \cdot (0.08)}{0.001044\ m^3/kg} = 2.913\ kg$$

$$\dot{m}_{evap} = \frac{2.913\ kg}{40 \times 60\ sec} = 1.21376 \times 10^{-3}\ kg/sec$$

$$\dot{Q} = \dot{m}_{evap} \times h_{fg} = 1.21376 \times 10^{-3}\ kg/sec \cdot 2257\ kJ/kg$$
$$= \underline{\underline{2.74\ kW}}$$

at $T = 100°C$ $h_{fg} = 2257\ kJ/kg$

b) double the pressure:

$P \approx 0.200\ MPa$ $T_{sat} = 120.23$

$h_{fg} = 2201.9\ kJ/kg$

$v_f = 0.001061\ m^3/kg$

$$\dot{m}_{evap} = \frac{2.74\ kJ/sec}{2201.9\ kJ/kg} = 1.2444 \times 10^{-3}\ kg/sec$$

$$m_{evap} = 1.2444 \times 10^{-3}\ kg/sec \times 0.001061\ m^3/kg \times (40 \times 60\ sec)$$
$$= 3.1687 \times 10^{-3}\ m^3 = \frac{\pi D^2}{4} \cdot L$$

$$L = \underline{\underline{0.08335\ m}}$$

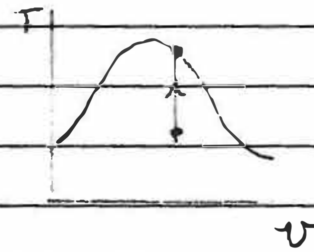
2.5

H_2O
85°C

$T_{sat} = 85°C$

$v_f = 0.001033 \ m^3/kg$

$v_g = 2.828 \ m^3/kg$



$$v_1 = \frac{2.0 m^3}{16 kg} = 0.125 \ m^3/kg$$

$$v_1 = v_f + x(v_g - v_f)$$

$$x = \frac{0.125 - 0.001033}{2.828 - 0.001033} = 0.04385$$

When the liquid is completely vaporized : $v_1 = v_2 = v_g$

$$v_2 = 0.125 \ m^3/kg$$

The temperature at this point :

$$T = T_{sat \ @ \ 0.125 m^3/kg} \cong 200.97°C$$

at $T = 200°C$ $\quad v_g = 0.12736$ $\quad$ P=1.5538 MPa

$T = 208°C$ $\quad v_g = 0.11521$ $\quad$ P=1.7230 MPa

after interpolation : 200.57 °C

After interpolation, P2=1.5867 MPa

2.5

$v_1 = \frac{83\ m^3}{100\,kg} = 0.83\ m^3/kg$

at $T_1 = 100°C$ @ sat. $\quad v_f = 0.001044\ m^3/kg \quad P_{1,sat} = 0.10135\ MPa$

$v_g = 1.6729\ m^3/kg$

Need to determine at 120C

∴ saturated mixture

$v_2 = v_1$

at $T_2 = 120°C \quad v_f = 0.001060\ m^3/kg$

$v_g = 0.7706\ m^3/kg$

It should be 125C $\quad P_{2,sat} = 0.2321\ MPa$

2.7

$P_1 = 1200\ kPa$ } superheated vapor $v_1 = 0.19234\ m^3/kg$
$T_1 = 250°C$

$T_2 = 120°C$ $v_f = 0.001060\ m^3/kg$
$v_g = 0.8919\ m^3/kg$

$v_2 = v_1$ and $v_f < v_2 < v_g$
$\therefore$ saturated mixture

$P_2 = P_{sat} = 0.19853\ MPa$

$$x = \frac{v_2 - v_f}{v_g - v_f} = 0.2147$$

$$h_2 = h_f + x\, h_{fg} = 503.71 + 0.2147(2202.6)$$
$$= \underline{\underline{976.6}}\ kJ/kg$$

2.8

$v_1 = v_2 = \frac{V}{m} = \frac{0.140\ m^3}{1\ kg} = 0.140\ m^3/kg$

$P_1 = 2\ MPa$ at $T = 400°C$ $v = 0.1512\ m^3/kg$

$T = 350°C$ $v = 0.13857\ m^3/kg$

using interpolation $T = 355.66°C$

A rigid tank $v_2 = v_1 = 0.140\ m^3/kg$

$T_{2\,sat} = 50°C$ $v_f = 0.001012\ m^3/kg$

$v_g = 12.03\ m^3/kg$

$\therefore$ v_2 saturated mixture.

$P_{2\,sat} = 12.349\ kPa$

$x = \frac{v_2 - v_f}{v_g - v_f} = 0.01155$

2.9

$$v_1 = v_2 = v_{CR} = 0.003155 \ m^3/kg$$

$$m = \frac{V}{v} = \frac{0.5 \ m^3}{0.003155 \ m^3/kg} = 158.48 \ kg$$

at $T_{sat} = 140°C$ $\quad v_f = 0.001080 \ m^3/kg$

$v_g = 0.5089 \ m^3/kg$

$$x = \frac{v_1 - v_f}{v_g - v_f} = 0.004086$$

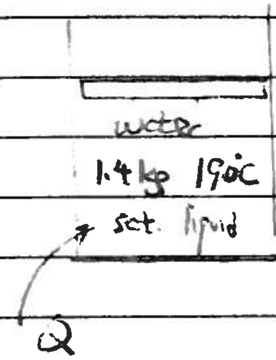
$$m_f = (1 - x_f)\, m_{total} = 157.83 \ kg$$

$$V_f = m_f v_f = 0.17045 \ m^3$$

2.10

$V_1 = m_1 \, v_{f_1} = 1.5\,kg \cdot 0.001141 \, m^3/kg$

$= 1.7115 \times 10^{-3} \, m^3$



$V_2 = 4 V_1 = 6.846 \times 10^{-3} \, m^3$

$v_2 = \dfrac{V_2}{m} = 4.564 \times 10^{-3} \, m^3/kg$

at $T_{sat} = 190°C$

$v_f = 0.001141 \, m^3/kg$

$u_f = 806.19 \, m^3/kg$

$v_2 = v_g = 4.664 \times 10^{-3} \, m^3/kg$ saturated vapor only

at $T = 370°C$ $\quad v_g = 0.004925 \, m^3/kg$

$T = 374.14°C$ $\quad v_g = 0.003155 \, m^3/kg$

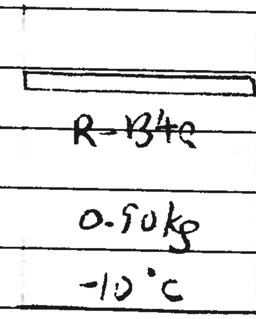
T_2 by interpolation $\cong 370.84°C$

$P_2 \cong 21.246 \, MPa$

$u_2 \simeq 2188.83 \, kJ/kg$

$\Delta U = m(u_2 - u_1) = \underline{\underline{2073.96 \, kJ}}$

2.10



$$P_2 = P_1 = P_{atm} + \frac{m_p \cdot g}{\pi D^2/4}$$

$$= 97.5\times10^3\ Pa + \frac{10 \cdot 9.81}{\pi (0.22)^2/4}$$

$$= 100.80\ kPa \sim 0.10\ MPa$$

At $\left. \begin{array}{l} T_1 = -10°C \\ P_1 = 0.10 MPa \end{array} \right\}$ superheated

$v_1 = 0.20686\ m^3/kg$

$h_1 = 244.70\ kJ/kg$

at $T_2 = 20°C$ $\quad v_2 = 0.23349\ m^3/kg$

$P_2 = 0.10 MPa$ $\quad h_2 = 270.02\ kJ/kg$

$V_1 = m v_1 = 0.90\ v_1 = 0.1862\ m^3$

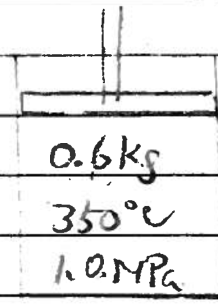
$V_2 = m v_2 = 0.90\ v_2 = 0.21014\ m^3$

$\Delta V = 0.0239\ m^3$

$\Delta H = m(h_2 - h_1) = 22.78\ kJ/kg$

2.12

$T = 350°C$
$P = 1.0 MPa$ } superheated steam



$v_1 = 0.2579 \ m^3/kg$

$P_2 = P_1 = 1.0 MPa$ $\quad T_{2\,sat} = 179.91°C$ @ 1 MPa $\quad v_f = 0.001127 \ m^3/kg$

$x_2 = 0.50$ $\quad v_g = 0.19444 \ m^3/kg$

$v_2 = v_f + x(v_g - v_f)$
$= 0.0977836 \ m^3/kg$

$\Delta V = m(v_2 - v_1) = -0.0961 \ m^3$

2.13

$T_{sat @ 800kPa} = 170.43°C$ $\quad v_f = 0.001115\ m^3/kg$

$v_g = 0.2404\ m^3/kg$

$m_f = \frac{V_f}{v_f} = \frac{0.004}{0.001115} = 3.59\ kg$

$m_g = \frac{V_g}{v_g} = \frac{0.95}{0.2404} = 3.952\ kg$

$m_t = m_f + m_g = 7.542\ kg$

$\left.\begin{array}{l} P_2 = 800\ kPa \\ T_2 = 250°C \end{array}\right\} v_2 = 0.2931\ m^3/kg$

$V_2 = m_t \cdot v_2 = \underline{\underline{2.21\ m^3}}$

2.14

$$v_1 = \frac{V}{m} = \frac{123}{100} = 0.123 \, m^3/kg$$

superheated

$P_1 = 200\,kPa$ } $T_1 = 40°C$

$v_1 = 0.123$ } $u_1 = 261.26 \, kJ/kg$

$$v_2 = \frac{v_1}{2} = \frac{0.123}{2} = 0.0615 \, m^3/kg$$

$T_{2 \, sat \, @ \, 200kPa} = -10.09°C$ $v_f = 0.0007532 \, m^3/kg$

$v_g = 0.0993 \, m^3/kg$

∴ mixture

$$x_2 = \frac{v_2 - v_f}{v_g - v_f} = 0.616$$

$u_2 = u_f + x \, u_{fg} = 36.69 + 0.616(221.43 - 36.69)$

$= 113.8 \, kJ/kg$

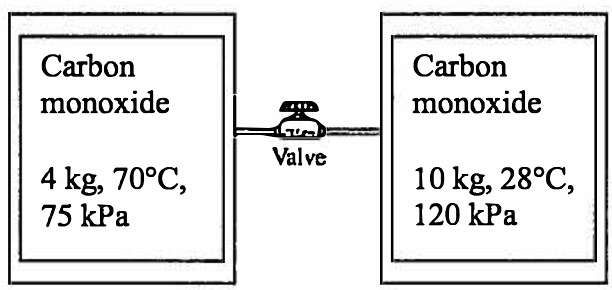
$\Delta u = u_2 - u_1 = -147.46 \, kJ/kg$

IDEAL GAS EQUATION OF STATE

3.1 If you are a frequent driver, you can easily realize that the pressure in your car tires depends on the ambient (outside) air temperature. Often, you fill your tires to the recommended tire pressure of 342 kPa absolute (or 35 psi gauge) during the summertime when the temperature is 30°C. Assuming that your tires are made by good brand companies and so these do not leak and their volume stays constant at $V = 0.025$ m^3, **i)** what will the tire pressure be during the winter when the temperature is -30°C? **ii)** How much air (in kg) would you need to add to the tire in the winter to bring the pressure back to the recommended pressure? **iii)** What would the resulting pressure be the next summer at about the same summer temperature of 30°C, and **iv)** how much air (mass) would you need to bleed of (remove) to get back to the recommended pressure? For Air: $R_s = 0.287$ kJ/kg·K

3.2 A piston-cylinder device initially contains 36 m^3 of an ideal gas at 90 kPa and 25°C. Through a thermodynamic process, the gas is now at 101.3 kPa and 4°C. What is the final volume of the gas?

3.3 Consider the system shown in the figure which consists of two tanks connected by a valve. One tank contains 4 kg of carbon monoxide at 70 °C and 75 kPa. The other tank holds 10 kg of the same gas at 28 °C and 120 kPa. The valve is opened and the gases are allowed to mix while receiving energy by heat transfer from the surroundings. The final equilibrium temperature is 40 °C. Applying the ideal gas model, determine the final equilibrium pressure. Note that for carbon mononxide: $R_s = 0.2968$ kJ/kg·K.



3.4 A piston-cylinder device initially contains 0.5 kg of argon at a volume of 0.075 m^3 at 600 kPa. The piston position is now adjusted by changing the weights until the volume doubles its original size, while heat is removed to keep the process isothermal. What is the final pressure after this process? Note that for argon: $R_s = 0.2081$ kJ/kg·K.

3.5 We divide a rigid vessel into two parts using a "magic" partition. Let one side of the vessel filled with an ideal gas at 800 °C and the other evacuated completely with a volume twice the size of the part filled with the gas. The partition is then removed to allow the gas to fill the entire tank. The gas is heated during the process to allow the pressure equal to the initial pressure. What is the final temperature of the gas inside this vessel?

3.6 Given a refrigerant-134a vapor at 0.80 MPa and 80°C, determine its specific volume using a) the thermodynamic table for the refrigerant-134a; b) the ideal gas equation of state; and c) compressibility chart.

3.7 Given a water vapor at 15 MPa and 350°C, determine its specific volume using a) the steam table; b) the ideal gas equation of state; and c) compressibility chart.

3.8 Methane gas initially at 8 MPa and 300 K is heated while maintaining constant pressure in a piston-cylinder device until its final volume has increased by 50%. Determine the final temperature using a) the ideal gas equation of state; and b) the compressibility chart.

3.9 A free-moving piston-cylinder device initially contains a saturated vapor of water at a temperature of 350°C. Heat is added to the system at constant pressure until the vapor gas volume has doubled. Determine the final temperature using a) the ideal gas equation of state; b) the compressibility chart; as well as the steam table.

3.10 There exist different ways to determine the change of an intensive thermodynamic properties, e.g., using **i)** the empirical data for h from the nitrogen table; **ii)** the empirical specific heat equation as a function of temperature; **iii)** the c_p value at the average temperature; **iv)** c_p value at the room temperature; and **v)** using specific heat ratio k at room temperature. In this question, determine the change of internal energy Δh [kJ/kg] of nitrogen due to the change of temperature from 500 to 1,200 K using all the aforementioned methods.

3.1

$P_1 = 342\ kPa$

$V_1 = 0.025\ m^3$

$T_1 = 30°C = 303\ K$

$$m_1 = \frac{P_1 V_1}{R_s T_1}$$

$$P_2 = \frac{m_2 R_s T_2}{V_2} \qquad m_2 = m_1 \quad V_2 = V_1 \qquad T_2 = -30°C = 243K$$

$$\therefore P_2 = \frac{P_1 V_1}{R_s T_1} \cdot \frac{R_s T_2}{V_2} = P_1 \frac{T_2}{T_1} = 342\ kPa \left(\frac{243\ K}{303\ K}\right)$$

$$= \underline{\underline{274.3\ kPa}}$$

Δm_{1-2} such that $P_2 = P_1$ at T_2

$$m_1 = \frac{P_1 V_1}{R_s T_1} \qquad m_2 = \frac{P_2 V_2}{R_s T_2} \qquad V_1 = V_2$$

want $P_2 = P_1$

$$m_2 - m_1 = \Delta m_{1-2} = \frac{PV}{R_s}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

$$= \underline{\underline{0.0243\ kg}}$$

$$m_2 = \frac{P_2 V_2}{R_s T_2} = 0.1226\ kg$$

$$P_3 = \frac{m_2 R_s T_3}{V_3} = \frac{(0.1226)(0.287)(303)}{0.025\ m^3} = 427\ kPa$$

need to bleed as much air as was added

$$\Delta m_{2-3} = \underline{\underline{0.0243\ kg}}$$

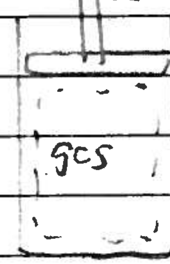
3.2

$V_1 = 36\, m^3$ $V_2 = ?$

$P_1 = 90\, kPa$ $P_2 = 101.3\, kPa$

$T_1 = 25°C = 298\, K$ $T_2 = 277\, K$

$$\frac{P_1 V_1}{R_s T_1} = \frac{P_2 V_2}{R_s T_2} \rightarrow V_2 = \frac{P_1 V_1}{T_1} \cdot \frac{T_2}{P_2} = 29.73\, m^3$$



closed system $m_1 = m_2$

3.3

$$P_f = \frac{m_{total} R_s T_f}{V_f} = \frac{(m_1+m_2) R_s T_f}{V_1 + V_2}$$

$$= \frac{(m_1+m_2) R_s T_f}{\left(\frac{m_1 R_s T_1}{P_1}\right) + \left(\frac{m_2 R_s T_2}{P_2}\right)}$$

$$= \frac{(m_1+m_2)\, T_f}{\frac{m_1 T_1}{P_1} + \frac{m_2 T_2}{P_2}}$$

$$\therefore \quad P_f = \frac{(4+10)\text{kg} \cdot (313\text{K})}{\left(\frac{4\text{kg} \cdot 343\text{K}}{75\times10^3\text{ Pa}}\right) + \left(\frac{10\text{kg} \cdot 301\text{K}}{120\times10^3\text{ Pa}}\right)}$$

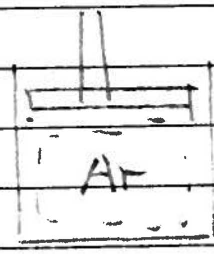
$$= 101022\text{ Pa} \simeq \underline{\underline{101.02}}\text{ kPa}$$

3.4

$m_1 = 0.5\,kg$

$V_1 = 0.075\,m^3$ $\quad V_2 = 2 \cdot V_1$

$P_1 = 600\,kPa$



closed system

isothermal process

$T_1 = T_2$

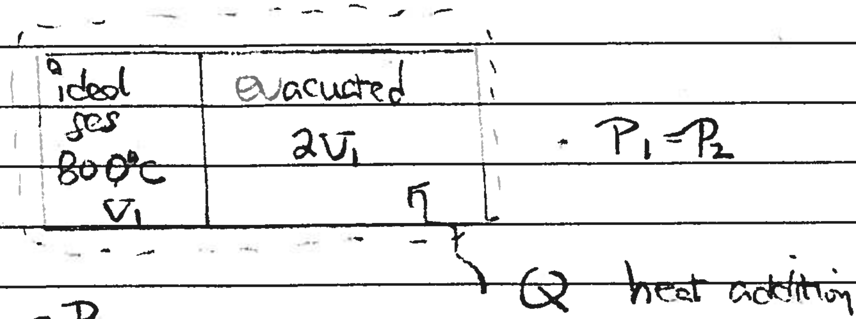
$$m = \frac{P_1 V_1}{\cancel{R}\,\cancel{T_1}} = \frac{P_2 V_2}{\cancel{R}\,\cancel{T_2}}$$

$$\therefore \quad P_1 V_1 = P_2 V_2$$

$$P_2 = P_1 \frac{V_1}{V_2} = P_1 \frac{V_1}{2V_1} = 0.5\,(600\,kPa)$$

$$= \underline{\underline{300\,kPa}}$$

3.5



$P_1 = P_2$

$P_2 = P_1$

$V_2 = V_1 + 2V_1 = 3V_1$

$m_t = m_1 + \cancel{m_2}^{\,0}$

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \Rightarrow T_2 = T_1 \frac{V_2}{V_1} = T_1 \frac{3\cancel{V_1}}{\cancel{V_1}}$$

$= 3(1073K)$

$= 3219K$

"or" ($2946\ ^\circ C$)

3.6

a) From the superheated table.

$$\left.\begin{array}{l} \text{at } P = 0.80\,MPa \\ T = 80°C \end{array}\right\} v = 0.03264\ m^3/kg$$

b) $R = 0.08149\ \frac{kJ}{kg \cdot K} = 0.08149\ kPa \cdot m^3/kg \cdot K$

$$v = \frac{RT}{P} = \frac{(0.08149)\cdot(353)}{0.80 \times 10^3\ kPa} = 0.03596\ m^3/kg$$

From table:

$T_{CR} = 374.3\ K$

$P_{CR} = 4.067\ MPa$

$$\left.\begin{array}{l} \therefore P_R = \dfrac{P}{P_{CR}} = \dfrac{0.80}{4.067} = 0.197 \\ T_R = \dfrac{T}{T_{CR}} = \dfrac{353}{374.3} = 0.943 \end{array}\right\} \begin{array}{l} \text{from chart:} \\ Z \cong 0.91 \end{array}$$

$$v = Z\, v_{ideal} = 0.91\,(0.03596) = \underline{\underline{0.03272\ m^3/kg}}$$

3.7

From superheated steam table

$$\left.\begin{array}{l} P = 15\,MPa \\ T = 350^\circ C \end{array}\right\} v = 0.01147\ m^3/kg$$

$$R_s = 0.4615\ kJ/kg\,K = 0.4615\ kPa \cdot m^3/kg\,K$$

$$v = \frac{R_s T}{P} = \frac{0.4615 \times (623)}{15 \times 10^3\ kPa} = 0.01917\ m^3/kg$$

For water:

$T_{CR} = 647.3\ K$

$P_{CR} = 22.09\ MPa$

$$\left.\begin{array}{l} P_R = \dfrac{15\,MPa}{22.09\,MPa} = 0.679 \\ T_R = \dfrac{623}{647} = 0.963 \end{array}\right\}$$

From chart:

$Z \cong 0.68$

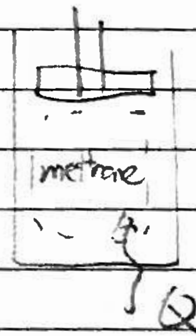
$$v = Z\, v_{ideal} = 0.01304\ m^3/kg$$

3.8

$R_S = 0.5182 \ kJ/kg\,K = 0.5182 \ kPa \cdot m^3/kg \cdot K$

$T_{CR} = 191.1K$

$P_{CR} = 4.64 MPa$



$P_1 = P_2 \qquad V_2 = 1.5 V_1$

$\therefore \ T_2 = T_1 \left(\frac{V_2}{V_1}\right) = 300\left(\frac{1.5}{1}\right)$

$= 450K$

initial:

$T_R = \frac{T_1}{T_{CR}} = \frac{300}{191} = 1.57$

$P_R = \frac{P_1}{P_{CR}} = \frac{8}{4.64} = 1.724$

From chart
$Z_1 = 0.88 \quad V_{R_1} = 0.80$

final:

$P_{R_2} = P_{R_1} = 1.724$

$V_{R_2} = 1.5 V_{R_1} = 1.5(0.80) = 1.2$

$Z_2 = 0.975$

$\therefore \ T_2 = \frac{P_2 V_2}{Z_2 R} = \frac{P_2}{Z_2} \frac{V_{R_2} T_{CR}}{P_{CR}} = \frac{8000kPa}{0.975} \frac{(1.2)(191.1K)}{4640kPa}$

$= \underline{\underline{406}} \ K$

3.9 $v_{1\,ideal} = \frac{R_s T_1}{P_1} = 0.01943\ m^3/kg$

$Z_1 = 0.88$

$\therefore v_{1\,actual} = 0.0171\ m^3/kg$

$$v_{R_2} = \frac{v_{2\,actual}}{R\ T_{CR}/P_{CR}} = \frac{1.5\ (0.0171)}{0.8182\left(\frac{191.1}{4.64\times10^3}\right)} = 1.202$$

From chart: $Z_2 = 0.975$

$$Z_2 = \frac{P_2 v_2}{R T_2}$$

since

$$T_2 = \frac{P_2 v_2}{Z_2 R_s} = \frac{P_2}{Z_2}\left(\frac{v_{R_2} T_{CR}}{P_{CR}}\right) \quad v_R = \frac{v}{R\ T_{CR}/P_{CR}}$$

3.9 Alternative Solution

$T_1 = 350°C$	$T_2 = ?$
$P_1 = ?$	$P_1 = P_2$ (const. P process)
$V_1 = ?$	$V_2 = 2V_1$

a) Ideal gas law to find T_2

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \Rightarrow T_2 = T_1 \frac{\cancel{P_2} \overset{2V_1}{V_2}}{\cancel{P_1} V_1} = 2T_1$$

$T_2 = 2(350+273.15) = \boxed{1246.3\,K}$

* IMPORTANT: For ideal gas law equations, must keep T in K

b) Use comp. chart + sat. property tables to find T_2

Must first find P_1 and P_{cr}:

$\xrightarrow{\text{sat. tables}} P_1 = P_{sat@T_1=350°C} = 16.513\ MPa$

$\xrightarrow{\text{Pg. ! Tables C (H}_2\text{O)}} P_{CR} = 22.09\ MPa$ (vapor ≈ water)

$T_{CR} = 647K$

$$P_{R_1} = \frac{P_1}{P_{CR}} = \frac{16.513\ MPa}{22.09\ MPa} = 0.74753$$

$$T_{R_1} = \frac{T_1}{T_{CR}} = \frac{623.15K}{647\ K} = 0.9629$$

State 1 - Read from comp. chart:

$P_{R_1} \approx 0.75$
$T_{R_1} \approx 1$) $Z_1 \approx 0.64 - \underline{0.65}$

—— T_R curves
----- v_R curves
0.5 spaces = major grid
0.05 spaces = minor grid

$v_{R_1} \approx \underline{0.80} - 0.82$; this is needed to obtain comp. info on state 2

Using the relation for V_1 and V_2:

$\therefore v_{R_2} = 2v_{R_1}$ since R_s, P_{CR} and T_{CR} are const. for same substance

$v_{R_2} = 2(0.80) = \underline{1.6}$

State 2 - Read from comp. chart:

since $P_1 = P_2$ $\quad$ $\left.\begin{array}{l} P_{R_2} \approx 0.75 \\ v_{R_2} \approx 1.6 \end{array}\right) \; Z_2 = 0.88 - \underline{0.90}$

Finally:

$$T_2 = \frac{P_2 v_2}{Z_2 R_s}$$

Ideal-gas law formula with comp. factor (Z)

- v_2 is the "actual" spec. volume at state 2, but we have a relation to substitute in v_{R_2} which is known:

$$v_{R_2} = \frac{v_2}{R_s T_{CR}/P_{CR}} \Rightarrow v_2 = \frac{v_{R_2} R_s T_{CR}}{P_{CR}}$$

so,

$$T_2 = \frac{P_2}{Z_2 \cancel{R_s}} \cdot \frac{v_{R_2} T_{CR} \cancel{R_s}}{P_{CR}}$$

$$T_2 = \frac{v_{R_2} P_2 T_{CR}}{Z_2 P_{CR}}$$

$$T_2 = \frac{(1.6)(16.513 \times 10^3 \, kPa)(647 \, K)}{(0.90)(22.09 \times 10^3 \, kPa)}$$

$$\boxed{T_2 = 859.83 \, K}$$

End of Alternate Solution

3.10

From table A-18

$$\bar{h}\Big|_{T=500K} = 14581 \text{ kJ/kmol}$$

$$\bar{h}\Big|_{T=1200K} = 36777 \text{ kJ/kmol} \qquad \Delta h = \frac{\Delta \bar{h}}{M}$$

$$\Delta \bar{h} = 22196 \text{ kJ/kmol} \qquad \Delta h = 792.71 \text{ kJ/kg}$$

$$M = 28 \text{ kg/kmol}$$

From table A-2C

$$\bar{C}_p = 28.9 - 0.001571T + 0.8081\times10^{-5}T^2 - 2.873\times10^{-9}T^3$$

$$[\text{kJ/kmol}\cdot\text{K}]$$

$$\Delta\bar{h} = \int_{T_1}^{T_2} \bar{C}_p\, dT$$

$$= \int_{500}^{1200} (28.9 - 0.001571T + 0.8081\times10^{-5}T^2 - 2.873\times10^{-9}T^3)\, dT$$

$$= 28.9T - \frac{0.001571}{2}T^2 + \frac{0.8081\times10^{-5}}{3}T^3 - \frac{2.873\times10^{-9}}{4}T^4\Big|_{500}^{1200}$$

$$= 36714.2 - 14545.44 = 22168.8 \text{ kJ/kmol}$$

$$\Delta h = \frac{\Delta\bar{h}}{M} = 791.74 \text{ kJ/kg}$$

average $T = \frac{500+1200}{2} = 850K$

$$\Delta h = \int_{T_1}^{T_2} C_p\Big|_{850K} dT = C_p\Big|_{850} \int_{T_1}^{T_2} dT = C_p\Big|_{850} (T_2 - T_1)$$

$$= \frac{31.639}{M} \frac{kJ}{kmol \cdot K} (T_2 - T_1)$$

$$= 1.12996 \frac{kJ}{kg \cdot K} (700)$$

$$= 790.97 \frac{kJ}{kg}$$

Using C_p at room T^o (298K)

$C_p = 1.039 \left[\frac{kJ}{kg \cdot K}\right]$

$$\Delta h = \int_{T_1}^{T_2} C_p dT = C_p\Big|_{298K} (T_2 - T_1) = 1.039 (700)$$

$$= 727.3 \frac{kJ}{kg}$$

Using k at 298K

$k = 1.40$ at 298K

$$C_p = \frac{k R_s}{k-1} = \frac{1.4 (0.2968)}{1.4-1} = 1.0388 \frac{kJ}{kg \cdot K}$$

$R_s = 0.2968 \frac{kJ}{kg \cdot K}$ $\qquad \Delta h = 1.0388 (T_2 - T_1) = 727.16 \frac{kJ}{kg}$

ENERGY TRANSFER BY WORK AND HEAT & THE FIRST LAW OF THERMODYNAMICS

4.1 Air is compressed polytropically along a path for which n = 1.30 in a closed system. The initial temperature and pressure are 17 °C and 100 kPa, respectively, and the final pressure is 500 kPa. Assume R_s = 0.287 kJ/kg·K and average specific heats c_v = 0.723 kJ/kg·K and c_p = 1.01 kJ/kg·K. Calculate: **a)** the final temperature in K; **b)** the work done on the gas, in kJ/kg; and **c)** the change of specific internal energy.

4.2 A piston-cylinder device initially contains 1m^3 of saturated water liquid at 200°C, which is now expanded isothermally until its quality is 70%. Calculate the final volume and the total work by this expansion.

4.3 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.

4.4 A piston-cylinder device initially contains 40 L of saturated liquid refrigerant-134a. The piston can move freely without friction and its mass is such that it maintains a pressure of 500 kPa on the refrigerant. What is the resulting work if the refrigerant is heated to a final temperature of 70°C?

4.5 0.25 kg of steam at 1MPa and 400°C is initially filled inside a piston-cylinder device made with a set of stops. The location of the stops corresponds to 55% of the initial volume. Now the steam is cooled. Determine the compression work if the final state is a) 1MPa and 250°C and b) 500kPa. Also find the temperature at the final state in part b).

4.6 2 kg of saturated vapor of water at 300 kPa is heated a constant pressure until the temperature changes to 200 °C. What is the work done by the steam during this process?

4.7 A piston-cylinder device initially has a volume of 8 m^3 and contains 1 kg of Helium at 150 kPa. The gas is now compressed to 4 m^3 while its pressure is kept constant. Determine the initial and final temperature and the compression work, in kJ. If the process is carried out in isothermal situation instead, what is the work, in kJ?

4.8 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.

4.9 A piston-cylinder device initially has a volume of 0.08 m^3 of Nitrogen at 150 kPa and 120°C. The gas is now allowed to expand under a polytropic path to a final state of 100 kPa and 100°C. Calculate the boundary work, in kJ.

4.10 3 kg of Nitrogen N_2 at 100 kPa and 300 K is initially contained in a piston-cylinder device. The gas is now compressed slowly according to the isentropic relationship $PV^{1.4}$ = constant until the final temperature is raised to 380 K. Determine the required input work for this thermodynamic process.

4.11 A spring-loaded piston-cylinder device initially contains 1 kg of water with 10% quality at 90°C. Heat is now added to the medium until the temperature reaches 250°C and pressure to 800 kPa. Calculate the total work resulted from this process is kJ.

4.12 A spring-loaded piston-cylinder device initially contains 2.0 kg of water with 25% quality at 1 MPa. Heat is now removed from the medium until it becomes a saturated liquid at a temperature of 100°C. Calculate the total work resulted from this process is kJ.

4.13 i. A single cylinder in a car engine has a maximum volume of 5×10^{-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 5×10^{-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)

4.14 A saturated mixture of liquid water and vapor at 100°C with 12.3% quality is initially contained in a rigid tank with a volume of 10 L. Heat is then supplied to this mixture until its temperature is 150°C. Calculate the heat transfer required for this process.

4.15 A saturated water vapor at 200°C is initially contained in a frictionless piston-cylinder device. It is condensed subsequently through an isothermal process to a saturated liquid. Determine the specific heat transfer and the work done during this process in kJ/kg.

4.16 A rigid vessel containing a fluid is stirred with a paddle wheel. The work input to the paddle wheel is 5100 kJ. The amount of heat removed from the tank is 1600 kJ. Consider the tank and the fluid inside a control surface and determine the change in internal energy of the control mass.

4.17 A saturated water vapor is initially contained in a piston-cylinder device. It is then cooled at constant pressure to a saturated liquid at 40 kPa. Determine the heat transferred and the work done during this process in kJ/kg.

4.18 A rigid tank with a volume of 5 m^3 contains 0.05 m^3 of saturated liquid water and 4.95 m^3 of saturated vapor at 0.1 MPa**.** The mixture is then heated until all the volume becomes saturated vapor only. What is the required heat input in kJ?

4.19 A piston-cylinder device initially contains 4 kg of a certain gas, which undergoes a polytropic process with n = 1.5. The initial pressure and volume are 300 kPa and 0.1 m^3, and the final volume is 0.2 m^3. The change in internal energy during the process is equal to - 4.6 kJ/kg (a decrease due to the expansion). Determine the net heat transfer for the process in kJ.

4.20 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.

4.21 A piston-cylinder device initially contains 0.35 kg of water vapor at 3.5 MPa, superheated by 7.4 °C. The stream now loses its heat to the surrounding and the piston moves down, hitting a set of stops at which point the cylinder contains saturated liquid water. The cooling continues until the cylinder contains water at 200 °C. Calculate the final pressure and quality, as well as the boundary work and total heat transfer.

4.22 2 kg of Air in a closed system undergoes an isothermal process from 600 kPa and 200 °C to 80 kPa. Calculate the initial volume, work done as well as the heat transfer.

4.23 1kg of carbon dioxide is initially contained in a spring-loaded piston-cylinder device. Heat is supplied from 100 kPa and 25 °C to 1000 kPa and 300°C. What is the heat transfer to and work done by the system?

4.24 A piston-cylinder device equipped with a paddle wheel contains initially air at 500 kPa and 27°C. The paddle wheel supplies now 50kJ/kg of work to the air. During this process heat is transferred to maintain a constant air temperature while allowing the air volume to triple. What is the amount of heat required?

4.25 A rigid system is built with two tanks initially separated by a partition. Tank A contains 2 kg steam at 1MPa and 300°C while tank B contains 3kg saturated liquid-vapor mixture at 150°C with a vapor quality of 50%. The partition is now removed and the two sides are allowed to mix until thermodynamic equilibrium is returned. If the pressure at the final state is 300 kPa, determine a) the temperature and quality of the steam (if mixture) at the final state and b) the amount of heat lost from the tanks.

4.26 A piston-cylinder device equipped with a set of stops on the top contains initially 3kg of air gas at 200 kPa and 27°C. The air is then heated, making the piston to rise until it hits the stops, at which point the volume is twice the initial volume before the heating process. Heat is continued to supply until the pressure reaches twice the initial pressure. Determine the total work done and the amount of heat transfer.

4.1

path : $PV^{1.3}$ = constant

$T_1 = 17°C = 290 K$

$P_1 = 100$ kPa

Given $R_s = 0.287$ kJ/kg.K

$C_{v\,average} = 0.723$ kJ/kg.K

$P_2 = 500$ kPa

$C_{p\,average} = 1.01$ kJ/kg.K

since $PV = mR_sT$

$$P_1 V_1^{1.3} = P_2 V_2^{1.3}$$

$$\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^{1.3} = \left(\frac{T_2/P_2}{T_1/P_1}\right)^{1.3}$$

$$\frac{P_1}{P_2} = \left(\frac{T_2}{T_1}\right)^{1.3} \left(\frac{P_1}{P_2}\right)^{1.3}$$

$$\frac{T_2}{T_1} = \left(\frac{P_1}{P_2}\right)^{\frac{1-1.3}{1.3}}$$

$$T_2 = T_1 \left(\frac{100}{500}\right)^{\frac{1-1.3}{1.3}} = 420.4 K$$

For a polytropic path :

$$W = \int_1^2 P\,dV = \frac{P_2V_2 - P_1V_1}{1-n} = \frac{mR_s(T_2 - T_1)}{1-n}$$

work input

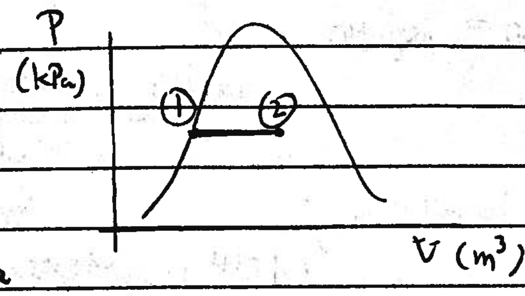
Since $P_1V_1 = mR_sT_1$

$\therefore$ specific work [kJ/kg] $\frac{W}{m} = \frac{R_s(T_2 - T_1)}{1-n} = -124.75$ kJ/kg

$$\Delta u = C_v(T_2 - T_1) = 0.723 \text{ kJ/kgK} \cdot (420.4 - 290) \text{ K}$$
$$= 94.28 \text{ kJ/kg}$$

4.2

expand isothermally



$P_1 = P_2 = P_{sat. @200°C} = 1554.9 \text{ kPa}$

from table

$v_1 = v_{f @200°C} = 0.001157 \text{ m}^3/\text{kg}$

$v_2 = v_f + x(v_g - v_f)$
$= 0.001157 + 0.70\ (0.12721 - 0.001157)$
$= 0.0893941$

$v_1 = \frac{V_1}{m} \rightarrow m = \frac{V_1}{v_1}$

$v_2 = \frac{V_2}{m}$

Same mass: $\frac{v_2}{v_1} = \frac{V_2}{V_1}$

$\therefore V_2 = \frac{v_2 V_1}{v_1}$

$= 0.0893941 \cdot \left(\frac{1 \text{ m}^3}{0.001157}\right)$

$= \underline{\underline{77.3 \text{ m}^3}}$

$W = \int_1^2 P\,dV = P(V_2 - V_1)$
$= 1554.9 \text{ kPa} \cdot (77.3 - 1) \text{ m}^3$
$= \underline{\underline{1.186 \times 10^5 \text{ kJ}}}$

4.3

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

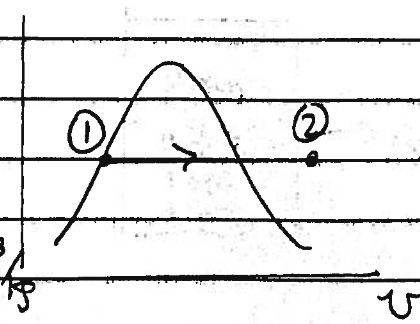
$$V_2 = \frac{m R_s T_2}{P_2} = \frac{(0.30\,kg)\,(0.2968\,kJ/kg\cdot K)\,(483\,K)}{75\ kPa}$$

$$= 0.5734\ m^3$$

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

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

4.4



For refrigerant -134a

$P_1 = 500\ kPa$, sat. liquid $\Big\}$ $v_1 = v_{f\,@500kPa} = 0.0008055\ m^3/kg$

$P_2 = 500\ kPa$, $T_2 = 70°C$ $\Big\}$ $v_2 = 0.052427\ m^3/kg$

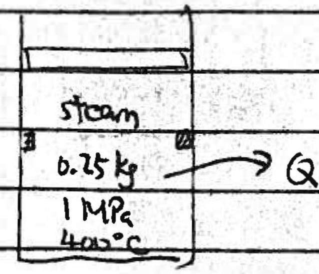
$$m = \frac{V_1}{v_1} = \frac{0.04\ m^3}{0.0008055\ m^3/kg} = 49.6\ kg$$

$$W = \int_1^2 P\,dV = P(V_2 - V_1) = mP(v_2 - v_1)$$ ← const. pressure path

$$= 49.6\,kg\,(500\,kPa)\cdot(0.052427 - 0.0008055)\,m^3$$

$$= \underline{\underline{1280.2\ kJ}}$$

4.5



$$\left.\begin{array}{l} P_1 = 1\ \text{MPa} \\ T_1 = 400°\text{C} \end{array}\right\} \quad v_1 = 0.30661\ \text{m}^3/\text{kg}$$

$$\left.\begin{array}{l} P_2 = 1\ \text{MPa} \\ T_2 = 250°\text{C} \end{array}\right\} \quad v_2 = 0.23275\ \text{m}^3/\text{kg}$$

a) During the constant pressure process:

$$W_b = mP(v_2 - v_1) = (0.25\ \text{kg})(1000\ \text{kPa})(0.23275 - 0.30661)\ \text{m}^3$$
$$= \underline{\underline{-18.47\ \text{kJ}}}$$

b) The volume at the final State is **55% of initial volume**

$$W_b = mP(0.55v_1 - v_1) = (0.25\ \text{kg})(1000\ \text{kPa})(0.55\times 0.30661 - 0.30661)\ \text{m}^3$$
$$= \underline{\underline{-34.5\ \text{kJ}}}$$

The temperature at the final state

$$\left.\begin{array}{l} P_2 = 0.50\ \text{MPa} \\ v_2 = (0.55\times 0.30661)\ \text{m}^3/\text{kg} = 0.1686355\ \text{m}^3/\text{kg} \end{array}\right\} \quad T_2 = T_{sat} = \underline{\underline{151.8°\text{C}}}$$

$\downarrow$

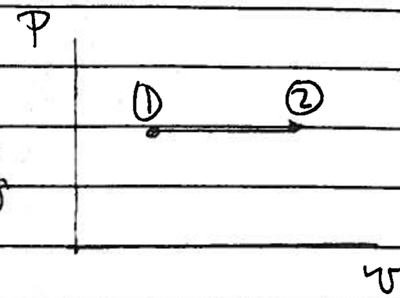
sat. mixture

since $v_f < v < v_g$

4.6

$P_1 = 300\,kPa$
sat. vapor

$\Big\}\ v_1 = v_{g@300kPa} = 0.60582\,m^3/kg$



$P_2 = 300\,kPa$
$T_2 = 200\,°C$

$\Big\}\ v_2 = 0.71643\,m^3/kg$

$$W = \int_1^2 P\,dV = mP_1(v_2 - v_1)$$
$$= (2\,kg)(300\,kPa)(0.71643 - 0.60582)\,m^3$$
$$= \underline{\underline{66.4\,kJ}}$$

4.7 R_s for helium $= 2.0769\ kJ/kg\,K$

initial volume : 1 kg, $8\,m^3$ $\Big\}$ $v_1 = \frac{V_1}{m} = \frac{8\,m^3}{1\,kg} = 8\,m^3/kg$

final state : $4\,m^3$

$T_1 = \frac{P_1 v_1}{R_s} = \frac{(150\,kPa)(8\,m^3/kg)}{2.0769\,kJ/kg \cdot K}$

constant pressure path $P = 150\,kPa$

$= \underline{\underline{577.8\,K}}$

$$\left.\begin{aligned} P_1 V_1 &= m R_s T_1 \\ P_2 V_2 &= m R_s T_2 \end{aligned}\right\} \quad T_2 = \frac{V_2}{V_1} T_1 = \left(\frac{4}{8}\right)\frac{m^3}{m^3}(577.8\,K) = \underline{\underline{288.9\,K}}$$

$$W = \int_1^2 P\,dV = P(V_2 - V_1) = (150\,kPa)(4-8)\,m^3$$
$$= \underline{\underline{-600\,kJ}}$$

4.8

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

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

for isothermal process:

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

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

$$P_2 V_2^n = P_3 V_3^n$$

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

$$V_3 = 0.01814\ m^3$$

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

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

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

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

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

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

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

4.9 $R_s = 0.2968\ kJ/kg\cdot K$ for N_2

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

$$m = \frac{P_1 V_1}{R_s T_1} = \frac{(150\ kPa)\cdot(0.08\ m^3)}{(0.2968)(393\ K)}$$

$$= \underline{\underline{0.10288}}\ kg$$

$$V_2 = \frac{m R_s T_2}{P_2} = \frac{(0.10288)(0.2968)(373\ K)}{100\ kPa}$$

$$= 0.1139\ m^3$$

$$P_1 V_1^{n} = P_2 V_2^{n}$$

$$(150\ kPa)(0.08\ m^3)^n = (100\ kPa)(0.1139\ m^3)^n$$

$$\frac{150}{100} = \left(\frac{0.1139}{0.08}\right)^n$$

$$\ln\left(\frac{150}{100}\right) = n \ln\left(\frac{0.1139}{0.08}\right)$$

$$n = \underline{\underline{1.15}}$$

$$W = \int_1^2 P\,dV = \int_1^2 \frac{c}{V^{-n}}\,dV = \int_1^2 c V^{-n}\,dV$$

$$= c\left[\frac{V^{1-n}}{1-n}\right]\Bigg|_1^2$$

$$= c\left(\frac{V_2^{1-n} - V_1^{1-n}}{1-n}\right)$$

$$= P_2 V_2^{n}\left(\frac{V_2^{1-n} - V_1^{1-n}}{1-n}\right)$$

$$= \frac{P_2 V_2 - P_1 V_1}{1-n} = \frac{(100)(0.1139) - (150)(0.08)}{1 - 1.15} = \underline{\underline{4.07\ kJ}}$$

4.10

$$P_1 V_1^n = P_2 V_2^n$$

$$W = \int_1^2 P\,dV$$

$$= \frac{P_2 V_2 - P_1 V_1}{1-n} \quad \text{for a polytropic process.}$$

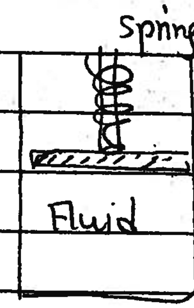
Using $PV = mR_sT$

R_s for N_2

$$W = \frac{mR_s(T_2 - T_1)}{1-n} = \frac{3 \cdot (0.2968)(380-300)}{1-1.4} = -178.1\,\text{KJ}$$

work input

4.11



initially 1 kg of water
90°C
quality $x = 0.10$

↓ heated until

$P = 800$ kPa
$T = 250°C$

⇒ Determine the total work during the process.

initial state :
at 90°C $P_{sat.} = 70.183$ kPa
$v_f = 0.001036$ m^3/kg
$v_g = 2.3593$ m^3/kg

$$v = v_f + x(v_g - v_f) = 0.23686 \ m^3/kg$$

Final state :
at $T = 250°C$
$P_{sat.} = 3976$ kPa $P < P_{sat.}$ at $T = 250°C$
∴ superheated

$v_2 = 0.29321$ m^3/kg

Under the effect of spring, the pressure rises linearly

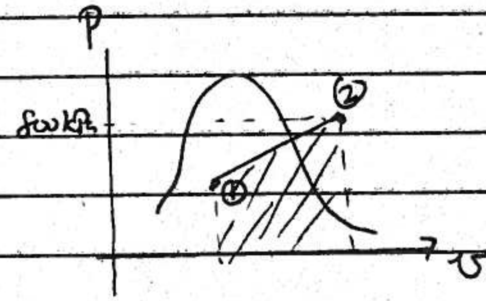
spring is linear in the range of interest

$F = kX$ linear with displacement (volume)

$P = \frac{F}{A}$ balance of force

The expansion process is quasi-equilibrium

↳ linear spring

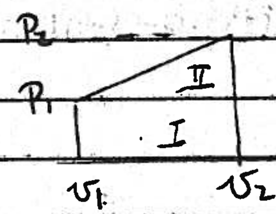


work is the area under the curve

$\int P\,dv$

$W = \text{area} = \frac{P_1+P_2}{2} m(v_2-v_1)$

area of trapezoid



$m(v_2-v_1)P_1 + m(v_2-v_1)\cdot\frac{(P_2-P_1)}{2}$

$= \frac{m(v_2-v_1)}{2}\left(2P_1+(P_2-P_1)\right)$

$= \frac{P_1+P_2}{2} m(v_2-v_1)$

$= \frac{(800\text{ kPa}) + 70.183\text{ kPa}}{2}(1)(0.29321-0.23686)$

$= \underline{\underline{24.52\text{ kJ}}}$

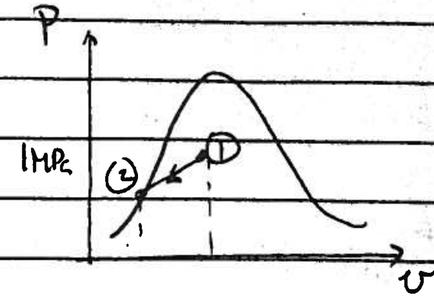
without spring - constant P

area I work against the piston and atmosphere

area II work against the spring

4.12

Initially a saturated mixture.



$$v_1 = v_f + x\,(v_g - v_f)$$

$$= 0.001127 + (0.25)(0.19436 - 0.001127)$$

$$= 0.04944 \ m^3/kg$$

Final state: $P_2 = 101.42$ kPa

$$v_2 = v_f = 0.001043 \ m^3/kg$$

spring loaded (see 4.11)*

$$W_b = \frac{P_1 + P_2}{2}\, m\,(v_2 - v_1)$$

$$= \frac{(1000 + 101.42)}{2}\,(2)\,(0.001043 - 0.04944)$$

$$= \underline{\underline{-53.3 \text{ kJ}}}$$

4.13

$$P_1 V_1 = m R_s T_1$$

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

$$P_1 V_1^n = P_2 V_2^n$$

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

For polytropic process:

$$W = \int_1^2 P\,dV = \frac{P_2 V_2 - P_1 V_1}{1-n} \qquad \underbrace{\quad}_{10V_1}$$

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

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

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

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

$$= -0.456\ kJ$$

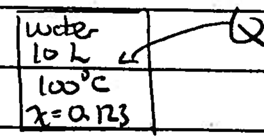
1st law: $\Delta U = \delta Q - \delta W$

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

4.14

$1L \rightarrow 1\,dm^3 \rightarrow 0.001\,m^3$

Rigid tank $\rightarrow$ no work done



$Q_{in} = \Delta U = m(u_2 - u_1)$ $\qquad$ Q_{in} = +ve positive

assuming K.E. and P.E. = 0

Initial State: $\qquad$ Table:

$T_1 = 100°C$, $x_1 = 0.123$ $\quad$ $v_f = 0.001043\ m^3/kg$ $\quad$ $u_f = 419.06\ kJ/kg$

$v_g = 1.6720\ m^3/kg$ $\quad$ $u_{fg} = u_g - u_f = 2087\ kJ/kg$

$v_1 = v_f + x(v_g - v_f)$
$= 0.2066\ m^3/kg$

$u_1 = u_f + x\,u_{fg} = 675.76\ kJ/kg$

Final State:
150°C

C.V. process $\quad v_2 = v_1 = 0.2066\ m^3/kg$

at 150°C $\quad v_f = 0.001091\ m^3/kg$, $v_g = 0.39248\ m^3/kg$ $\quad v_f < v_2 < v_g$

$\therefore$ two phase saturated mixture

$x = \dfrac{v_2 - v_f}{v_g - v_f} = \dfrac{0.2066 - 0.001091}{0.39248 - 0.001091} = \underline{\underline{0.5250}}$

at 150°C: $u_f = 631.66\ kJ/kg$

$u_{fg} = u_g - u_f = 1927.4\ kJ/kg$ $\qquad \therefore u_2 = u_f + x\,u_{fg} = 1643.5\ kJ/kg$

$Q_{in} = m(u_2 - u_1) = \dfrac{V_1}{v_1}(1643.5 - 675.76) = \underline{\underline{46.9\ kJ}}$

$m = \dfrac{V_1}{v_1} = 0.04841\ kg$

4.15

isothermal process

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

$$du = \delta q - \delta w$$

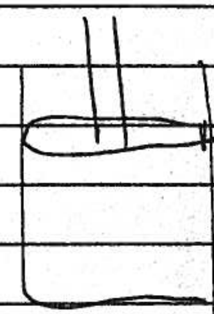
initial state:

$T_1 = 200°C$, $x_1 = 1$ } $v_1 = v_g = 0.12721\ m^3/kg$, $u_1 = u_g = 2594.2\ kJ/kg$

$P_1 = P_2 = 1554.9\ kPa$

$T_2 = 200°C$, $x_2 = 0$ } $v_2 = v_f = 0.001157\ m^3/kg$, $u_2 = u_f = 850.46\ kJ/kg$

$$W = \int_1^2 P\,dV = mP(v_2 - v_1)$$

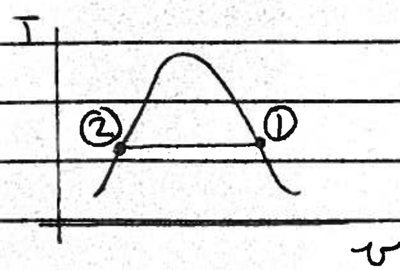


$$\frac{W}{m} = w = P(v_2 - v_1)$$
$$= (1554.9)(0.001157 - 0.12721)$$
$$= -196.0\ kJ/kg$$

* during phase change T = constant and P = const as well in 'a' piston cylinder device

$$q = (u_2 - u_1) + w$$
$$= (850.46 - 2594.2) + (-196)$$
$$= -1939.74\ kJ/kg$$

heat loss. (removal)



4.16

$\Delta P.E.$ and $\Delta K.E.$ neglected

$$dE_{sys} = \delta Q - \delta W$$

$$U_2 - U_1 = Q_{12} - W_{1-2}$$

work supplied

$$= (-1600\,kJ) - (-5100\,kJ)$$

heat removed

$$= +3500\,kJ$$

4.17

constant pressure process

$du = \delta q - \delta w$

$\delta q = du + \delta w = du + p\,dv$

$= dh$ since $h = u + pv$

$dh = du + p\,dv$

at 40 kPa

$h_{fg} = 2318.4\ kJ/kg$

$q = h_2 - h_1 = h_f - h_g = -h_{fg}$

$h_f = 317.62\ kJ/kg$

$h_g = 2636.1\ kJ/kg$

$\therefore\ \delta q = -h_{fg} = \underline{\underline{-2318.4}}\ kJ/kg$

$v_1 = v_g\ @\ 40kPa = 3.9933\ m^3/kg$

$v_2 = v_f\ @\ 40kPa = 0.001026\ m^3/kg$

$w = \int_1^2 p\,dv = (40kPa)(0.001026\ m^3/kg - 3.993\ m^3/kg)$

$= \underline{\underline{-159.7}}\ kJ/kg$

4.18

state 1

$P_1 = 0.1\ MPa$

$V_f = 0.05\ m^3$ $\qquad V_{total} = 5\ m^3$

$V_g = 4.95\ m^3$

@ 0.1MPa

$v_f = 0.001043\ m^3/kg$

$u_f = 417.36\ kJ/kg$

$v_g = 1.6940\ m^3/kg$

$u_g = 2506.1\ kJ/kg$

state 2

$x_2 = 1$

$V_2 = 5\ m^3 = V_g$

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

$$U_2 - U_1 = Q_{1-2} - \cancel{W_{1-2}}^{\,0}$$

rigid tank

To compute U_1, we have

$$u_1 = u_f + x\,u_{fg}$$

$$u_1 + u_f + \frac{m_g}{m} u_{fg}$$

$$\underbrace{m u_1}_{} = m u_f + m_g u_{fg}$$

$$U_1 = (m_f + m_g) u_f + m_g (u_g - u_f)$$

$$= m_f u_f + m_g u_g$$

$$m_f = \frac{V_f}{v_f} = \frac{0.05}{\underbrace{0.001043}_{v_f \text{ @ } 0.1\text{MPa}}} = 47.94\ kg$$

$$m_g = \frac{V_g}{v_g} = \frac{4.95}{1.6940} = 2.92\ kg$$

$$U_1 = 47.94\,(417.36) + 2.92\,(2506.1)$$
$$= \underline{\underline{27326\ kJ}}$$

To find U_2, we know $x_2 = 1$ and so, $v_2 = \dfrac{V_{total}}{m_{total}}$

$$v_2 = \frac{5}{47.94 + 2.92} = 0.0983\ m^3/kg$$

$$v_g = 0.09831\ m^3/kg$$

at table A-5

$P = 2250\ kPa$ $\quad v_g = 0.088717\ m^3/kg$ $\quad u_g = 2600.9\ kJ/kg$

$P = 2000\ kPa$ $\quad v_g = 0.099587\ m^3/kg$ $\quad u_g = 2599.1\ kJ/kg$

$\therefore$ $P_2 = 2.031\ MPa$ by interpolation

$u_2 = 2600.5\ kJ/kg = u_{g_2}$

$$U_2 = m u_2 = 50.86\,(2600.5) = 132261\ kJ$$

$$Q_{1-2} = U_2 - U_1 = \underline{\underline{+104\,935\ kJ}}$$

heat supplied

4.19

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

$$U_2 - U_1 = Q_{12} - W_{12}$$

polytropic process $P_2 V_2^n = P_1 V_1^n$

$$\frac{mR_sT_2}{V_2} V_2^n = \frac{mR_sT_1}{V_1} V_1^n$$

$$Q_{12} = (U_2 - U_1) + W_{12}$$

$$T_2 (V_2)^{n-1} = T_1 V_1^{n-1}$$

$$\frac{T_2}{T_1} = \left(\frac{V_2}{V_1}\right)^{1-n}$$

$$W_{12} = \int_1^2 P\,dV = \frac{P_2 V_2 - P_1 V_1}{1-n}$$

$$P_2 = P_1 \left(\frac{V_1}{V_2}\right)^n$$

$$= \frac{(106.066)(0.2) - (300)(0.1)}{1 - 1.5}$$

$$= 106.066\ kPa$$

$$= \underline{\underline{17.57\ kJ}}$$

$$Q_{12} = (4\,kg)(-4.6\,kJ/kg) + 17.6\,kJ$$

$$= \underline{\underline{-0.8\ kJ}}$$

4-83 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 transferred to the argon in kJ. Assume constant properties.

Assume: closed system

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

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

ideal gas.

$1 \rightarrow 2$ isothermal

$2 \rightarrow 3$ (isobaric)

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

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

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

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

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

$$= 0.6407\ kg$$

$1 \rightarrow 2$ 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

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

$1 \rightarrow 2$: 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

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

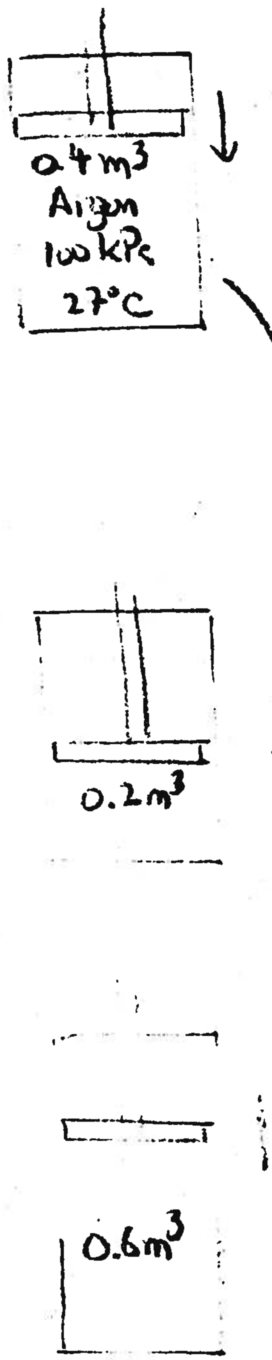
$$\therefore \quad m c_v (T_3 - T_1) = Q_{net} - (-27.7\ kJ + 80\ kJ)$$

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

$$= +172.3\ kJ$$

input

(1)



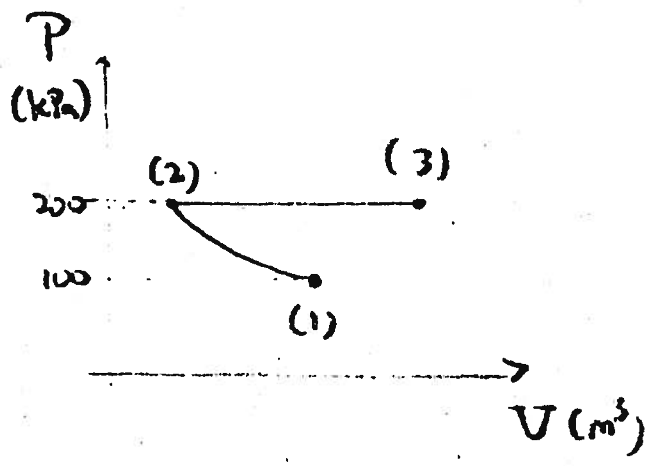
set of stops

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

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

Isothermal process
$T = \text{const.}$

Isobaric process
$P = \text{const.}$



Determine net Q to the argon in kJ

4-149 : A piston-cylinder device initially contains 0.35 kg steam at 3.5 MPa, superheated by 7.4°C. Now the steam loses heat to the surroundings and the piston moves down, hitting a set of stops at which point the cylinder contains saturated liquid water. The cooling continues until the cylinder contains water at 200°C.

Determine the final pressure & quality, the boundary work and total heat transfer.

First law for the whole process

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

$$U_3 - U_1 = Q_{1-3} - W_{1-2} \qquad \text{since } W_{2-3} = 0$$

Initially : (from A-4 through A-6)

$$T_{sat} @ 3.5\,MPa = 242.56°C$$

$$T_1 = T_{sat.} + \Delta T = 242.56 + 7.4 = 250°C$$

$$\left.\begin{array}{l} P_1 = 3.5\,MPa \\ T_1 = 250°C \end{array}\right\} \quad \left.\begin{array}{l} v_1 = 0.05875\ m^3/kg \\ u_1 = 2623.9\ kJ/kg \end{array}\right\} \text{ superheated.}$$

$P_2 = P_1 = 3.5\,MPa$ | $v_2 = 0.001235\ m^3/kg$
$x_2 = 0$ | $u_2 = 1045.4\ kJ/kg$

@ 200°C

$v_3 = v_2 = 0.001235\ m^3/kg$ | $v_f = 0.001157\ m^3/kg$
$T_3 = 200°C$ | $v_g = 0.12721\ m^3/kg$

$x_3 = 0.00062$
$P_3 = 1555\ kPa$
$u_3 = 851.55\ kJ/kg$

$v_3 = v_f + x(v_g - v_f)$

$x = \dfrac{v_3 - v_f}{v_g - v_f}$

$\therefore\ W_{1-2} = m P_1 (v_2 - v_1)$

$= (0.35)(3500\ kPa)(0.001235 - 0.05875)$

$= -70.45\ kJ$

$\therefore\ Q_{1-3} = m(u_3 - u_1) + W_{12}$

$= (0.35)(851.55 - 2623.9) + (-70.45)$

$= -690.8\ kJ$

Q_{out}

4.22

isothermal

$\cancel{dU}^{0} = \delta Q - \delta W$

$Q_{12} = W_{12}$

$$V_1 = \frac{m R_g T_1}{P_1} = \frac{(2\ kg)(0.287\ kJ/kg\,K)(473K)}{600\ kPa} = 0.4525\ m^3$$

$$W = \int_1^2 P\,dV = P_1 V_1 \ln\left(\frac{V_2}{V_1}\right) = m R_g T_1 \ln\left(\frac{V_2}{V_1}\right) = m R_g T_1 \ln\left(\frac{P_1}{P_2}\right)$$

$$= 2 \cdot (0.287)(473) \ln\left(\frac{600}{80}\right)$$

$$= 547.1\ kJ$$

$Q_{12} = W_{12} = 547.1\ kJ$

heat supplied

4.23

spring loaded

$dU = \delta Q - \delta W$

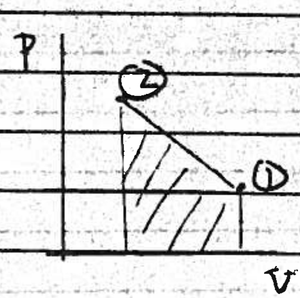
$$V_1 = \frac{m R_o T_1}{P_1} = \frac{(1\,kg)(0.1889\,kJ/kg\,K)(298\,K)}{100\,kPa} = 0.5629\ m^3$$

$$V_2 = \frac{m R_o T_2}{P_2} = \frac{(1\,kg)(0.1889\,kJ/kg)(573\,K)}{1000\,kPa} = 0.1082\ m^3$$

for linear spring (see 4.11)

$$W = \frac{P_1 + P_2}{2}(V_2 - V_1) = \frac{100+1000}{2}(0.1082 - 0.5629)$$

$$= \underline{\underline{-250.1\,kJ}}$$



$$Q_{12} = W_{12} + (U_2 - U_1)$$

$$= (-250.1\,kJ) + m C_v (T_2 - T_1)$$

$$= -250.1 + 1 \cdot 0.657\,kJ/kg\,K \cdot (573 - 298) = \underline{\underline{-69.4\,kJ}}$$

4.24

$$dU = \delta Q - \delta W$$ work done by the isothermal process + work input from paddle wheel.

isothermal $\underset{0}{\cancel{dU}} = Q_{12} - W_{12}$

For air (ideal gas) and an isothermal process:

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

$$w = \frac{W}{m} = P_1 v_1 \ln\left(\frac{v_2}{v_1}\right) = R_g T_1 \ln\left(\frac{3}{1}\right)$$

$$= (0.287)(300)\ln 3$$

$$= 94.6 \text{ kJ/kg}$$

$$Q_{12} = W_{12}$$

"or"

$$q_{12} = w_{12} = w_{paddle} + w_{\substack{isothermal\\process}}$$

$$= \underset{\text{supplied}}{(-50 \text{ kJ/kg})} + (94.6 \text{ kJ/kg})$$

$$= \underset{\text{heat input}}{\underline{\underline{+44.6}}} \text{ kJ/kg}$$

4.26

$$dU = \delta Q - \cancel{\delta W}^{0}$$

$$Q_{1-2} = \Delta U_{A_{1-2}} + \Delta U_{B_{1-2}}$$

$$= [m(u_2 - u_1)]_{tank\ A} + [m(u_2 - u_1)]_{tank\ B}$$

tank A :

$P_1 = 1000\ kPa$, $T_1 = 300°C$ } $v_1 = 0.25799\ m^3/kg$, $u_1 = 2793.7\ kJ/kg$

tank B :

$T_1 = 150°C$, $x_1 = 0.50$ } $v_f = 0.001091\ m^3/kg$, $u_f = 631.66\ kJ/kg$, $v_g = 0.39248\ m^3/kg$, $u_g = 1927.4\ kJ/kg$ (?)

$$v_1 = v_f + x(v_g - v_f) = 0.19679\ m^3/kg$$

$$u_1 = u_f + x(u_g - u_f) = 1595.4\ kJ/kg$$

$$V_{total} = V_A + V_B = m_A v_{1A} + m_B v_{1B}$$

$$= 2 \cdot (0.25799) + 3 \cdot (0.19679) = 1.106\ m^3$$

$$m_{total} = m_A + m_B = 3 + 2 = 5\ kg$$

$$v_2 = \frac{V_{total}}{m_{total}} = \frac{1.106\ m^3}{5\ kg} = 0.22127\ m^3/kg$$

∴ Final state :

$P_2 = 300\ kPa$, $v_2 = 0.22127\ m^3/kg$ } $T_2 = T_{sat} = 133.5°C$

$$x_2 = \frac{v_2 - v_f}{v_g - v_f} = \frac{0.22127 - 0.001073}{0.60582 - 0.001073} = 0.3641$$

$$u_2 = u_f + x\, u_{fg} = 561.11 + 0.3641 \cdot (1982.1)$$
$$= 1282.8\ \mathrm{kJ/kg}$$

$$\therefore\ Q_{12} = [m(u_2 - u_1)]_A + [m(u_2 - u_1)]_B$$
$$= (2\,\mathrm{kg})(1282.8 - 2793.7) + 3 \cdot (1282.8 - 1855.4)$$
$$= \underline{\underline{-3955\ \mathrm{kJ}}}$$

4.26

Initial state

$$V_1 = \frac{m R_g T_1}{P_1} = 3 \cdot \frac{(0.287)(300)}{200} = 1.29\ m^3$$

Final state

$$V_3 = 2V_1 = 2.58\ m^3 \qquad P_3 = 2P_1 = 400\ kPa$$

$$\frac{P_1 V_1}{T_1} = \frac{P_3 V_3}{T_3} \rightarrow T_3 = \frac{P_3}{P_1}\left(\frac{V_3}{V_1}\right) T_1 = \frac{400\ kPa}{200\ kPa} \times 2 \times 300\ K$$

$$= 1200\ K$$

$1 \rightarrow 2$

$$W_{12} = \int_1^2 P\,dV = P_2 (V_2 - V_1) \quad \text{constant pressure process.}$$

$$= (200)(2.58 - 1.29)$$

$$= \underline{\underline{258\ kJ}}$$

$$\left.\begin{aligned} u_1 &= u_{@300K} = 214.07\ kJ/kg \\ u_2 &= u_{@1200K} = 933.33\ kJ/kg \end{aligned}\right\} \text{from table}$$

"or" can be approximated by $(u_3 - u_1) = c_v (T_3 - T_1)$

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

$$Q_{1-3} = m(u_3 - u_1) + W_{12} \qquad W_{2-3} = 0$$

$$= (3)(933.33 - 214.07) + 258$$

$$= \underline{\underline{2416\ kJ}}$$

note the specific heat c_v approximated at $\frac{300+1200}{2} = 750K$

$$\Rightarrow c_{v\,average} = 0.800\ \frac{kJ}{kg \cdot K}$$

$$(u_3 - u_1) = 0.800(1200 - 300)$$

$$= 720$$

$$Q_{1-3} = 3 \cdot (720) + 258 = \underline{2418\ kJ}$$

CONTROL VOLUME ANALYSIS

Conservation of mass

5.1 Air with density of 2.10 kg/m^3 is flowing steadily into a nozzle at 35 m/s and leaves at 175 m/s with density of 0.77 kg/m^3. If the inlet area of the nozzle is 90 cm^2, determine the mass flow rate through the nozzle, and the exit area of the nozzle.

5.2 To design a hair dryer, it should contain the following basic components: a duct of constant diameter with a few layers of electric resistors, a small fan to pull the air in and to force it through the heating resistors. If the density of air is 1.18 kg/m^3 at the inlet and 0.90 kg/m^3 at the exit, what is the percent increase in the velocity of air as it flows through the dryer?

5.3 (Tutorial) Air is flowing at a velocity of 175 m/s into a 1-m^2 inlet of an aircraft engine at 100 kPa and 18°C. Compute the volume flow rate, in m^3/s, at the engine's inlet and the mass flow rate, in kg/s, at the engine's outlet.

5.4 (Tutorial) A pump is used to increase the water pressure from 70 kPa at the inlet to 700 kPa at the outlet. Water first enters this pump at 15°C through a 1-cm-diameter opening and leaves through a 1.5 cm-diameter outlet. The mass flow rate through the pump is 0.6 kg/s. Compute the velocity of the water at the inlet and outlet. Will these velocities change significantly if the inlet temperature is raised to 40 °C?

Nozzles and diffusers

5.5 Air at 75 kPa and 127°C is flowing steadily into an adiabatic diffuser at a rate of 5500 kg/h and leaves at 100 kPa. The velocity of the air stream changes from 220 to 20 m/s as it passes through the diffuser. Determine the exit temperature of the air and the exit area of the diffuser.

5.6 (Tutorial) An adiabatic nozzle is having a steady flow of carbon dioxide at 1 MPa and 500°C with a mass flow rate of 5000 kg/h and leaves at 100 kPa and 400 m/s. The inlet area of the nozzle is 35 cm^2. Determine a) the inlet velocity and b) the exit temperature.

5.7 (Tutorial) The stators in a gas turbine are designed to increase the kinetic energy of the gas passing through them adiabatically. Air flows steadily into a set of these nozzles at 2 MPa and 371°C with a velocity of 24.4 m/s and leaves the nozzles at 1.724 MPa and 341°C. What is the velocity at the exit of the nozzles?

5.8 (Tutorial) Steam flows steadily with a velocity of 10 m/s into a nozzle at 400 °C and 800 kPa, and leaves at 300 °C and 200 kPa. The nozzle is not adiabatic and hence, there is a heat loss which is found to be at a rate of 25 kW. The nozzle inlet area is 800 cm^2. What is the velocity and the volume flow rate of the steam at the nozzle exit?

5.9 A steady flow of Refrigerant-134a is found in a diffuser. At the inlet, its state is a saturated vapor at 800 kPa with a velocity of 100 m/s. At the outlet, the R-134a leaves at 900 kPa and 40 °C. The refrigerant is also receiving heat from the surrounding at a rate of 1.8 kJ/s (or 1.8 kW) as it passes through the diffuser. Also, it is found that the exit area is 75% greater than the inlet area. What are the exit velocity and the mass flow rate of the refrigerant?

Turbines and Compressors

5.10 (Tutorial) A steady flow of Refrigerant-134a enters a compressor at 180 kPa as a saturated vapor with a flow rate of 0.40 m^3/min and leaves at 700 kPa. The power supplied to the refrigerant is measured to be 2.50 kW. What is the temperature of R-134a at the exit of the compressor?

5.11 Refrigerant-134a enters a compressor at a flow rate of 1.20 m^3/min with thermodynamic condition of 100 kPa and -24°C. The flow leaves the compressor at 800 kPa and 60 °C. Determine the mass flow rate of R-134a and the power required by the compressor.

5.12 (Tutorial) 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.

5.13 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.

5.14 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.

5.15 (Tutorial) 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.

5.16 (Tutorial) 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.

5.17 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.

5.18 (Tutorial) 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.

5.19 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.

Throttling devices

5.20. (Tutorial) 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. The exit pressure is 100 kPa. Assuming that 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.

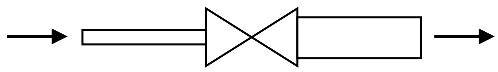


Fig.5.20

5.21. Consider an adiabatic throttling valve with water entering at pressure of 1.6 MPa, a temperature of 150°C and a velocity of 4.5 m/s. The exit pressure is 300 kPa. Determine the velocity at the exit.

Heat Exchanger

5.22. Two kg of water are condensed per second 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.

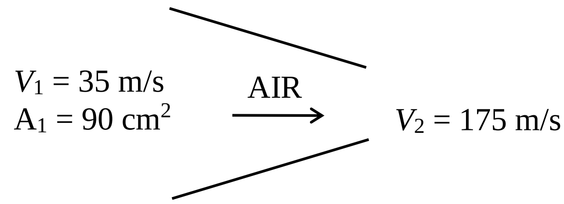
5.23. (Tutorial) The exhaust gases of a car are to be used to heat up water. 0.5 kg/s of hot gases enter the heat exchanger at a temperature of 250°C and leave at a 150°C. If 0.5 kg/s of water enter the heat exchanger with an inlet temperature of 20°C, determine the temperature of the water at the exit.

Assume Cp for the hot gases and for the water to be 1.08 and 4.186 kJ/kg K, respectively.

Conservation of mass

Question 1.

Flow through the nozzle is steady.



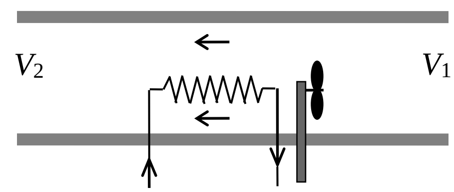
$$\dot{m} = \rho_1 A_1 V_1 = (2.10 \text{ kg/m}^3)(0.009 \text{ m}^2)(35 \text{ m/s}) = \mathbf{0.6615 \text{ kg/s}}$$

There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. Then the exit area of the nozzle is determined to be

$$\dot{m} = \rho_2 A_2 V_2 \longrightarrow A_2 = \frac{\dot{m}}{\rho_2 V_2} = \frac{0.6615 \text{ kg/s}}{(0.77 \text{ kg/m}^3)(175 \text{ m/s})} = 0.00491 \text{ m}^2 = \mathbf{49.1 \text{ cm}^2}$$

Question 2.

Flow through the nozzle is steady.



There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. Then,

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

$$\rho_1 A V_1 = \rho_2 A V_2$$

$$\frac{V_2}{V_1} = \frac{\rho_1}{\rho_2} = \frac{1.18 \text{ kg/m}^3}{0.90 \text{ kg/m}^3} = 1.311 \quad \text{(or, and increase of } \mathbf{31.1\%}\text{)}$$

Therefore, the air velocity increases 31.1% as it flows through the hair drier.

Question 3.

Air is an ideal gas. The flow is steady.

The gas constant of air is $R_s = 0.287$ kPa·m^3/kg·K

The inlet volume flow rate is

$$\dot{V}_1 = A_1 V_1 = (1 \text{ m}^2)(175 \text{ m/s}) = \mathbf{175 \text{ m}^3/\text{s}}$$

The specific volume at the inlet is

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(18 + 273 \text{ K})}{100 \text{ kPa}} = 0.8352 \text{ m}^3/\text{kg}$$

Since the flow is steady, the mass flow rate remains constant during the flow. Then,

$$\dot{m} = \frac{\dot{V}_1}{v_1} = \frac{175 \text{ m}^3/\text{s}}{0.8352 \text{ m}^3/\text{kg}} = \mathbf{209.53 \text{ kg/s}}$$

<u>Question 4.</u>

Flow through the pump is steady.

The inlet state of water is compressed liquid, approximated as a saturated liquid at the given temperature. At 15°C and 40°C, we have:

$$\left.\begin{array}{l} T = 15°\text{C} \\ x = 0 \end{array}\right\} \boldsymbol{v}_1 = 0.001001\,\text{m}^3/\text{kg}$$

$$\left.\begin{array}{l} T = 40°\text{C} \\ x = 0 \end{array}\right\} \boldsymbol{v}_1 = 0.001008\,\text{m}^3/\text{kg}$$

The velocity of the water at the inlet is

$$V_1 = \frac{\dot{m}\boldsymbol{v}_1}{A_1} = \frac{4\dot{m}\boldsymbol{v}_1}{\pi D_1^2} = \frac{4(0.6\text{ kg/s})(0.001001\,\text{m}^3/\text{kg})}{\pi(0.01\,\text{m})^2} = \mathbf{7.647\ m/s}$$

Since the mass flow rate and the specific volume remains constant, the velocity at the pump exit is

$$V_2 = V_1\frac{A_1}{A_2} = V_1\left(\frac{D_1}{D_2}\right)^2 = (7.647\text{ m/s})\left(\frac{0.01\,\text{m}}{0.015\,\text{m}}\right)^2 = \mathbf{3.3987\ m/s}$$

Using the specific volume at 40°C, the water velocity at the inlet becomes

$$V_1 = \frac{\dot{m}\boldsymbol{v}_1}{A_1} = \frac{4\dot{m}\boldsymbol{v}_1}{\pi D_1^2} = \frac{4(0.6\text{ kg/s})(0.001008\,\text{m}^3/\text{kg})}{\pi(0.01\,\text{m})^2} = \mathbf{7.7006\ m/s}$$

which is a 0.7% increase in velocity.

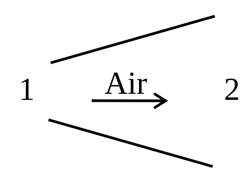
Nozzles and diffusers

Question 5.

Potential energy changes are negligible. The device is adiabatic. There is no shaft work. The gas constant of air is 0.287 kPa.m^3/kg.K. The specific heat is assumed to be constant c_p = 1.013 kJ/kg-K.

There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take diffuser 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

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



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

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

$$0 = h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} \quad ,$$

$$0 = c_p(T_2 - T_1) + \frac{V_2^2 - V_1^2}{2} = (1.013)\text{kJ/kgK } (T_2 \text{ - } 400\text{K}) + \frac{(20 \text{ m/s})^2 - (220 \text{ m/s})^2}{2}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right)$$

T_2 = **423.7 K**

(*b*) The specific volume of air at the diffuser exit is

$$\boldsymbol{v}_2 = \frac{RT_2}{P_2} = \frac{(0.287 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(423.7 \text{ K})}{(100 \text{ kPa})} = 1.216 \text{ m}^3/\text{kg}$$

From conservation of mass,

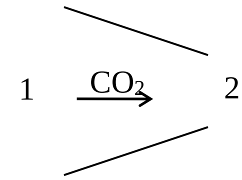
$$\dot{m} = \frac{1}{\boldsymbol{v}_2} A_2 V_2 \longrightarrow A_2 = \frac{\dot{m}\boldsymbol{v}_2}{V_2} = \frac{(5500/3600 \text{ kg/s})(1.216 \text{ m}^3/\text{kg})}{20 \text{ m/s}} = \mathbf{0.0929 \ \ m^2}$$

Question 6.

The gas constant R_s of CO_2 is 0.1889 kPa.m^3/kg.K and the specific heat at constant pressure c_p is assumed to be a constant of 1.126 kJ/kg.K

There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. Using the ideal gas relation, the specific volume is determined to be

$$\boldsymbol{v}_1 = \frac{RT_1}{P_1} = \frac{(0.1889\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(773\ \text{K})}{1000\ \text{kPa}} = 0.146\ \text{m}^3/\text{kg}$$



Thus,

$$\dot{m} = \frac{1}{\boldsymbol{v}_1} A_1 V_1 \longrightarrow V_1 = \frac{\dot{m}\boldsymbol{v}_1}{A_1} = \frac{(5000/3600\ \text{kg/s})(0.146\ \text{m}^3/\text{kg})}{35\times 10^{-4}\,\text{m}^2} = 57.9\ \textbf{m/s}$$

We take nozzle 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

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

For steady state:

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

$$\dot{m}(h_1 + V_1^2/2) = \dot{m}(h_2 + \text{V}_2^2/2) \quad (\text{since } \dot{Q} \cong \dot{\text{W}} \cong \Delta\text{pe} \cong 0)$$

$$0 = h_2 - h_1 + \frac{V_2^2 - V_1^2}{2}$$

Substituting,

$$0 = h_2 - h_1 + \frac{V_2^2 - V_1^2}{2}$$

$$0 = c_p(T_2 - T_1) + \frac{V_2^2 - V_1^2}{2}$$

$$0 = 1.126\text{kJ/kgK}\,(T_2 - 773\text{K}) + \frac{(400\text{m/s})^2 - (57.9\text{m/s})^2}{2}\cdot\left(\frac{1\text{kJ}}{1000\text{J}}\right)$$

$$T_2 = 703.4\text{K}$$

Therefore the exit temperature of CO_2 is obtained to be T_2 = **703.4 K**

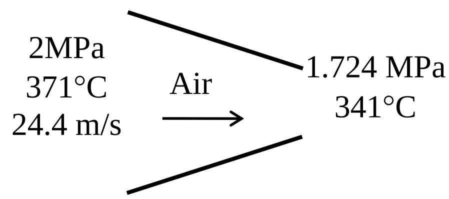
Question 7.

Properties The specific heat of air at the average temperature of ~350°C is c_p = 1.008 kJ/kg·K.

There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take nozzle 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

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

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



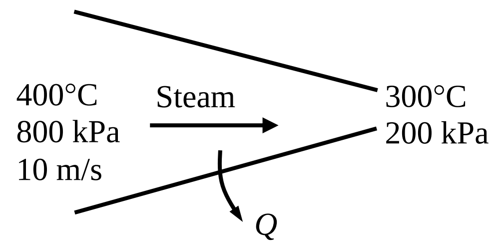
$$\dot{m}(h_1 + V_1^2/2) = \dot{m}(h_2 + V_2^2/2)$$
$$h_1 + V_1^2/2 = h_2 + V_2^2/2$$

Solving for exit velocity,

$$V_2 = \left[V_1^2 + 2(h_1 - h_2)\right]^{0.5} = \left[V_1^2 + 2c_p(T_1 - T_2)\right]^{0.5}$$
$$= \left[(24.4\text{ m/s})^2 + 2(1.008\text{kJ/kg - K})(644 - 614)\text{K} * \frac{1000\text{J}}{1\text{kJ}}\right]^{0.5}$$
$$= \mathbf{247 m/s}$$

Question 8.

This is a steady-flow process. Potential energy change is negligible. There is no shaft work done.



We take the steam 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:

Energy balance: $$\cancel{\frac{de}{dt}} = q - \cancel{w_s} + (h_i + V_i^2/2 + \cancel{gZ_i}) - (h_e + V_e^2/2 + \cancel{gZ_e}) = 0$$

or $$h_1 + \frac{V_1^2}{2} + q = h_2 + \frac{V_2^2}{2} \qquad \text{where } q = \frac{\dot{Q}}{\dot{m}}$$

The properties of steam at the inlet and exit are (Table A-6)

$$\left.\begin{array}{l} P_1 = 800 \text{ kPa} \\ T_1 = 400°\text{C} \end{array}\right\} \begin{array}{l} \boldsymbol{v}_1 = 0.38429 \text{ m}^3/\text{kg} \\ h_1 = 3267.7 \text{ kJ/kg} \end{array}$$

$$\left.\begin{array}{l} P_2 = 200 \text{ kPa} \\ T_1 = 300°\text{C} \end{array}\right\} \begin{array}{l} \boldsymbol{v}_2 = 1.31623 \text{ m}^3/\text{kg} \\ h_2 = 3072.1 \text{ kJ/kg} \end{array}$$

The mass flow rate of the steam is

$$\dot{m} = \frac{1}{\boldsymbol{v}_1} A_1 V_1 = \frac{1}{0.38429 \text{ m}^3/\text{s}} (0.08 \text{ m}^2)(10 \text{ m/s}) = 2.082 \text{ kg/s}$$

Substituting,

$$3267.7 \text{ kJ/kg} + \frac{(10 \text{ m/s})^2}{2}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right) + \frac{(-25 \text{ kJ/s})}{2.082 \text{ kg/s}} = 3072.1 \text{ kJ/kg} + \frac{V_2^2}{2}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right)$$

$$\longrightarrow V_2 = \mathbf{606 \text{ m/s}}$$

The volume flow rate at the exit of the nozzle is

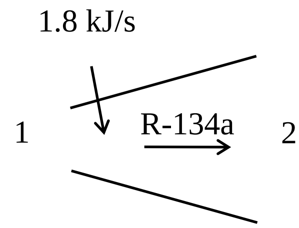
$$\dot{\boldsymbol{V}}_2 = \dot{m}\boldsymbol{v}_2 = (2.082 \text{ kg/s})(1.31623 \text{ m}^3/\text{kg}) = \mathbf{2.74 \text{ m}^3/\text{s}}$$

*Note that $\dot{Q}$ = - 25 kW (the negative sign denotes heat loss from the system to the surrounding). Therefore, q = $\frac{\dot{Q}}{\dot{m}} = \frac{(-25 \text{ kJ/s})}{2.082 \text{ kg/s}}$

Question 9.

This is a steady-flow process. Potential energy changes are negligible. There is no work.

From the R-134a tables



$$\left.\begin{array}{l} P_1 = 800 \text{ kPa} \\ sat.vapor \end{array}\right\} \begin{array}{l} \boldsymbol{v}_1 = 0.025621 \text{ m}^3\text{/kg} \\ h_1 = 267.29 \text{ kJ/kg} \end{array}$$

and

$$\left.\begin{array}{l} P_2 = 900 \text{ kPa} \\ T_2 = 40°\text{C} \end{array}\right\} \begin{array}{l} \boldsymbol{v}_2 = 0.023375 \text{ m}^3\text{/kg} \\ h_2 = 274.17 \text{ kJ/kg} \end{array}$$

There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. Then the exit velocity of R-134a is determined from the steady-flow mass balance to be

$$\frac{1}{\boldsymbol{v}_2} A_2 V_2 = \frac{1}{\boldsymbol{v}_1} A_1 V_1 \longrightarrow V_2 = \frac{\boldsymbol{v}_2}{\boldsymbol{v}_1}\frac{A_1}{A_2} V_1 = \frac{1}{1.75}\frac{(0.023375 \text{ m}^3\text{/kg})}{(0.025621 \text{ m}^3\text{/kg})}(100 \text{ m/s}) = \mathbf{52.13 \text{ m/s}}$$

We take diffuser 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

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

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

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

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

Substituting, the mass flow rate of the refrigerant is determined to be

$$+1.8 \text{ kJ/s} = \dot{m}\left((274.17 - 267.29)\text{kJ/kg} + \frac{(52.13 \text{ m/s})^2 - (100 \text{ m/s})^2}{2}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2\text{/s}^2}\right)\right)$$

It yields

$$\dot{m} = \mathbf{0.556 \text{ kg/s}}$$

Turbines and Compressors

<u>Question 10.</u>

This is a steady-flow process. Kinetic and potential energy changes are negligible. Heat transfer with the surroundings is negligible. So **adiabati**c system.

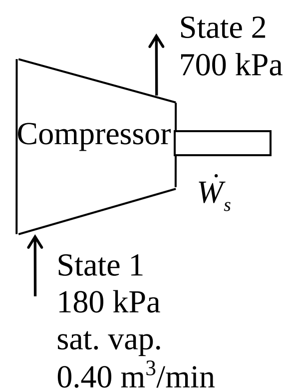
We take the compressor as the system, which is a control volume since mass crosses the boundary. Noting that one fluid stream enters and leaves the compressor, the energy balance for this steady-flow system can be expressed in the rate form as

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

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

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

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



From R134a tables (Table A-12)

$$\left.\begin{array}{l} P_1 = 180\ \text{kPa} \\ x_1 = 0 \end{array}\right\} \begin{array}{l} h_1 = 242.86\ \text{kJ/kg} \\ v_1 = 0.1104\ \text{m}^3/\text{kg} \end{array}$$

The mass flow rate is

$$\dot{m} = \frac{\dot{V}_1}{v_1} = \frac{(0.40/60)\ \text{m}^3/\text{s}}{0.1104\ \text{m}^3/\text{kg}} = 0.0604\ \text{kg/s}$$

Substituting for the exit enthalpy,

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

$$(-2.5\ \text{kJ/s}) = (0.0604\ \text{kg/s})(242.86 - h_2)\text{kJ/kg} \longrightarrow h_2 = 284.25\ \text{kJ/kg}$$

From Table,

$$\left.\begin{array}{l} P_2 = 700\ \text{kPa} \\ h_2 = 284.25\ \text{kJ/kg} \end{array}\right\} T_2 = \mathbf{48^\circ C}$$

$\dot{W}_s$ **= - 2.5 kW** (negative value) since the work is supplied to the system to run the compressor.

Question 11.

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

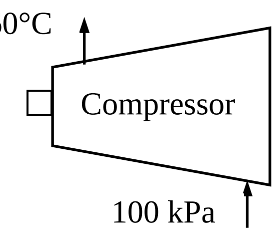
We take the compressor as the system, which is a control volume since mass crosses the boundary. Noting that one fluid stream enters and leaves the compressor, the energy balance for this steady-flow system can be expressed in the rate form as

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

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

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

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



From R134a tables:

$$\left.\begin{array}{l} P_1 = 100\ \text{kPa} \\ T_1 = -24°\text{C} \end{array}\right\} \begin{array}{l} h_1 = 236.33\ \text{kJ/kg} \\ v_1 = 0.1947\ \text{m}^3/\text{kg} \end{array}$$

$$\left.\begin{array}{l} P_2 = 800\ \text{kPa} \\ T_2 = 60°\text{C} \end{array}\right\} h_2 = 296.81\ \text{kJ/kg}$$

The mass flow rate is

$$\dot{m} = \frac{\dot{V}_1}{v_1} = \frac{(1.20/60)\ \text{m}^3/\text{s}}{0.1947\ \text{m}^3/\text{kg}} = \mathbf{0.1027\ kg/s}$$

Substituting,

$$\dot{W}_s = \dot{m}(h_1 - h_2) = (0.1027\ \text{kg/s})(236.33 - 296.81)\text{kJ/kg} = \mathbf{-6.21 kW}$$

Work input to the system

Question 12.

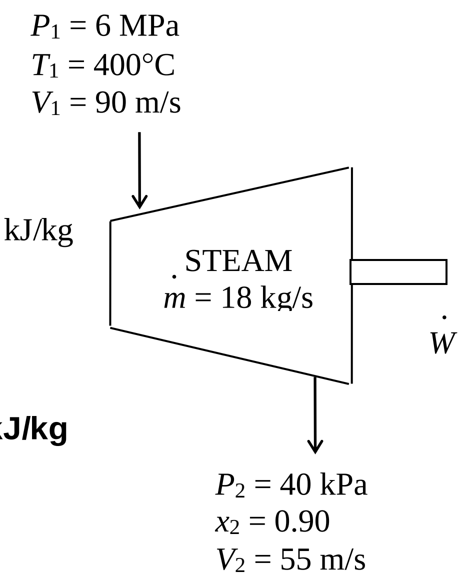
This is a steady-flow process. Potential energy changes are negligible. The device is adiabatic and thus heat transfer is negligible.

From the steam tables

$$\left.\begin{array}{l} P_1 = 6 \text{ MPa} \\ T_1 = 400°\text{C} \end{array}\right\} \begin{array}{l} \boldsymbol{v}_1 = 0.047420 \text{ m}^3\text{/kg} \\ h_1 = 3178.3 \text{ kJ/kg} \end{array}$$

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

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

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

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

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

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,

$$\dot{m} = \frac{1}{\boldsymbol{v}_1} A_1 V_1 \longrightarrow A_1 = \frac{\dot{m}\boldsymbol{v}_1}{V_1} = \frac{(18 \text{ kg/s})(0.047420 \text{ m}^3\text{/kg})}{90 \text{ m/s}} = \mathbf{0.00948 \text{ m}^2}$$

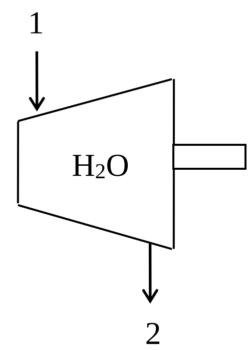
Question 13.

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

Properties From the steam tables

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

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



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.

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.

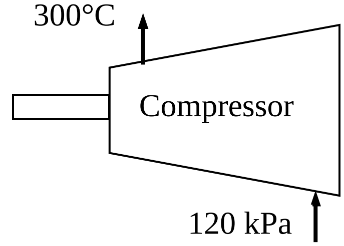
The energy balance for this steady-flow system can be expressed in the rate form as

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

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

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

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



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

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

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

Question 15.

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

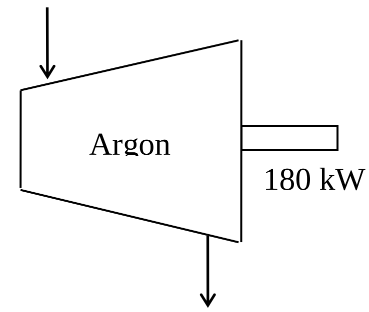
There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. The inlet specific volume of argon and its mass flow rate are

$$\boldsymbol{v}_1 = \frac{RT_1}{P_1} = \frac{(0.2081\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(723\text{ K})}{1500\text{ kPa}} = 0.1003\text{ m}^3/\text{kg}$$

Thus,

$$\dot{m} = \frac{1}{\boldsymbol{v}_1}A_1V_1 = \frac{1}{0.1003\text{ m}^3/\text{kg}}(0.0055\text{ m}^2)(50\text{ m/s}) = 2.742\text{ kg/s}$$

A_1 = 55 cm^2
P_1 = 1500 kPa
T_1 = 450°C
V_1 = 50 m/s



P_2 = 140 kPa
V_2 = 140 m/s

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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

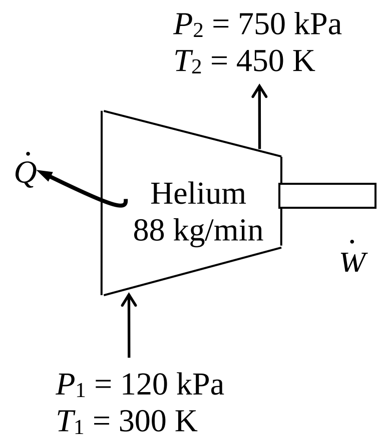
T_2 = **580.4K**

Question 16.

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



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

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

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

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

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**

Question 17.

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

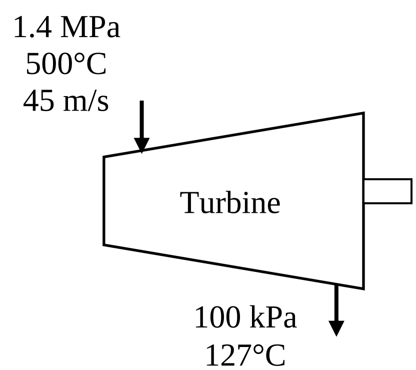
There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the turbine as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as

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

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

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

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



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

$$\boldsymbol{v}_1 = \frac{RT_1}{P_1} = \frac{(0.287\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(500+273\ \text{K})}{1400\ \text{kPa}} = 0.1585\ \text{m}^3/\text{kg}$$

$$\dot{m} = \frac{A_1V_1}{\boldsymbol{v}_1} = \frac{(0.18\ \text{m}^2)(45\ \text{m/s})}{0.1585\ \text{m}^3/\text{kg}} = \mathbf{51.1\ kg/s}$$

Similarly at the outlet,

$$\boldsymbol{v}_2 = \frac{RT_2}{P_2} = \frac{(0.287\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(127+273\ \text{K})}{100\ \text{kPa}} = 1.148\ \text{m}^3/\text{kg}$$

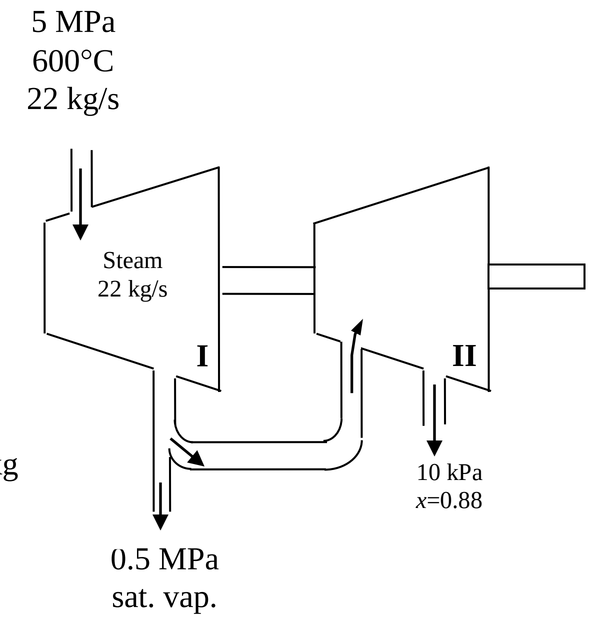
$$V_2 = \frac{\dot{m}\boldsymbol{v}_2}{A_2} = \frac{(51.1\ \text{kg/s})(1.148\ \text{m}^3/\text{kg})}{1\ \text{m}^2} = 58.66\ \text{m/s}$$

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

$$\begin{aligned}\dot{W}_s &= \dot{m}\left(c_p(T_1 - T_2) + \frac{V_1^2 - V_2^2}{2}\right)\\ &= (51.1\ \text{kg/s})\left[(1.048\ \text{kJ/kg}\cdot\text{K})(773-400)\text{K} + \frac{(45\ \text{m/s})^2 - (58.66\ \text{m/s})^2}{2}\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right)\right]\\ &= \mathbf{19{,}939\ kW}\end{aligned}$$

Question 18.

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

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

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

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

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

Substituting, the power output of the turbine is

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

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

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

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

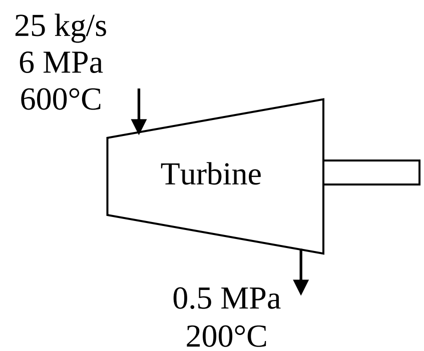
We take the turbine as the system, which is a control volume since mass crosses the boundary. Noting that one fluid stream enters and leaves the compressor, the energy balance for this steady-flow system can be expressed in the rate form as

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

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

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

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



Substituting,

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

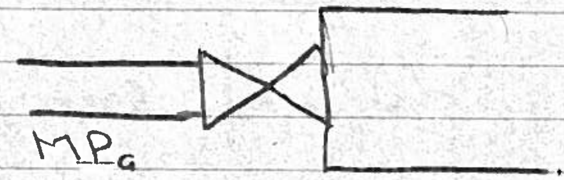
$$= (+19{,}000\ \text{kW}) + (25\ \text{kg/s})\left[(2855.8 - 3658.8)\text{kJ/kg} + \frac{(175 - 0\ \text{m/s})^2}{2}\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right)\right]$$

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

Negative for heat loss.

Problem 5.20

(1)



(2)

$P_1 = 1.2\ MPa$

$T_1 = 20^\circ C$

$V_1 = V_2$

$T_2 = ?$

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

- conservation of mass:

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

- 1^{st} law of Thermo

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

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

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

for an ideal gas this leads to $T_1 = T_2 = 20^\circ C$

Determination of A_2/A_1

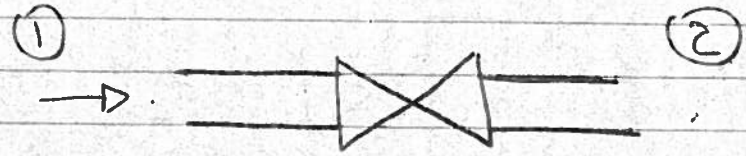
$$\dot{m}_1 = \dot{m}_2 \Leftrightarrow \frac{\cancel{V_1} A_1}{v_1} = \frac{\cancel{V_2} A_2}{v_2}$$

$$\Rightarrow \frac{A_1}{R\cancel{T_1}/P_1} = \frac{A_2}{R\cancel{T_2}/P_2} \Rightarrow A_1 P_1 = A_2 P_2$$

A2/A1=12

Problem 5.21

A2/A1=12



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

$T_1 = 250\,°C$

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

- conservation of mass

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

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

We have to assume $A_1 = A_2$.

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

- 1st law of Thermo

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

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

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

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

✓ ✓ ? ?

we have 1 eq but 2 unknowns.

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

$$h_2 = h_1 = 2919.9 \ kJ/kg$$

we also have:

$$\vartheta_1 = \vartheta\Big|_{\substack{1.6 MPa \\ 250°C}} = 0.1419 \ kg/m^3$$

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

we have to get ϑ_2? by interpolation

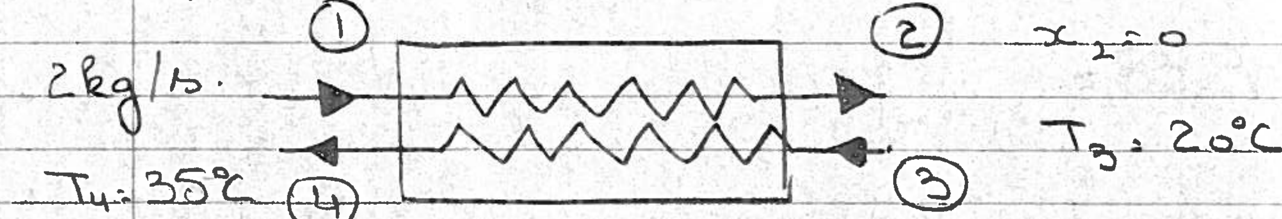
$$\vartheta_2 = 0.7588 \ kg/m^3$$

Then $\quad V_2 = \vartheta_2 \dfrac{V_1}{\vartheta_1} = 0.7588 \dfrac{4.5}{0.1419}$

$$V_2 = 24.06 \ m/s.$$

Problem 5.22

$P_1: 50\,kPa$, $T_1: 300°C$



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

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

0

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

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

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

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

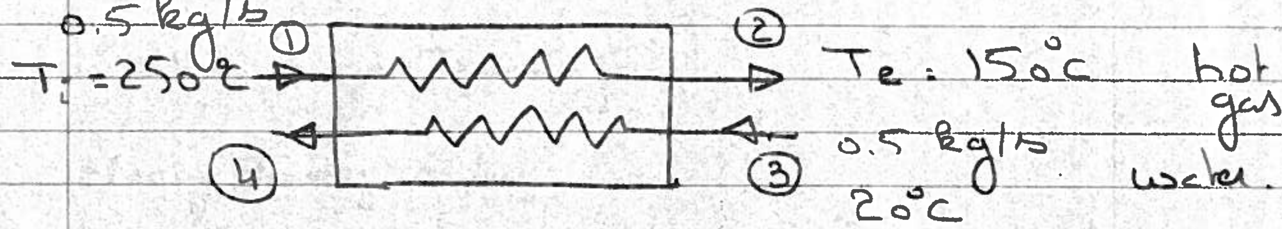
$$h_2 = h\Big|_{\substack{P_2 = 50\ kPa \\ x_2 = 0}} = 340.54\ kJ/kg$$

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

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

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

Problem 5.23



$Cp_{HG} = 1.08$ 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

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

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

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

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

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

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

Then $T_4 = 45.0°C$

SECOND LAW OF THERMODYNAMICS

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

6.2 (Tutorial) Your refrigerator extracts 2.5 kJ of energy form the food in the cabinet. If its compressor requires 1.5 kJ as input, determine the coefficient of performance of the refrigerator and the amount of heat rejected into the room.

6.3 In order to heat up your room during winter you need a 2000 W heater, determine the COP of the heater if you want the energy consumption not to exceed 500 W.

6.4 Could you cool down an apartment by opening the door of the refrigerator? Explain why. To make this theoretically feasible, what modification you have to introduce?

6.5 (Tutorial) A simple Rankine cycle requires 2 MW of heat in the boiler and rejects 1 MW into a nearby river. Assuming the work of the pump is negligible, determine the thermal efficiency of the cycle and the power produced by the turbine.

6.6 1) Sketch a cycle that violates the Kelvin-Planck statement of the second law of thermodynamics. 2) Sketch a cycle that violates the Clausius statement of the second law of thermodynamics. 3) Show that a cycle that violates Kevin-Planck statement will also violate Clausius statement of the second law of thermodynamics.

6.7 You have access to two heat reservoirs of 200°C and 23°C. What will be the maximal efficiency of any heat engine designed to work between the two reservoirs?

6.8 (Tutorial) 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?

6.9 What is the maximal performance of a heat pump operating between reservoirs of 5°C and 23°C?

6.10 Estimate the maximal performance of your home refrigerator?

6.11 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?

6.12 A household refrigerator uses refrigerant-134a as the working fluid. The refrigerant enters the evaporator coils at 100 kPa with a vapor quality of 0.20 and leaves at the same pressure and -26°C. If the compressor consumes 550W of power and the COP of the refrigerator is 1.25, what is the mass flow rate of the refrigerant and the rate of heat rejection to the kitchen air.

6.13 A heat engine receives heat from a thermal reservoir at 1200 °C and has a maximum thermal efficiency of 38%. The heat engine does maximum work equal to 600 kJ. What is the heat supplied to the heat engine from the reservoir? What is the heat rejection and the temperature of the lower temperature reservoir?

6.14 An inventor claims to have developed a heat pump that provides a 180 kW heating effect for a 293 K household while only consuming 70 kW of power and using a heat source at 273 K. Can this claim be possible?

6.15 (Tutorial) A heat pump is used to heat a house and keep it at 20°C. On a day when the average outdoor temperature remains at about 2°C, the house is estimated to lose heat at a rate of 120,000 kJ/hr. A power input of 5 kW is needed to run the heat pump. Is this HP powerful enough to do the job?

Chapter 6

Second law of thermodynamics

6.1

$1\ hp = 0.7457\ kW$

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

$\eta_{th} = \frac{W}{Q} = \frac{22.37}{35} = 0.64$ should 0.39

should be (35 +22.37)

$\eta_{th} = 64\%$ should be 39%

6.2

- Coef of performance:

$$CoP = \frac{Q_L}{W_{in}} = \frac{2.5}{1.5} = 1.67$$

- Heat rejected

1^{st} law of thermodynamics.

$$Q_H = Q_L + W = 2.5 + 1.5 = 4 \text{ kJ}$$

your refrigerator rejects 4 kJ of heat into your room in order to extract 2.5 kJ of heat from your food.

6.3 Heating a room

$\dot{Q}_H = 2000\ W$

W_{in} (electric work) $= 500\ W$

$$CoP = \frac{2000}{500} = 4$$

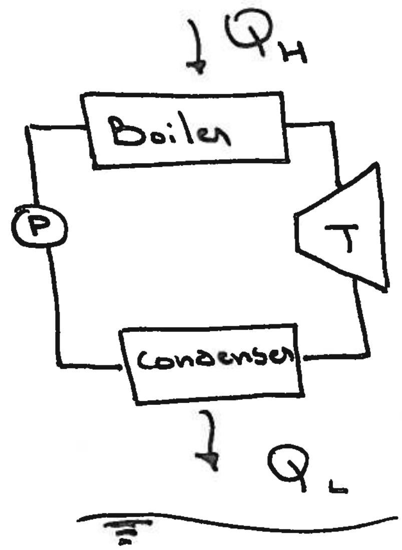
6.4

No, you can not cool down an apartment by opening the door of the refrigerator because the heat rejected Q_H is always higher than the heat extracted (for cooling) Q_L.

To make this feasible, you have to reject the heat Q_H outside the apartment.

or use a cooling fluid.

6.5



- $\dot{Q}_H = 2\,MW$

  $\dot{Q}_L = 1\,MW$

- Thermal efficiency

$$\eta_{th} = \frac{\dot{W}_{out} - \cancel{\dot{W}_{in}}}{\dot{Q}_H}$$

$$= \frac{\dot{W}_{out}}{\dot{Q}_H} = \frac{\dot{Q}_H - \dot{Q}_L}{\dot{Q}_H} = 1 - \frac{\dot{Q}_L}{\dot{Q}_H}$$

$$\eta_{th} = 1 - \frac{1}{2} = 0.5$$

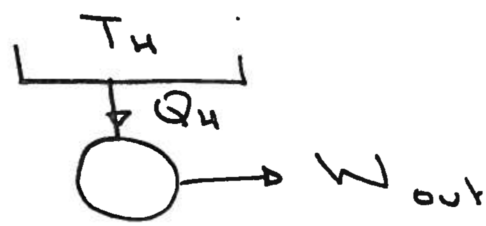
$$\eta_{th} = 50\%$$

- Power produced:

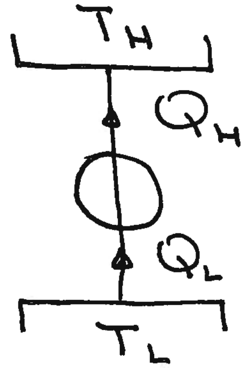
$$\dot{W}_{out} = \dot{Q}_H - \dot{Q}_L = 2 - 1 = 1\,MW$$

6.6

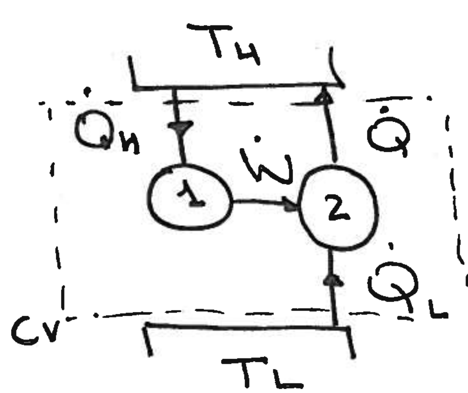
- cycle that violates Kelvin-Planck statement



- cycle that violates Clausius statement



- Equivalence between Kelvin-Planck statement and Clausius statement.



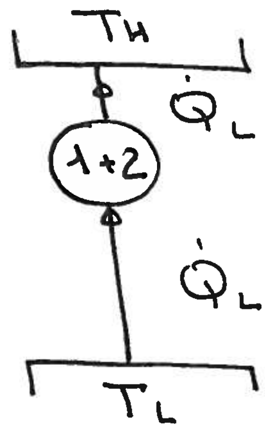
Let us consider a cycle that violates Kelvin-Planck (cycle 1)

if we consider both cycles

$\dot{Q} = \dot{W} + \dot{Q}_L$ for cycle 2

but from cycle 1 $\dot{Q}_H = \dot{W}$

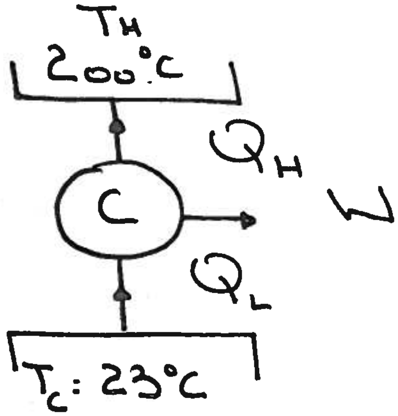
Then, the complete CV can be represented ans



The cycle transfers heat from T_L to T_H with no heat in. This violates Clausius statement.

6.7

The maximal efficiency is the efficiency of a Carnot cycle working between the two reservoirs

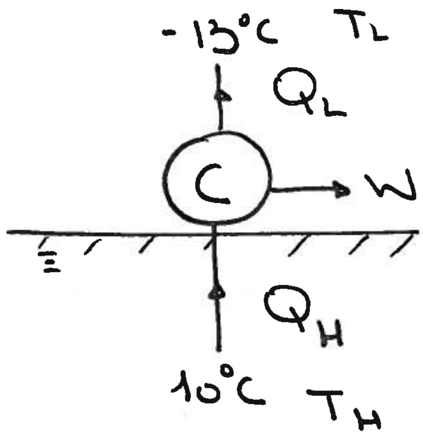


$$\eta_c = 1 - \frac{T_L}{T_H} = 1 - \frac{23 + 273.15}{200 + 273.15}$$

$$\eta_c = 37.4\%$$

Any heat engine working between 23°C and 200°C will never exceed 37.4% efficiency.

6.8



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%.

6.9

We have to compute the CoP of a Carnot heat pump operating between 5°C and 23°C

$$CoP\Big|_{Carnot} = \frac{T_H}{T_H - T_L} = \frac{273.15 + 23}{(273.15 + 23) - (273.15 + 5)}$$

$$CoP\Big|_{Carnot} = 16.45$$

6.10

You have to determine your room T° and also the T° inside the refrigerator. Then, you can compute $CoP\Big|_{Carnot}$ for a Carnot refrigerator

6.11

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 $400\text{ K} = T_L$

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

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

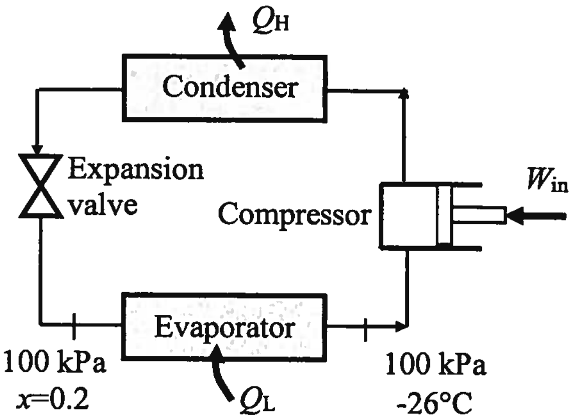
So, $\eta_{inventor} > \eta_{carnot}$ impossible (so far ....)

6.12

The properties of R-134a at the evaporator inlet and exit states from Tables:

$$\left.\begin{array}{l} P_1 = 100\text{ kPa} \\ x_1 = 0.2 \end{array}\right\} h_1 = 60.71\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_2 = 100\text{ kPa} \\ T_2 = -26°\text{C} \end{array}\right\} h_2 = 234.74\text{ kJ/kg}$$



(*a*) The refrigeration load is:

$$\dot{Q}_L = (\text{COP})\dot{W}_{\text{in}} = (1.25)(0.550\text{ kW}) = 0.6875\text{ kW}$$

The mass flow rate of the refrigerant is determined from:

$$\dot{m}_R = \frac{\dot{Q}_L}{h_2 - h_1} = \frac{0.6875\text{ kW}}{(234.74 - 60.71)\text{ kJ/kg}} = \mathbf{0.00395\ kg/s}$$

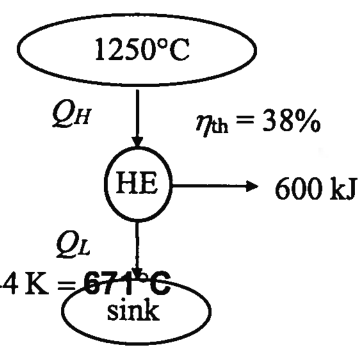
(*b*) The rate of heat rejected from the refrigerator is:

$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{\text{in}} = 0.6875 + 0.55 = \mathbf{1.2375\ kW}$$

6.13

Applying the definition of the thermal efficiency and an energy balance to the heat engine:

:



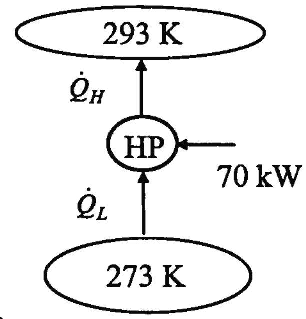
$$Q_H = \frac{W_{\text{net}}}{\eta_{\text{th}}} = \frac{600\text{ kJ}}{0.38} = \mathbf{1579\ kJ}$$

$$Q_L = Q_H - W_{\text{net}} = 1579 - 600 = \mathbf{979\ kJ}$$

$$\eta_{\text{th,max}} = 1 - \frac{T_L}{T_H} \longrightarrow 0.38 = 1 - \frac{T_L}{(1250 + 273)\text{ K}} \longrightarrow T_L = 944\text{ K} = \mathbf{671°C}$$

6.14

Apply the definition of the heat pump coefficient of performance:



$$\mathrm{COP}_{\mathrm{HP}} = \frac{\dot{Q}_H}{\dot{W}_{\mathrm{net,in}}} = \frac{180\,\mathrm{kW}}{70\,\mathrm{kW}} = 2.571$$

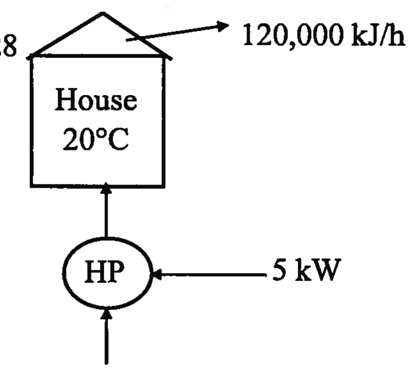
The maximum COP of a heat pump is:

$$\mathrm{COP}_{\mathrm{HP,max}} = \frac{1}{1 - T_L / T_H} = \frac{1}{1-(273\,\mathrm{K})/(293\,\mathrm{K})} = 14.7$$

Since the actual COP is less than the maximum COP, the claim is **valid.**

6.15

The power input to a heat pump will be a minimum when the heat pump operates in a reversible manner. The COP of a reversible heat pump is:



$$\mathrm{COP}_{\mathrm{HP,rev}} = \frac{1}{1-(T_L / T_H)} = \frac{1}{1-(2+273\,\mathrm{K})/(20+273\,\mathrm{K})} = 16.28$$

The required power input to this reversible heat pump is determined from the definition of the COP:

$$\dot{W}_{\mathrm{net,in,min}} = \frac{\dot{Q}_H}{\mathrm{COP}_{\mathrm{HP}}} = \frac{120{,}000\,\mathrm{kJ/h}}{16.28}\left(\frac{1\,\mathrm{h}}{3600\,\mathrm{s}}\right) = \mathbf{2.05\ kW}$$

This heat pump is **powerful enough** since 5 kW > 2.05 kW.

Rankine cycle

7.1 This problem analyzes a simple ideal Rankine cycle with R-134a as the working fluid. The boiler operates at 1.6 MPa, the condenser at 0.4 MPa, and the turbine inlet at 80 °C. The flow leaving the turbine has a temperature of 28°C. The pump requires a specific work of 0.95 kJ/kg. Determine the mass flow rate of R-134a required for a 750 kW power production and the resulting thermal efficiency of the cycle. Assume no loss or heat transfer between each open-system components.

7.2 (Tutorial) Steam is the working fluid in an ideal Rankine cycle. Saturated vapor enters the turbine at 8.0 MPa and the flow leaves the turbine as a saturated two-phase mixture with a vapor quality of 67.45%. Saturated liquid exits the condenser at a pressure of 0.0075 MPa. The net power output of the cycle is 100 MW. The pump consumes a specific work of 8.06 kJ/kg. Calculate for the thermal efficiency of the cycle, the mass flow rate of the steam, in kg/h and the rate of heat transfer in the boiler and that from the condensing steam through the condenser, both in MW. Calculate also the mass flow rate of the condenser cooling water, in kg/h, if cooling water enters the condenser at 15 °C and exits at 35 °C.

Brayton cycle

7.3 (Tutorial) An aircraft engine is operating on a ideal Brayton cycle with a pressure ratio of 15. Heat is added to the cycle at a rate of 500 kW; the mass flow rate in the engine is 1kg/s and the air entering the compressor is at 70 kPa and 0°C. Determine the power output by this engine and its thermal efficiency. Assume constant specific heats at room temperature.

7.4 A gas turbine power plant is operating on the simple Brayton cycle with air that has a pressure ratio of 12. The compressor and turbine inlet temperatures are 300K and 1000K, respectively. Determine the required mass flow rate of air for a net power ouput of 65 MW. Assume both isentropic compressor and turbine (i.e., polytropic with $n = k$) and constant specific heats at room temperature.

Otto cycle

7.5 (Tutorial) An engine with a compression ratio of 9.0 is running on an air-standard Otto cycle. Prior to the compression process (modeled by a polytropic process with $n = k = 1.4$), the air is at 100 kPa, 32°C and 600 cm^3. The temperature at the end of the polytropic, expansion process is 800 K. Determine the highest temperature and pressure in the cycle; b) the amount of heat transferred in kJ and c) the thermal efficiency. Assume constant specific heat values at room temperature.

7.6 A1.6-L SI engine is operating on a 4-strokes Otto cycle with a compression ratio of 11. The air is at 100 kPa and 37°C at the beginning of the compression process, and the maximum pressure in the cycle is 8 MPa. The compression and expansion process may be modeled as isentropic (i.e., polytropic process with $n = k = 1.4$. Determine a) the temperature at the end of the expansion process, b) the net work output and the thermal efficiency. Assume constant specific heats at 850 K temperature.

Question #1

Steady operating conditions exist. Kinetic and potential energy changes are negligible.
From the refrigerant tables,

$$h_1 = h_{f@\,0.4\text{ MPa}} = 63.94\text{ kJ/kg}$$
$$v_1 = v_{f@\,0.4\text{ MPa}} = 0.0007907\text{ m}^3\text{/kg}$$

$$h_2 = h_1 - w_p = 63.94 - (-0.95) = 64.89\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 1.6\text{ MPa} \\ T_3 = 80°\text{C} \end{array}\right\} h_3 = 305.07\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_4 = 0.4\text{ MPa} \\ T_4 = 28°\text{C} \end{array}\right\} h_4 = 273.21\text{ kJ/kg}\ \text{ superheated (interpolation)}$$

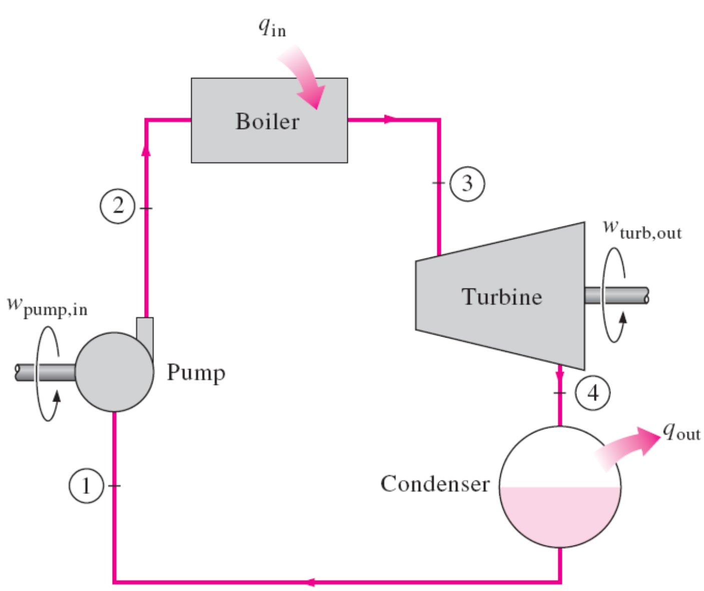
Thus,

$$q_{\text{boiler}} = h_3 - h_2 = 305.07 - 64.89 = 240.18\text{ kJ/kg}$$
$$q_{\text{condenser}} = h_1 - h_4 = 63.94 - 273.21 = -209.27\text{ kJ/kg}$$
$$w_{\text{turbine}} = h_3 - h_4 = 305.07 - 273.21 = 31.86\text{kJ/kg}$$
$$w_{\text{net}} = w_{turbine} + w_{pump} = 31.86 + (-0.95) = 30.91\text{ kJ/kg}$$

The mass flow rate of the refrigerant and the thermal efficiency of the cycle are then

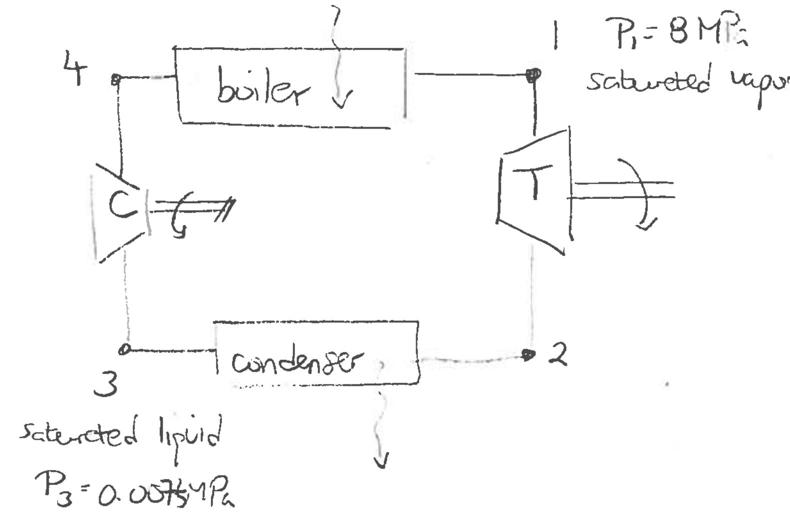
$$\dot{m} = \frac{\dot{W}_{\text{net}}}{w_{\text{net}}} = \frac{750\text{ kJ/s}}{30.91\text{ kJ/kg}} = \mathbf{24.26\ kg/s}$$

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{209.27}{240.18} = \mathbf{0.129}$$



Question 1

$\sum \dot{W}_{net} = 100\,MW$



State 1

$h_1 = 2758.0\ kJ/kg$

State 2

$x = 0.6745$

$P_2 = P_3 = 0.0075\,MPa$

@ 7.5 kPa

$h_2 = h_f + x\, h_{fg}$

$= 168.79 + 0.6745\,(2406)$

$= 1791.64\ kJ/kg$

State 3

$h_3 = h_{f\,@7.5\,kPa} = 168.79\ kJ/kg$

State 4

$0 = -w_p + (h_3 - h_4)$

$h_4 = h_3 - w_p = 168.79 - (-8.06) = 176.85\ kJ/kg$

$\sum w_{net} = w_{turbine} + w_{pump}$

$(h_1 - h_2) + (-8.06) = 958.3\ kJ/kg$

$w_{net} = \frac{\dot{W}_{net}}{\dot{m}} \Rightarrow \dot{m} = 104.35\ kg/s = 3.757 \times 10^5\ kg/hr$

$$\dot{Q}_{boiler} = \dot{m}(h_1 - h_4) = 104.35 \times (2758 - 176.85)$$

$$= \underline{\underline{269.34\ MW}}$$

$$\dot{Q}_{condenser} = \dot{m}(h_3 - h_2) = 104.35 \times (168.79 - 1791.64)$$

$$= -\underline{\underline{169.34}}\ MW$$

$$\eta = \frac{\Sigma \dot{W}_{net}}{\dot{Q}_{in}} = \frac{100\ MW}{269.34\ MW} = 0.371 \quad (37.1\%)$$

heat exchanger for the cooling process:

$$\frac{\dot{m}_{cw}}{\dot{m}_{cycle}} = \frac{(h_2 - h_3)}{(h_{cw,out} - h_{cw,in})}$$

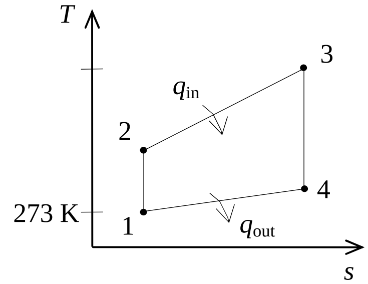
$$h_{cw,in} \simeq h_{f@15°C} = 62.99\ kJ/kg$$

$$h_{cw,out} \simeq h_{f@35°C} = 146.68\ kJ/kg$$

$$\therefore \dot{m}_{cw} = 2023.5\ kg/s = \underline{\underline{7.285 \times 10^6}}\ kg/hr$$

Question #3

Steady operating conditions exist. The air-standard assumptions are applicable. Kinetic and potential energy changes are negligible. Air is an ideal gas with constant specific heats. The properties of air at room temperature are c_p = 1.005 kJ/kg·K and k = 1.4



For the isentropic compression process,

$$T_2 = T_1 r_p^{(k-1)/k} = (273\,\text{K})(15)^{0.4/1.4} = 591.8\,\text{K}$$

The heat addition is

$$q_{\text{in}} = \frac{\dot{Q}_{\text{in}}}{\dot{m}} = \frac{500\,\text{kW}}{1\,\text{kg/s}} = 500\,\text{kJ/kg}$$

Applying the first law to the heat addition process,

$$q_{\text{in}} = c_p(T_3 - T_2)$$

$$T_3 = T_2 + \frac{q_{\text{in}}}{c_p} = 591.8\,\text{K} + \frac{500\,\text{kJ/kg}}{1.005\,\text{kJ/kg}\cdot\text{K}} = 1089\,\text{K}$$

The temperature at the exit of the turbine is

$$T_4 = T_3\left(\frac{1}{r_p}\right)^{(k-1)/k} = (1089\,\text{K})\left(\frac{1}{15}\right)^{0.4/1.4} = 502.3\,\text{K}$$

Applying the first law to the adiabatic turbine and the compressor produce

$$w_{\text{T}} = c_p(T_3 - T_4) = (1.005\,\text{kJ/kg}\cdot\text{K})(1089 - 502.3)\text{K} = 589.6\,\text{kJ/kg}$$

$$w_{\text{C}} = c_p(T_2 - T_1) = (1.005\,\text{kJ/kg}\cdot\text{K})(591.8 - 273)\text{K} = 320.4\,\text{kJ/kg}$$

The net power produced by the engine is then

$$\dot{W}_{\text{net}} = \dot{m}(w_{\text{T}} - w_{\text{C}}) = (1\,\text{kg/s})(589.6 - 320.4)\text{kJ/kg} = \mathbf{269.2\ kW}$$

Finally the thermal efficiency is

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{in}}} = \frac{269.2\,\text{kW}}{500\,\text{kW}} = \mathbf{0.538}$$

Question #4

Steady operating conditions exist. The air-standard assumptions are applicable. Kinetic and potential energy changes are negligible. Air is an ideal gas with constant specific heats. The properties of air at room temperature are c_p = 1.005 kJ/kg·K and k = 1.4.

Using the isentropic relations,

$$T_{2s} = T_1\left(\frac{P_2}{P_1}\right)^{(k-1)/k} = (300\text{ K})(12)^{0.4/1.4} = 610.2\text{ K}$$

$$T_{4s} = T_3\left(\frac{P_4}{P_3}\right)^{(k-1)/k} = (1000\text{ K})\left(\frac{1}{12}\right)^{0.4/1.4} = 491.7\text{ K}$$

$$w_{\text{s,C,in}} = h_{2s} - h_1 = c_p\left(T_{2s} - T_1\right) = (1.005\text{ kJ/kg}\cdot\text{K})(610.2 - 300)\text{K} = 311.75\text{ kJ/kg}$$

$$w_{\text{s,T,out}} = h_3 - h_{4s} = c_p\left(T_3 - T_{4s}\right) = (1.005\text{ kJ/kg}\cdot\text{K})(1000 - 491.7)\text{K} = 510.84\text{ kJ/kg}$$

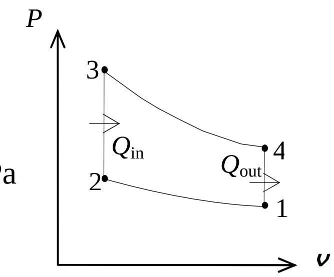
$$w_{\text{s,net,out}} = w_{\text{s,T,out}} - w_{\text{s,C,in}} = 510.84 - 311.75 = 199.1\text{ kJ/kg}$$

$$\dot{m}_s = \frac{\dot{W}_{\text{net,out}}}{w_{\text{s,net,out}}} = \frac{65{,}000\text{ kJ/s}}{199.1\text{ kJ/kg}} = \mathbf{326.5\ \ kg/s}$$

Question #5

The properties of air at room temperature are c_p = 1.005 kJ/kg·K, c_v = 0.718 kJ/kg·K, R_s = 0.287 kJ/kg·K, and k = 1.4.

Process 1-2: isentropic compression.



$$T_2 = T_1\left(\frac{v_1}{v_2}\right)^{k-1} = (305\text{ K})(9.0)^{0.4} = 734.5\text{ K}$$

$$\frac{P_2 v_2}{T_2} = \frac{P_1 v_1}{T_1} \longrightarrow P_2 = \frac{v_1}{v_2}\frac{T_2}{T_1}P_1 = (9.0)\left(\frac{734.5\text{ K}}{305\text{ K}}\right)(100\text{ kPa}) = 2167\text{ kPa}$$

Process 3-4: isentropic expansion.

$$T_3 = T_4\left(\frac{v_4}{v_3}\right)^{k-1} = (800\text{ K})(9.0)^{0.4} = \mathbf{1926.5\text{ K}}$$

Process 2-3: v = constant heat addition.

$$\frac{P_3 v_3}{T_3} = \frac{P_2 v_2}{T_2} \longrightarrow P_3 = \frac{T_3}{T_2}P_2 = \left(\frac{1926.5\text{ K}}{734.5\text{ K}}\right)(2167\text{ kPa}) = \mathbf{5683.8\text{ kPa}}$$

$$m = \frac{P_1 V_1}{RT_1} = \frac{(100\text{ kPa})(0.0006\text{ m}^3)}{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(305\text{ K})} = 6.8544\times10^{-4}\text{ kg}$$

$$Q_{2\text{-}3} = m(u_3 - u_2) = mc_v(T_3 - T_2) = (6.8544\times10^{-4}\text{ kg})(0.718\text{ kJ/kg}\cdot\text{K})(1926.5 - 734.5)\text{K} = \mathbf{0.587\text{ kJ}}$$

$$W_{1-2} = m(u_1 - u_2) = mc_v(T_1 - T_2) = (6.8544\times10^{-4}\text{ kg})(0.718\text{ kJ/kg}\cdot\text{K})(305 - 734.5)\text{K} = -0.2114\text{ kJ}$$

$$W_{3-4} = m(u_3 - u_4) = mc_v(T_3 - T_4) = (6.8544\times10^{-4}\text{ kg})(0.718\text{ kJ/kg}\cdot\text{K})(1926.5 - 800)\text{K} = 0.5544\text{ kJ}$$

$$Q_{4-1} = m(u_1 - u_4) = mc_v(T_1 - T_4) = (6.8544\times10^{-4}\text{ kg})(0.718\text{ kJ/kg}\cdot\text{K})(305 - 800)\text{K} = -0.2436\text{ kJ}$$

Then:

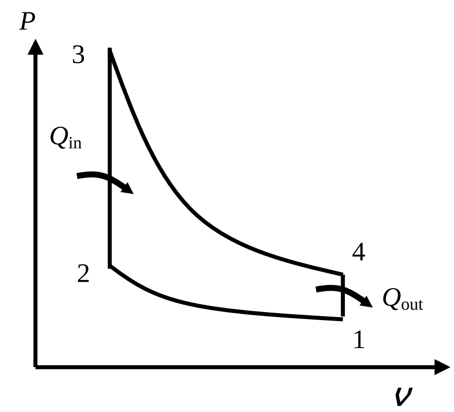
$$W_{\text{net}} = W_{1\text{-}2} + W_{3-4} = (-0.2114) + (0.5544) = 0.343kJ$$

$$\eta_{\text{th}} = \frac{W_{\text{net,out}}}{Q_{\text{in}}} = \frac{0.343\text{ kJ}}{0.587\text{ kJ}} = \mathbf{58.4\%}$$

Question #6

Properties The properties of air at 850 K are c_p = 1.110 kJ/kg·K, c_v = 0.823 kJ/kg·K, R_s = 0.287 kJ/kg·K, and k = 1.349

(*a*) Process 1-2: polytropic compression



$$T_2 = T_1\left(\frac{v_1}{v_2}\right)^{n-1} = (310\text{ K})(11)^{1.349-1} = 715.8\text{ K}$$

$$P_2 = P_1\left(\frac{v_1}{v_2}\right)^{n} = (100\text{ kPa})(11)^{1.349} = 2540\text{ kPa}$$

$$w_{1-2} = (u_1 - u_2) = c_v(T_1 - T_2) = -333.97\text{ kJ/kg}$$

Process 2-3: constant volume heat addition

$$T_3 = T_2\left(\frac{P_3}{P_2}\right) = (715.8\text{K})\left(\frac{8000\text{ kPa}}{2540\text{ kPa}}\right) = 2254.5\text{ K}$$

$$q_{2\text{-}3} = u_3 - u_2 = c_v(T_3 - T_2)$$
$$= (0.823\text{ kJ/kg}\cdot\text{K})(2254.5 - 715.8)\text{K} = 1266.4\text{kJ/kg}$$

Process 3-4: polytropic expansion.

$$T_4 = T_3\left(\frac{v_3}{v_4}\right)^{n-1} = (2254.5\text{ K})\left(\frac{1}{11}\right)^{1.349-1} = 976.3\text{ K}$$

$$P_4 = P_3\left(\frac{v_2}{v_1}\right)^{n} = (8000\text{ kPa})\left(\frac{1}{11}\right)^{1.349} = 315\text{ kPa}$$

$$w_{3-4} = (u_3 - u_4) = c_v(T_3 - T_4) = (0.823\text{ kJ/kg}\cdot\text{K})(2254.5 - 976.3)\text{K} = 1051.96\text{ kJ/kg}$$

Process 4-1: constant volume heat rejection.

(*b*) The net work output and the thermal efficiency are

$$w_{\text{net}} = w_{12} + w_{34} = (-333.97) + (1051.96) = 717.99\text{ kJ/kg}$$

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{2\text{-}3}} = \frac{717.99\text{ kJ/kg}}{1266.4\text{ kJ/kg}} = 0.5669 = 56.7\% = 1\text{-}\left(\frac{1}{r}\right)^{k-1} = 1 - \left(\frac{1}{11}\right)^{1.349-1}$$

ENTROPY AND ISENTROPIC EFFICIENCY

8.1 Air is compressed steadily by a compressor which consumes 25 kW of power. The air temperature is maintained constant at 25°C during this compression process as a result of heat transfer to the surrounding at 17°C. Determine the rate of entropy change of the system (i.e., air).

8.2 A rigid tank is divided into two equal parts by a partition. One part is filled with 3 kg of compressed liquid water at 400 kPa and 60°C while the other side is evacuated. The partition is removed and water expands into the entire tank until the tank reaches a pressure of 40 kPa. What is the entropy change of the water during this process?

8.3 Steam is expanded in an isentropic turbine (i.e., during the expansion inside the turbine the entropy remains constant). It enters the turbine at 6 MPa and 400°C, and leaves the turbine at 100 kPa. What is the change in the specific enthalpy of the water between the turbine inlet and outlet?

8.4 A cylinder contains 0.5kg of N_2 gas initially at 37 °C and 140 kPa. The gas is compressed polytropically with n = 1.3 until the volume is reduced by half. Determine the entropy change of nitrogen during this process.

8.5 Steam is expanded in an isentropic turbine. At the inlet, the steam is at 2MPa and 360 °C. The flow leaves the turbine at 100 kPa. What is the work produced by this turbine?

8.6 2 kg of saturated water vapor initially at 600 kPa is expanded adiabatically in a piston-cylinder device until it reaches a pressure of 100kPa. It is said to produce 700 kJ of work from this process. What is the entropy change during this process? Is it realistic?

8.7 Air initially at 800 kPa and 100 °C with a velocity of 25 m/s is expanded in an adiabatic nozzle by a polytropic process with n = 1.3. It exits the nozzle with a pressure of 180 kPa. Determine the temperature and velocity at the nozzle exit.

8.8 5-kg of Air initially at 600 kPa and 410°C is expanded adiabatically in a piston-cylinder device until the pressure is 100 kPa. Assuming it produces 550 kJ of displacement work, what is the entropy change during this process and if this process is realistic. Assume constant air properties evaluated at 300 K.

8.9 Steam initially at 7 MPa, 600°C, and 75 m/s enters an adiabatic turbine and leaves it at 50 kPa, 150°C and 130 m/s. If the power output of the turbine is 5 MW, what are the mass flow rate of the steam and the isentropic efficiency of the turbine?

8.10 Air is expanded by an adiabatic turbine from 1.8MPa and 320 °C to 100 kPa. Determine the isentropic efficiency if the air leaves the turbine at 0 °C.

8.11 Air is compressed by an adiabatic compressor from 27 °C and 95 kPa to 277 °C and 600 kPa. Determine the isentropic efficiency of the compressor and the exit temperature of air for the isentropic case. Assume constant air properties evaluated at room temperature.

8.12 Refrigerant-134a initially as saturated vapor at 100 kPa enters an adiabatic compressor with an isentropic efficiency of 0.80 at a volume flow rate of 0.7 m^3/min, and leaves the compressor at 1MPa. Determine the compressor exit temperature and power input to the compressor.

8.13 Consider a simple Brayton cycle using air as the working fluid. The pressure ratio of this cycle is 12. The maximum cycle temperature is 600°C. The compressor inlet is at 90 kPa and 15°C. Which will have the greatest impact on the back-work ratio W_C/W_T: a compressor isentropic efficiency of 90% or a turbine isentropic efficiency of 90%. Assume constant specific heats of air at room temperature.

8.14 A simple Rankine cycle with water as the working fluid operates between 6MPa and 50kPa.The turbine's inlet temperature is 450°C. The isentropic efficiency of the turbine is 94%. Pressure and pump losses are negligible. The water leaving the condenser is subcooled by 6.3°C. The mass flow rate is given to be 20 kg/s and the specific pump work is 6.1 kJ/kg. Determine the rate of heat addition in the boiler, the power input to the pumps, the net power, and the thermal efficiency of the cycle.

8.15 A simple ideal Rankine cycle with water as the working fluid is considered. The working fluid operates its condenser at 40°C and its boiler at 300°C. The pump requires a specific work input of 8.65 kJ/kg. Determine the work output from the turbine, the heat addition in the boiler, and the thermal efficiency of the cycle.

8.16 A gas turbine power plant that operates on the simple Brayton cycle with air as the working fluid has a pressure ratio of 12. The inlet temperature of the compressor and turbine are 300K and 1000 K, respectively. Determine the required mass flow rate of air for a net power output of 70 MW, assuming both the compressor and the turbine have an isentropic efficiency of a) 100% and b) 85%. Assume constant air properties evaluated at room temperature.

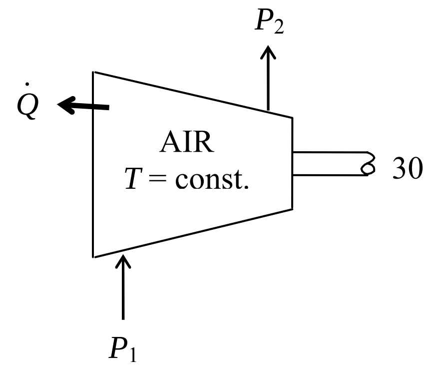
Question 8.1

Noting that $h = h(T)$ for ideal gases, hence, $h_1 = h_2$ since $T_1 = T_2 = 25°C$. From the steady energy equation:

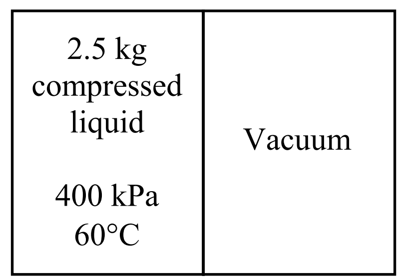
$$\dot{Q} = \dot{W} = -25\ \text{kW}$$

The rate of entropy change of air is:

$$\Delta\dot{S}_{\text{air}} = \frac{\dot{Q}_{\text{air}}}{T_{\text{sys}}} = \frac{-25\ \text{kW}}{298\ \text{K}} = \mathbf{-0.08389\ kW/K}$$



Question 8.2



The properties of the water are

$$\left.\begin{array}{l} P_1 = 400\ \text{kPa} \\ T_1 = 60°\text{C} \end{array}\right\} \begin{array}{l} \boldsymbol{v}_1 \cong \boldsymbol{v}_{f@60°\text{C}} = 0.001017 \text{m}^3/\text{kg} \\ s_1 = s_{f@60°\text{C}} = 0.8313\ \text{kJ/kg}\cdot\text{K} \end{array}$$

$$\boldsymbol{v}_2 = 2\boldsymbol{v}_1 = (2)(0.001017) = 0.002034\ \text{m}^3/\text{kg}$$

$$\left.\begin{array}{l} P_2 = 40\ \text{kPa} \\ \boldsymbol{v}_2 = 0.002034\ \text{m}^3/\text{kg} \end{array}\right\} \begin{array}{l} x_2 = \dfrac{\boldsymbol{v}_2 - \boldsymbol{v}_f}{\boldsymbol{v}_{fg}} = \dfrac{0.002034 - 0.001026}{3.993 - 0.001026} = 0.0002524 \\ s_2 = s_f + x_2 s_{fg} = 1.0261 + (0.0002524)(6.6430) = 1.0278\ \text{kJ/kg}\cdot\text{K} \end{array}$$

Then the entropy change of the water:

$$\Delta S = m(s_2 - s_1) = (3\ \text{kg})(1.0278 - 0.8313)\ \text{kJ/kg}\cdot\text{K} = \mathbf{0.5895\ kJ/K}$$

Question 8.3

The initial state is superheated vapor:

$$\left.\begin{array}{l} P_1 = 6\ \text{MPa} \\ T_1 = 400°\text{C} \end{array}\right\} \begin{array}{l} h_1 = 3178.3\ \text{kJ/kg} \\ s_1 = 6.5432\ \text{kJ/kg}\cdot\text{K} \end{array} \quad \text{(Table A-6)}$$

The entropy is constant during the process. The final state is a mixture since the entropy is between s_f and s_g for 100 kPa. The properties at this state are:

$$x_2 = \frac{s_2 - s_f}{s_{fg}} = \frac{(6.5432 - 1.3028)\ \text{kJ/kg}\cdot\text{K}}{6.0562\ \text{kJ/kg}\cdot\text{K}} = 0.8653$$

$$h_2 = h_f + x_2 h_{fg} = 417.51 + (0.8653)(2257.5) = 2370.9\ \text{kJ/kg}$$

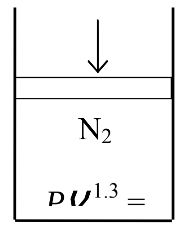
The change in the enthalpy across the turbine:

$$\Delta h = h_2 - h_1 = 2370.9 - 3178.3 = \mathbf{-807.4\ kJ/kg}$$

Question 8.4

N_2 as an ideal gas. Nitrogen has constant specific heats at room temperature: R_s = 0.2968 kJ/kg.K and c_v = 0.743 kJ/kg.K.

From the polytropic relation,



$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{n-1} \longrightarrow T_2 = T_1\left(\frac{v_1}{v_2}\right)^{n-1} = (310\text{ K})(2)^{1.3-1} = 381.7\text{ K}$$

Then the entropy change of nitrogen:

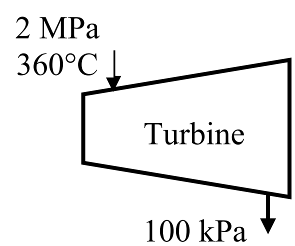
$$\Delta S_{N_2} = m\left(c_{v,\text{avg}}\ \mathbf{ln}\frac{T_2}{T_1} + R\,\mathbf{ln}\frac{V_2}{V_1}\right)$$

$$= (0.50\text{ kg})\left((0.743\text{ kJ/kg}\cdot\text{K})\ln\frac{381.7\text{ K}}{310\text{ K}} + (0.2968\text{ kJ/kg}\cdot\text{K})\ln(0.5)\right) = \mathbf{-0.02557\ kJ/K}$$

Question 8.5

The process is isentropic. For steady state: $\dot{m}_1 = \dot{m}_2 = \dot{m}$. From the energy balance for this steady-flow system:

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



The inlet state properties are

$$\left.\begin{array}{l} P_1 = 2\text{ MPa} \\ T_1 = 360°\text{C} \end{array}\right\} \begin{array}{l} h_1 = 3159.9\text{ kJ/kg} \\ s_1 = 6.9938\text{ kJ/kg}\cdot\text{K} \end{array}$$

For this isentropic process, the final state properties are

$$\left.\begin{array}{l} P_2 = 100\text{ kPa} \\ s_2 = s_1 = 6.9938\text{ kJ/kg}\cdot\text{K} \end{array}\right\} \begin{array}{l} x_2 = \dfrac{s_2 - s_f}{s_{fg}} = \dfrac{6.9938 - 1.3028}{6.0562} = 0.9397 \\ h_2 = h_f + x_2 h_{fg} = 417.51 + (0.9397)(2257.5) = 2538.9\text{ kJ/kg} \end{array}$$

Substituting,

$$w = h_1 - h_2 = (3159.9 - 2538.9)\text{ kJ/kg} = \mathbf{621.0\ kJ/kg}$$

Question 8.6

From Tables: $\left.\begin{array}{l} P_1 = 600\ \text{kPa} \\ x_1 = 1 \end{array}\right\} \begin{array}{l} u_1 = 2566.8\ \text{kJ/kg} \\ s_1 = 6.7593\ \text{kJ/kg}\cdot\text{K} \end{array}$

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

$$-W = \Delta U = m(u_2 - u_1) \quad (\text{since } Q = \text{KE} = \text{PE} = 0)$$

$$u_2 = u_1 + \frac{W}{m} = 2566.8\ \text{kJ/kg} + \frac{700\ \text{kJ}}{2\ \text{kg}} = 2216.8\ \text{kJ/kg}$$

The entropy at the final state is:

$$\left.\begin{array}{l} P_2 = 100\ \text{kPa} \\ u_2 = 2216.8\ \text{kJ/kg} \end{array}\right\} \begin{array}{l} x_2 = \dfrac{u_2 - u_f}{u_{fg}} = \dfrac{2216.8 - 417.40}{2088.2} = 0.8617 \\ s_2 = s_f + x s_{fg} = 1.3028 + 0.8617 \times 6.0562 = 6.5215\ \text{kJ/kg}\cdot\text{K} \end{array}$$

The entropy change is

$$\Delta s = s_2 - s_1 = 6.5215 - 6.7593 = \mathbf{-0.238\ kJ/kg\cdot K}$$

The process is not realistic since entropy cannot decrease during an adiabatic process. In the limiting case of a reversible (and adiabatic) process, the entropy remains constant.

Question 8.7

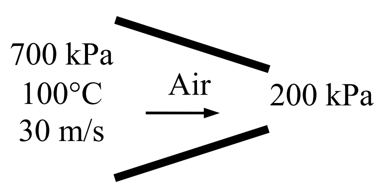
Air is an ideal gas with constant specific heats. At room temperature are $c_p = 1.005$ kJ/kg·K and $k = 1.4$. For the polytropic process $P\boldsymbol{v}^n = \text{Constant}$:

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{(n-1)/n} = (373\ \text{K})\left(\frac{180\ \text{kPa}}{800\ \text{kPa}}\right)^{0.3/1.3} = \mathbf{264.4\ K}$$

For steady state: $\dot m_1 = \dot m_2 = \dot m$. The energy balance for this steady-flow system is:

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

$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2}$$



Solving for the exit velocity,

$$V_2 = \left[V_1^2 + 2(h_1 - h_2)\right]^{0.5}$$

$$= \left[V_1^2 + 2c_p(T_1 - T_2)\right]^{0.5}$$

$$= \left[(25\ \text{m/s})^2 + 2(1.005\ \text{kJ/kg}\cdot\text{K})(373 - 264.4)\text{K}\left(\frac{1000\ \text{m}^2/\text{s}^2}{1\ \text{kJ/kg}}\right)\right]^{0.5}$$

$$= \mathbf{468\ m/s}$$

Question 8.8

Air is an ideal gas with constant specific heats. The properties of air at 300 K are c_p = 1.005 kJ/kg·K, c_v = 0.718 kJ/kg·K and k = 1.4. Also, R_s = 0.287 kJ/kg·K

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

$$-W = \Delta U = m(u_2 - u_1) \quad (\text{since } Q = \text{KE} = \text{PE} = 0)$$

$$-W = mc_v(T_2 - T_1)$$

$$W = mc_v(T_1 - T_2) \longrightarrow T_2 = T_1 - \frac{W}{mc_v} = (410 + 273\text{ K}) - \frac{550\text{ kJ}}{(5\text{ kg})(0.718\text{ kJ/kg}\cdot\text{K})} = 529.8\text{ K}$$

From the entropy change relation of an ideal gas,

$$\Delta s_{\text{air}} = c_p \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1}$$

$$= (1.005\text{ kJ/kg}\cdot\text{K})\ln\frac{529.8\text{ K}}{683\text{ K}} - (0.287\text{ kJ/kg}\cdot\text{K})\ln\frac{100\text{ kPa}}{600\text{ kPa}}$$

$$= \mathbf{0.259\ kJ/kg \cdot K}$$

Since the entropy change is positive for this adiabatic process, the process is irreversible and realistic.

Question 8.9

From the steam tables:

$$\left.\begin{array}{l} P_1 = 7\text{ MPa} \\ T_1 = 600°\text{C} \end{array}\right\} \begin{array}{l} h_1 = 3650.6\text{ kJ/kg} \\ s_1 = 7.0910\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 50\text{ kPa} \\ T_2 = 150°\text{C} \end{array}\right\} h_{2a} = 2780.2\text{ kJ/kg}$$

For steady state: $\dot{m}_1 = \dot{m}_2 = \dot{m}$. The energy balance for this steady-flow system is:

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

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

Substituting, the mass flow rate of the steam is:

$$5000\text{ kJ/s} = -\dot{m}\left(2780.2 - 3650.6 + \frac{(130\text{ m/s})^2 - (75\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right)\right)$$

$$\dot{m} = \mathbf{5.78\ \ kg/s}$$

The isentropic exit enthalpy of the steam and the power output of the isentropic turbine:

$$\left.\begin{array}{l} P_{2s} = 50\text{ kPa} \\ s_{2s} = s_1 \end{array}\right\} \begin{array}{l} x_{2s} = \dfrac{s_{2s} - s_f}{s_{fg}} = \dfrac{7.0910 - 1.0912}{6.5019} = 0.9228 \\ h_{2s} = h_f + x_{2s}h_{fg} = 340.54 + (0.9228)(2304.7) = 2467.3\text{ kJ/kg} \end{array}$$

and

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

$$\dot{W}_s = -(5.78\,\text{kg/s})\left(2467.3 - 3650.6 + \frac{(130\text{ m/s})^2 - (75\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right)\right)$$

$$= 6807\text{ kW}$$

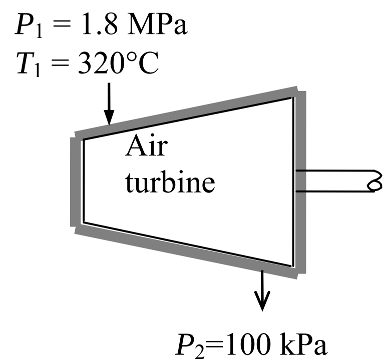
Then the isentropic efficiency of the turbine becomes

$$\eta_T = \frac{\dot{W}_a}{\dot{W}_s} = \frac{5000\text{ kW}}{6807\text{ kW}} = 0.735 = \mathbf{73.5\%}$$

Question 8.10

Air is an ideal gas with constant specific heats.

The properties of air at the anticipated average temperature of 400 K are $c_p = 1.013$ kJ/kg·°C and $k = 1.395$



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

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

The isentropic exit temperature is

$$T_{2s} = T_1\left(\frac{P_{2s}}{P_1}\right)^{(k-1)/k} = (320 + 273\text{ K})\left(\frac{100\text{ kPa}}{1800\text{ kPa}}\right)^{0.395/1.395} = 261.6\text{ K}$$

From the definition of the isentropic efficiency,

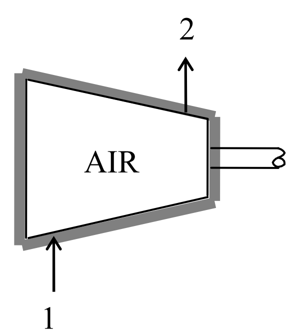
$$\eta_T = \frac{w_{a,\text{out}}}{w_{s,\text{out}}} = \frac{h_1 - h_2}{h_1 - h_{2s}} = \frac{c_p(T_1 - T_2)}{c_p(T_1 - T_{2s})} = \frac{T_1 - T_2}{T_1 - T_{2s}} = \frac{593 - 273}{593 - 261.6} = \mathbf{0.966} = \mathbf{96.6\%}$$

Question 8.11

Air is an ideal gas with constant specific heats ($k = 1.4$)

The isentropic exit temperature is

$$T_{2s} = T_1\left(\frac{P_{2s}}{P_1}\right)^{(k-1)/k} = (27 + 273\text{ K})\left(\frac{600\text{ kPa}}{95\text{ kPa}}\right)^{0.4/1.4} = 508\text{ K}$$

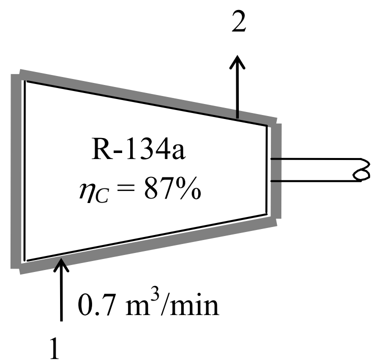


Then the isentropic efficiency becomes

$$\eta_C = \frac{h_{2s} - h_1}{h_{2a} - h_1} = \frac{c_p(T_{2s} - T_1)}{c_p(T_2 - T_1)} = 0.832 = \mathbf{83.2\%}$$

Question 8.12

From the refrigerant tables



$$\left.\begin{array}{l} P_1 = 100 \text{ kPa} \\ \text{sat. vapor} \end{array}\right\} \begin{array}{l} h_1 = h_{g@100 \text{ kPa}} = 234.44 \text{ kJ/kg} \\ s_1 = s_{g@100 \text{ kPa}} = 0.95183 \text{ kJ/kg} \cdot \text{K} \\ \boldsymbol{v}_1 = \boldsymbol{v}_{g@100 \text{ kPa}} = 0.19254 \text{ m}^3\text{/kg} \end{array}$$

$$\left.\begin{array}{l} P_2 = 1 \text{ MPa} \\ s_{2s} = s_1 \end{array}\right\} h_{2s} = 282.51 \text{ kJ/kg}$$

From the isentropic efficiency relation,

$$\eta_C = \frac{h_{2s} - h_1}{h_{2a} - h_1} \longrightarrow h_{2a} = h_1 + (h_{2s} - h_1)/\eta_C = 234.44 + (282.51 - 234.44)/0.87 = 289.69 \text{ kJ/kg}$$

Thus,

$$\left.\begin{array}{l} P_{2a} = 1 \text{ MPa} \\ h_{2a} = 289.69 \text{ kJ/kg} \end{array}\right\} T_{2a} = \mathbf{56.5°C}$$

The mass flow rate of the refrigerant is determined from

$$\dot{m} = \frac{\dot{\boldsymbol{V}}_1}{\boldsymbol{v}_1} = \frac{0.7/60 \text{ m}^3\text{/s}}{0.19254 \text{ m}^3\text{/kg}} = 0.06059 \text{ kg/s}$$

For steady state: $\dot{m}_1 = \dot{m}_2 = \dot{m}$:

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

$$\dot{W}_\text{a} = \dot{m}(h_1 - h_2)$$

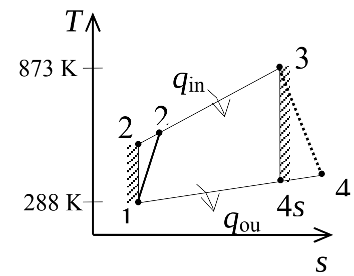
Substituting, the power input to the compressor becomes,

$$\dot{W}_\text{a} = (0.06059 \text{ kg/s})(234.44 - 289.69)\text{kJ/kg} = \mathbf{-3.35 \text{ kW}}$$

Question 8.13

Air is an ideal gas with constant specific heats. The properties of air at room temperature are c_p = 1.005 kJ/kg·K and $k = 1.4$.

For the compression process,



$$T_{2s} = T_1\left(\frac{P_2}{P_1}\right)^{(k-1)/k} = (288\text{ K})(12)^{0.4/1.4} = 585.8\text{ K}$$

$$\eta_C = \frac{h_{2s} - h_1}{h_2 - h_1} = \frac{c_p(T_{2s} - T_1)}{c_p(T_2 - T_1)} \longrightarrow T_2 = T_1 + \frac{T_{2s} - T_1}{\eta_C}$$

$$= 288 + \frac{585.8 - 288}{0.90} = 618.9\text{ K}$$

For the expansion process,

$$T_{4s} = T_3\left(\frac{P_4}{P_3}\right)^{(k-1)/k} = (873\text{ K})\left(\frac{1}{12}\right)^{0.4/1.4} = 429.2\text{ K}$$

$$\eta_T = \frac{h_3 - h_4}{h_3 - h_{4s}} = \frac{c_p(T_3 - T_4)}{c_p(T_3 - T_{4s})} \longrightarrow T_4 = T_3 - \eta_T(T_3 - T_{4s})$$

$$= 873 - (0.90)(873 - 429.2)$$

$$= 473.6\text{ K}$$

The isentropic and actual work of compressor and turbine are

$$W_{\text{Comp},s} = c_p(T_{2s} - T_1) = (1.005\text{ kJ/kg}\cdot\text{K})(585.8 - 288)\text{K} = 299.3\text{ kJ/kg}$$

$$W_{\text{Comp}} = c_p(T_2 - T_1) = (1.005\text{ kJ/kg}\cdot\text{K})(618.9 - 288)\text{K} = 332.6\text{ kJ/kg}$$

$$W_{\text{Turb},s} = c_p(T_3 - T_{4s}) = (1.005\text{ kJ/kg}\cdot\text{K})(873 - 429.2)\text{K} = 446.0\text{ kJ/kg}$$

$$W_{\text{Turb}} = c_p(T_3 - T_4) = (1.005\text{ kJ/kg}\cdot\text{K})(873 - 473.6)\text{K} = 401.4\text{ kJ/kg}$$

The back work ratio for 90% efficient compressor and isentropic turbine case is

$$r_{\text{bw}} = \frac{W_{\text{Comp}}}{W_{\text{Turb},s}} = \frac{332.6\text{ kJ/kg}}{446.0\text{ kJ/kg}} = \mathbf{0.7457}$$

The back work ratio for 90% efficient turbine and isentropic compressor case is

$$r_{\text{bw}} = \frac{W_{\text{Comp},s}}{W_{\text{Turb}}} = \frac{299.3\text{ kJ/kg}}{401.4\text{ kJ/kg}} = \mathbf{0.7456}$$

The two results are almost identical.

Question 8.14

From the steam tables,

$$\left.\begin{array}{l} P_1 = 50\ \text{kPa} \\ T_1 = T_{\text{sat @ 50 kPa}} - 6.3 = 81.3 - 6.3 = 75°\text{C} \end{array}\right\} \begin{array}{l} h_1 \cong h_{f\text{ @ }75°\text{C}} = 314.03\ \text{kJ/kg} \\ \boldsymbol{v}_1 = \boldsymbol{v}_{f\text{ @ }75°\text{C}} = 0.001026\ \text{m}^3/\text{kg} \end{array}$$

$$w_{\text{p,}} = -6.10\ \text{kJ/kg}$$

$$h_2 = h_1 - w_{\text{p}} = 314.03 - (-6.10) = 320.13\ \text{kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 6000\ \text{kPa} \\ T_3 = 450°\text{C} \end{array}\right\} \begin{array}{l} h_3 = 3302.9\ \text{kJ/kg} \\ s_3 = 6.7219\ \text{kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 50\ \text{kPa} \\ s_4 = s_3 \end{array}\right\} \begin{array}{l} x_{4s} = \dfrac{s_4 - s_f}{s_{fg}} = \dfrac{6.7219 - 1.0912}{6.5019} = 0.8660 \\ h_{4s} = h_f + x_{4s} h_{fg} = 340.54 + (0.8660)(2304.7) = 2336.4\ \text{kJ/kg} \end{array}$$

$$\eta_{\text{T}} = \frac{h_3 - h_4}{h_3 - h_{4s}} \longrightarrow h_4 = h_3 - \eta_{\text{T}}(h_3 - h_{4s}) = 3302.9 - (0.94)(3302.9 - 2336.4) = 2394.4\ \text{kJ/kg}$$

Thus,

$$\dot{Q}_{\text{in}} = \dot{m}(h_3 - h_2) = (20\ \text{kg/s})(3302.9 - 320.13)\text{kJ/kg} = \mathbf{59{,}660\ kW}$$

$$\dot{W}_{\text{T,out}} = \dot{m}(h_3 - h_4) = (20\ \text{kg/s})(3302.9 - 2394.4)\text{kJ/kg} = 18{,}170\ \text{kW}$$

$$\dot{W}_{\text{P}} = \dot{m}w_{\text{P}} = (20\ \text{kg/s})(\text{-}6.10\ \text{kJ/kg}) = \mathbf{-122\ kW}$$

$$\dot{W}_{\text{net}} = \dot{W}_{\text{T,out}} + \dot{W}_{\text{P}} = 18{,}170 + (-122) = \mathbf{18{,}050\ kW}$$

and

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{in}}} = \frac{18{,}050}{59{,}660} = \mathbf{0.3025}$$

Question 8.15

From the steam tables,

$$P_1 = P_{\text{sat @ 40°C}} = 7.385 \text{ kPa}$$
$$P_2 = P_{\text{sat @ 300°C}} = 8588 \text{ kPa}$$
$$h_1 = h_{f\text{@ 40°C}} = 167.53 \text{ kJ/kg}$$
$$\boldsymbol{\nu}_1 = \boldsymbol{\nu}_{f\text{@ 40°C}} = 0.001008 \text{ m}^3\text{/kg}$$

$$w_\text{p} = -8.65 \text{ kJ/kg}$$
$$h_2 = h_1 - w_\text{p} = 167.53 - (-8.65) = 176.18 \text{ kJ/kg}$$

$$\left.\begin{array}{l} T_3 = 300°\text{C} \\ x_3 = 1 \end{array}\right\} \begin{array}{l} h_3 = 2749.6 \text{ kJ/kg} \\ s_3 = 5.7059 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} T_4 = 40°\text{C} \\ s_4 = s_3 \end{array}\right\} \begin{array}{l} x_4 = \dfrac{s_4 - s_f}{s_{fg}} = \dfrac{5.7059 - 0.5724}{7.6832} = 0.6681 \\ h_4 = h_f + x_4 h_{fg} = 167.53 + (0.6681)(2406.0) = 1775.1 \text{ kJ/kg} \end{array}$$

Thus,

$$w_\text{T} = h_3 - h_4 = 2749.6 - 1775.1 = \mathbf{974.5\ kJ/kg}$$
$$q_\text{in} = h_3 - h_2 = 2749.6 - 176.18 = \mathbf{2573.4\ kJ/kg}$$
$$q_\text{out} = h_1 - h_4 = 167.53 - 1775.1 = -1607.6 \text{ kJ/kg}$$

The thermal efficiency of the cycle is

$$\eta_\text{th} = 1 - \frac{|q_\text{out}|}{|q_\text{in}|} = 1 - \frac{|-1607.6|}{\|2573.4\|} = \mathbf{0.375}$$

Question 8.16

Air is an ideal gas with constant specific heats.

The properties of air at room temperature are c_p = 1.005 kJ/kg·K and k = 1.4.

Using the isentropic relations,

$$T_{2s} = T_1\left(\frac{P_2}{P_1}\right)^{(k-1)/k} = (300\text{ K})(12)^{0.4/1.4} = 610.2\text{ K}$$

$$T_{4s} = T_3\left(\frac{P_4}{P_3}\right)^{(k-1)/k} = (1000\text{ K})\left(\frac{1}{12}\right)^{0.4/1.4} = 491.7\text{ K}$$

$$w_{\text{s,C,}} = h_1 - h_{2s} = c_p(T_1 - T_{2s}) = (1.005\text{ kJ/kg}\cdot\text{K})(300 - 610.2)\text{K} = -311.75\text{ kJ/kg}$$

$$w_{\text{s,T}} = h_3 - h_{4s} = c_p(T_3 - T_{4s}) = (1.005\text{ kJ/kg}\cdot\text{K})(1000 - 491.7)\text{K} = 510.84\text{ kJ/kg}$$

$$w_{\text{s,net,}} = w_{\text{s,T}} + w_{\text{s,C}} = 510.84 + (-311.75) = 199.1\text{ kJ/kg}$$

$$\dot{m}_s = \frac{\dot{W}_{\text{net,}}}{w_{\text{s,net,}}} = \frac{70{,}000\text{ kJ/s}}{199.1\text{ kJ/kg}} = \mathbf{352\ \ kg/s}$$

The net work output is determined to be

$$w_{\text{a,net}} = w_{\text{a,T}} + w_{\text{a,C}} = \eta_T w_{\text{s,T}} + w_{\text{s,C}} / \eta_C$$
$$= (0.85)(510.84) + (-311.75)/0.85 = 67.5\text{ kJ/kg}$$

$$\dot{m}_a = \frac{\dot{W}_{\text{net}}}{w_{\text{a,net,}}} = \frac{70{,}000\text{ kJ/s}}{67.5\text{ kJ/kg}} = \mathbf{1037\ \ kg/s}$$