Elementary process of chemical process
Basic principles

$\frac{1}{101 kPa} = \frac{x}{10125}$ 3773.998

Differences between scientific method and engineering method ✓

✓ unit operations and unit processes

A cooking pan whose ID = 20 cm is filled with water and covered with a 4kg lid. If the Patm = 101 kPa, determine the temperature at which the water starts boiling.

$P = \frac{F}{A}$ $A = \frac{\pi D^2}{4} = \frac{\pi (0.2)^2}{4} = 0.0314 m^2$

$W_{Lid} = m_{Lid} \times g$ $P = \frac{39.24}{0.0314} = 1249.7 Pa$

$= 4 \times 9.81 = 39.24 N$

$P_T = P_{atm} + P_{Lid}$

$= 101000 + 1249.7$

$= 102.25 kPa$

T	P
°C	kPa
100	101.33
x	102.25
102	108.78

$\frac{x_1 - 100}{102 - 100} = \frac{102.25 - 101.33}{108.78 - 101.33}$ $x_1 = 100.25°C$

$\frac{102 - 100}{102 - x_2} = \frac{108.78 - \cancel{102.25}\ 101.33}{108.78 - 102.25}$

$x_2 = 100.25°C$

For a specific vol of $0.2 m^3/kg$. Find the quality of steam if the absolute pressure is a) 40 kPa b) 630 kPa. What is the temperature of each case

T	P
°C	kPa
75	38.55
x	40.00
76	40.19

$\frac{x_1 - 75}{76 - 75} = \frac{40 - 38.55}{40.19 - 38.55}$

$x = 75.88°C$

a)

v_f	v_{fg}
1.026	4133.1
v_{f_1}	v_{fg_1}
1.027	3974.6

$\frac{40 - 38.55}{40.19 - 38.55} = \frac{v_{f_1} - 1.026}{1.027 - 1.026} = \frac{v_{fg_1} - 4133.1}{3974.6 - 4133.1}$

$v_{f_1} = 1.02688$ $v_{fg_1} = 3992.965 cm^3/g$

$$\frac{0.2\,m^3}{kg}\left|\frac{100(cm)^3}{1\,m^3}\right|\frac{1\,kg}{1000\,g}$$

$\therefore \nu = 0.2\,m^3/kg = 200\,cm^3/g$

$$x = \frac{200 - 1.02688}{3992.963}$$

$= 0.0498$

T	P	ν_f	ν_{fg}
°C	kPa	cm^3/g	cm^3/g
160	618.06	1.102	305.7
T_2	630	ν_{f2}	ν_{fg2}
162	650.16	1.105	291.3

$T_2 = 160.74°C$ $\quad \nu_{f2} = 1.103$ $\quad \nu_{fg2} = 300.34$

$$x = \frac{200 - 1.103}{30}$$

A 1.8 m^3 rigid tank contains steam T = 220°C. One-third of the volume is in liquid phase and the rest is in vapour form. Determine a) Pressure of the steam b) Quality of saturated mixture c) Density of the mixture

$V_{lp} = \frac{1}{3}V \qquad V_{vp} = \frac{2}{3}V$

T/°C	P/kPa	$\nu_f/cm^3/g$	ν_g	ν_{fg}
220°	2319.8	1.190	86.04	84.85

$$\therefore \nu = \frac{1}{\rho} = \frac{V}{m} \qquad m = \frac{V}{\nu} \qquad m_f = \frac{V_f}{\nu_f} \qquad m_f = \frac{1.19\ \frac{1}{3}(1.8)}{0.00119} = 504.2\,kg$$

$$m_g = \frac{\frac{2}{3}(1.8)}{0.08604} = 13.947\,kg$$

$$m_T = 518.147\,kg \qquad x = \frac{m_g}{m_T} = \frac{13.947}{518.147} = 0.0269$$

$$\rho = \frac{m}{V} = \frac{518.147}{1.8} = 287.86\,kg/m^3$$

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

4 kg of water is placed in an enclosed volume of $1m^3$. Heat is added until the temp is 150°C. Find a) The pressure b) mass of the vapour c) volume of the vapour

$P = T_{sat@150°C} = 476 kPa$

$$\nu = \frac{V}{m} = \frac{1}{4} = 0.25 m^3/kg = 250 cm^3/g$$

b) From steam tables, $\nu_f = 1.091 cm^3/g$ $\nu_{fg} = 391.4 cm^3/g$

$$x = \frac{\nu - \nu_f}{\nu_{fg}} \quad \frac{250 - 1.091}{391.4} = 0.636 \quad \text{but } x = \frac{m_g}{m_{Tot}} \quad \therefore m_g = 0.636 \times 4 = 2.543 kg$$

c) $\nu_g = \frac{V_g}{m_g}$ $V_g = \nu_g m_g$ From steam tables, $\nu_g = 392.4 cm^3/g$

$$\therefore V_g = 2.543 \times 0.3924 = 0.998 m^3$$

A piston cylinder device contains $0.1m^3$ of liquid water and $0.9m^3$ of water vapour in equilibrium at 800 kPa. Heat is transferred at constant pressure until the temperature reaches 350°C.

a) Initial temperature of the water b) Total mass of the water

c) The final volume

$V_f = 0.1m^3$ $V_g = 0.9m^3$ $P = 800 kPa$ $T_2 = 350°C$

T/°C	P/kPa	$\nu_g / cm^3/g$	ν_f
170	792.02	242.6	1.114
$x T_1$	800	x, ν_{g1}	x, ν_{f1}
172	831.06	231.7	1.117

$T_1 = 170.4°C$ $\nu_{g_1} = 240.37 cm^3/g$ $\nu_{f_1} = 1.1146 cm^3/g$
$0.0011146 m^3/kg$

$m_T = m_f + m_g$

$$\nu_f = \frac{V_f}{m_f} \quad m_f = \frac{0.1}{1.1146} = \frac{0.1}{0.0011146} = 89.718 kg$$

$$m_g = \frac{V_g}{\nu_g} = \frac{0.9}{0.24037} = 3.744 kg$$

$$\therefore m_T = 89.718 + 3.744 = 93.462 kg$$

From super-heated tables, @ 800kPa under 350°C $\nu = 354.34$

$$\nu = \frac{V_T}{m_T} \quad V_T = 93.462 \times 0.35434 = 33.117 m^3$$

Determine the specific volume of the superheated water at 10MPa and 400°C using a) Ideal gas eqn b) generalised compressibility ~~factor~~ chart c) steam table d) Determine the error involved in the first two cases

$P = 10\,MPa$ $T = 400°C$ From Table B-2 on the steam table $R = 0.4615\,kJ/kg \cdot K$

a) $P\upsilon = RT$

$$\upsilon = \frac{0.4615 \times 673.5}{10^4} = 0.03106\,m^3/kg$$

b) $P_r = \frac{P}{P_c}$ $P_c = 22080.5\,kPa$ ~~from~~ and $T_c = 647.15\,K$

$$P_r = \frac{10^4}{22080} = 0.453 \qquad T_R = \frac{T}{T_c} \qquad T_R = \frac{673.15}{647.15} = 1.040$$

$$P\upsilon = ZRT \qquad \upsilon = \frac{ZRT}{P} \qquad \upsilon = Z V_{ideal}$$

$$Z = 0.84 \qquad V_{co} = 0.84 \times 0.03106 = 0.02609$$

b) $P = 10{,}000\,kPa$, $T = 400°C$ $\Big\}$ $\upsilon_{steam} = 26.408\,cm^3/g = 0.026408\,m^3/kg$

Error $(\upsilon_{ideal}) = \frac{\upsilon_{steam} - \upsilon_{ideal}}{\upsilon_{steam}} \times 100\%$

$$= \left|\frac{0.026408 - 0.03106}{0.026408}\right| \times 100\%$$

$$\simeq 17.62\%$$

Error $(\upsilon_{co}) = \frac{\upsilon_{steam} - \upsilon_{co}}{\upsilon_{steam}} \times 100$

$$= \frac{0.026408 - 0.02609}{0.026408} \times 100$$

$$= 1.2\%$$

$\upsilon = Z V_{ideal}$

First Law Of Thermodynamics

Derive an expression for work of a gas undergoing polytropic process with $n \neq 1$

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

$PV^n = C$

$P = CV^{-n}$

$W = \int_1^2 CV^{-n}\,dV$

$= C\int_1^2 V^{-n}\,dV$

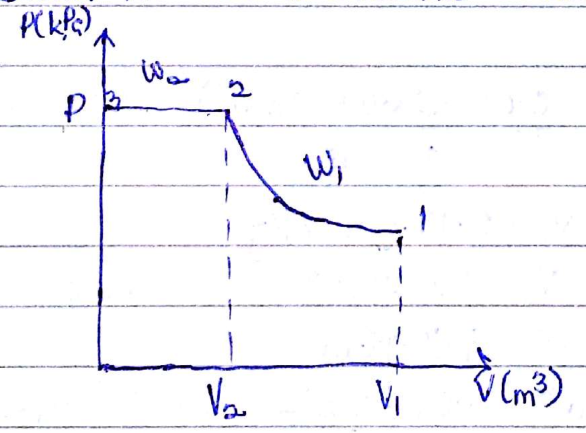
$= \dfrac{CV^{-n+1}}{-n+1} \qquad = \dfrac{CV^{1-n}}{1-n}$

$= C\left(\dfrac{V_2^{1-n} - V_1^{1-n}}{1-n}\right)$

~~$W = CV_2 \cdot V^{-n} - CV_1 V^{-n}$~~

$W = \dfrac{CV_2^{-n} \cdot V_2 - CV_1^{-n} \cdot V_1}{1-n}$

An ideal gas undergoes a two-step process beginning at state 1. It is isothermally compressed to state 2, then isobarically compressed to state 3. Derive an expression for the workdone. Sketch the process



$W = W_1 + W_2$

$PV^n = C$ when $n = 1$ isothermal process

$P = \dfrac{C}{V} \qquad C = PV$

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

$= C\int_1^2 \dfrac{1}{V}\,dV$

$= C\ln V\Big|_1^2 \qquad C\ln\dfrac{V_2}{V_1}$

$W_1 = P_1V_1 \ln\dfrac{V_2}{V_1}$

$\dfrac{D_{steam} - V_{ideal}}{V_{steam}} \times 100 \Big|_0^{r}$

For isobaric process $n=0$ $PV^0=C$ $P=C$

$W=\int PdV$

$W=\int Cdv$ $W=C\int_2^3 dV$

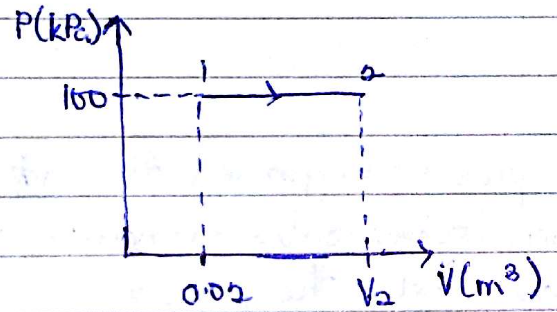
$= C|V|_2^3$

$= C(V_3-V_2)$

$= P(V_3-V_2)$

$$W = P_1V_1\ln\frac{V_2}{V_1} + P(V_3-V_2)$$

A piston cylinder arrangement has 2kg of water with $V_1 = 0.02m^3$ and $T_1 = 50°C$. When $P = 100kPa$, the piston leaves the stops. The water is heated from its initial state to its final state of 200°C. Find the workdone by the water



Isobaric process

$W = P(V_2-V_1)$

$\left\{ \text{Wrong} \quad \frac{V_1}{T_1} = \frac{V_2}{T_2} \quad V_2 = \frac{0.02\times(250+273.15)}{323.15} = 0.02928m^3 \text{ Wrong} \right\}$

From steam tables, $\left.\begin{matrix} P = 100kPa \\ T_2 = 200°C \end{matrix}\right\}$ $v_2 = 2.1723 m^3/kg$

$V_2 = 2\times 2.1723$ Correct

$\therefore = 4.3446 m^3$

$W = 100(4.3446-0.02)$

$= 432.46kJ$

$\left\{ W^* = 100(0.02928-0.02) = 0.928kJ \right\}$ Wrong

Sketch a P-V diagram showing the ff. process in the cycle

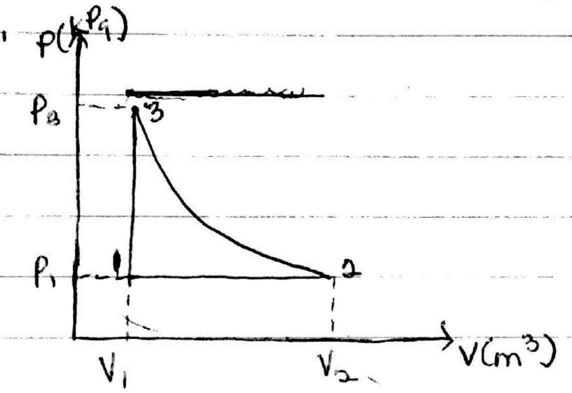
Process (1-2): Isobaric work output of 10.5kJ from an initial volume of 0.028m^3 and pressure at 1.4bar

Process (2-3): Isothermal compression

Process (3-1): Isochoric heat transfer to its original volume from 0.028m^3. Calculate

a) The maximum volume of the cycle b) Isothermal work in kJ

c) Net work in kJ. d) Heat transfer during isobaric expansion in kJ



a) For isobaric process,

$$W = P(V_2 - V_1)$$

$$10.5 = 140(V_2 - 0.028)$$

$$V_2 = 0.103m^3$$

b) For isothermal process,

$$P_2V_2 = P_3V_3$$

$$P_3 = \frac{P_2V_2}{V_3}$$

$$= \frac{140 \times 0.103}{0.028}$$

$$= 515 kPa$$

$$W = P_2V_2 \ln\frac{V_3}{V_2}$$

$$= 140 \times 0.103 \ln\left(\frac{0.028}{0.103}\right)$$

$$= -18.78 kJ$$

c) $W_{net} = W_{12} + W_{23} + W_{31}$ $\quad W_{31} = 0$ (Isochoric process)

$$= 10.5 - 18.78$$

$$= -8.28 kJ$$

d) $Q - W = \Delta U$ but $\Delta u = 0$ because of isobaric process

$\Delta U = Q - W$

$Q = \Delta U + W$

Since it is a rigid tank, volume is constant (isochoric)

$\therefore \Delta W = 0$ $\qquad u = u_f + x u_{fg}$

$Q = \Delta U$

$\Delta U = m \Delta u$

$= m(u_2 - u_1)$

P	u_{fg}	u_f
1098.3	1804.9	779.6
~~1148.8~~	x	x_1
1100	u_{fg1}	~~788.4~~ u_{f1}
1148.8	1797.3	788.4

P	v_g
1985.2	100.26
2000	x
2065.1	96.46

$v_g = 0.0996 m^3/kg$

$u_{fg1} = 1804.6 kJ/kg$ $\qquad u_{f1} = 779.9 kJ/kg$

$\therefore u_1 = 779.9 + 0.92(1804.6)$

$= 2440.132 kJ/kg$

P	v_f	v_{fg}
1098.3	1.133	176.5
1100	v_{f1}	v_{fg1}
1148.8	1.136	169.0

$v_{f1} = 1.1331 cm^3/g$ $\qquad v_{fg1} = ~~17~~0.1762 m^3/kg$

$v_1 = v_{f1} + x v_{fg1}$

$= 1.1331 + (0.92 \times 176.278)$

$= 163.4 cm^3/g$

$v_1 = v_2 = 0.1634 m^3/kg$

$\therefore v_1 = v_2 > v_g @ P_{sat} = 2000 kPa$ $\therefore$ it's superheated

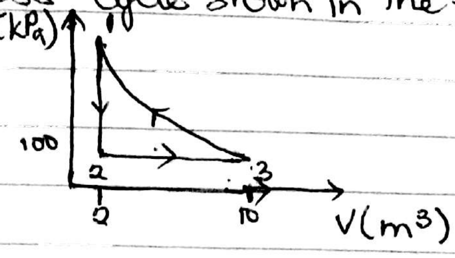
$\left.\begin{array}{l} P_2 = 2000 kPa \\ v_2 = 0.1634 m^3/kg \end{array}\right\} u_2 \doteq 3031.0 kJ/kg$

$Q = \Delta U = 0.05(3031 - 2440.132)$

$Q = \Delta U = 29.54 kJ$

176.278

2kg of air experiences the 3 process cycle shown in the figure below. Calculate the net work



From 1 to 2, it is isochoric, $W = 0$

From 2 to 3, it is isobaric, $W = P(V_2 - V_1)$

$W = 100(10-2)$

$= 800 \text{ kJ}$

From ~~3~~ 3 to 1, it is isothermal, $W = P_3 V_3 \ln\left(\frac{V_1}{V_3}\right)$

$= 100(10) \cancel{\ln\left(\frac{10}{2}\right)} \ln\left(\frac{2}{10}\right)$

$= \cancel{321.8}\ -1609.44 \text{ kJ}$

$\therefore W = 800 - 1609.44$

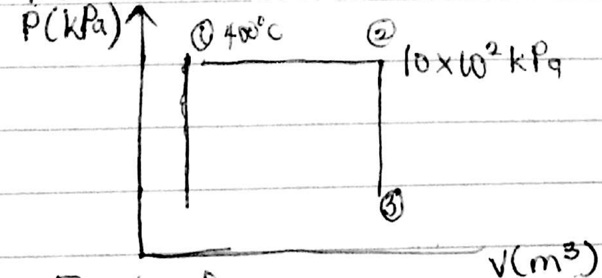
$= -809.44 \text{ kJ}$

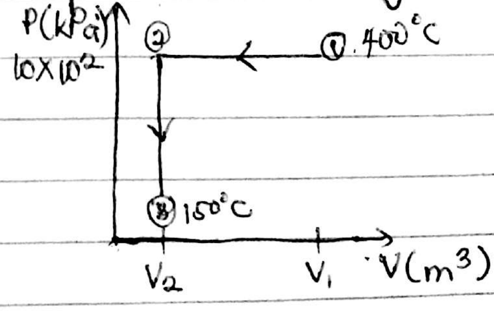
Water contained in a piston cylinder assembly ~~a~~ undergoes 2 processes in series from an initial state where $P_1 = 10$ bar and $T_1 = 400°C$. Process 1-2, the water is cooled as it is compressed at a constant pressure of 10 bar to saturated vapour state. Process 2-3, the water is cooled at constant volume to 150°C

a) Sketch the process on PV diagram

b) Determine the work for the overall process in kJ/kg

c) Determine the heat transfer for the overall process in kJ/kg





$P_1 = 10 \times 10^5 \text{ Pa}$ $T_1 = 400°C$

From 1 to 2, isobaric

$W = P(V_2 - V_1)$

~~W = 10×~~

For point 1, it is superheated, $V_1 = 306.49 \text{ cm}^3/\text{g} = 0.30649 \text{ m}^3/\text{kg}$

$U_1 = 2957.9 \text{ kJ/kg}$

$W = W_{12} + W_{23}$

From 2 to 3, isochoric, $W = 0$

$T_{sat} = 400°C$

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From

P	v_g
957.36	~~193.8~~ 202.5
1000	x
1002.7	193.8

$V_2 = v_g$ @ $P_{sat} = 10\,bar$

$x = 0.194\, m^3/kg$

$W = 1000(0.194 - 0.3064)$
$= -112.17\, kJ/kg$

$Q \cdot \Delta u = (u_2 - u_1) + (u_3 - u_2)$
$= u_3 - u_1$

$\Delta u = \Delta q - \Delta w$

$q = \cancel{E}\cdot W + (u_3 - u_1)$
$= -112.17 + (1583.49 - 295.79)$
$= -1486.88\, kJ/kg$

$V_2 = V_3 = 0.194\, m^3/kg$

$u_3 = u_{f3} + x\, u_{fg3}$

$x = \dfrac{V_3 - v_{f3}}{v_{fg3}} = 0.494$

$u_3 = 631.6 + 0.494(1926.4)$
$= 1583.49\, kJ/kg$

Air flows steadily in pipe at 300kPa, 77°C and 25m/s at a rate of 18kg/min. Determine a) diameter of the pipe b) rate of flow energy c) Rate of energy transport by mass d) error involved in (c) if ko K.E is neglected. Property of air $R = 0.287\, kJ/kgK$ $c_p = 1.008\, kJ/kgK$

300kPa, 77°C $\longrightarrow$ 25m/s, 18kg/min

~~$\dot{m} = \rho$~~ $Pv = RT$

$v = \dfrac{RT}{P}$ $\quad v = \dfrac{0.287 \times 350.15}{300}$ $\quad v = 0.335\, m^3/kg$

$A = \dfrac{\pi D^2}{4}$ $\quad D = \sqrt{\dfrac{4A}{\pi}}$ $\quad \dot{m} = \rho V A$ $\quad A = \dfrac{\dot{m}}{\rho V}$ $\quad \rho v = \dfrac{1}{\rho}$ $\quad \rho = \dfrac{1}{v}$

$A = \dfrac{v\dot{m}}{V} = \dfrac{0.335 \times \frac{18}{60}}{25}$ $\quad A = 0.00402\, m^2$

$D = \sqrt{\dfrac{4 \times 0.00402}{\pi}}$ $\quad D = 0.0715\, m$

b) $W_{flow} = \cancel{\dot{m}\rho}\ \dot{m} P v$
$= 18/60 \times 300 \times 0.335$
$= 30.15\, kW$

c) $E = \dot{m}(h + \frac{1}{2}\cancel{m}V^2)$
$h = c_p T$
$h = 1.008 \times (350)$
$= 352.8\, kW$
$E = \dfrac{18}{60}(352.8 + \dfrac{1}{2000}(25)^2)$
$=$ ~~199.59~~ kW
105.94 kW

$v = \dfrac{V}{n}$ $\quad m =$

$\dot{E} = \dot{m} C_p T \qquad \dot{E} = \frac{18}{60}(1.008 \times 350)$

$= 105.84\,kW$

$Error = \frac{105.94 - 105.84}{105.94} \times 100 = 0.09$

Steam at 3MPa and 400°C enters an adiabatic steadily with $v = 40\,m/s$ and leaves at 2.5MPa and 300m/s. Determine a) the exit temperature b) the ratio of inlet to exit area $\frac{A_1}{A_2}$

$$h_1 + \frac{v_1^2}{2} = h_2 + \frac{v_2^2}{2}$$

$\left.\begin{array}{l} P_1 = 3MPa \\ T_1 = 400°C \end{array}\right\} \begin{array}{l} h_1 = 3232.5\,kJ/kg \\ \upsilon_1 = 0.09931\,m^3/kg \end{array}$

$h_2 = h_1 + \frac{v_1^2}{2} - \frac{v_2^2}{2}$

$= 3232.5 + -\left(\frac{300^2 - 40^2}{2000}\right)$

$= 3188.3\,kJ/kg$

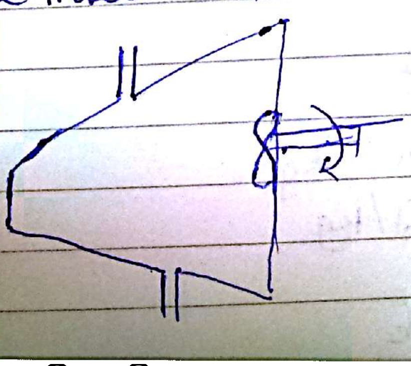
$\left.\begin{array}{l} P_2 = 2.5MPa \\ h_2 = 3188.3\,kJ/kg \end{array}\right\} \begin{array}{l} T_2 = 376.6°C \\ \upsilon_2 = 0.11533\,m^3/kg \end{array}$

$\rho_1 V_1 A_1 = \rho_2 V_2 A_2$

$\frac{1}{\upsilon_1} A_1 V_1 = \frac{1}{\upsilon_2} A_2 V_2$

$\frac{A_1}{A_2} = \frac{\upsilon_1 V_2}{V_1 \upsilon_2} = 6.46$

Steam flows steadily through an adiabatic turbine. Inlet conditions are 10MPa, 450°C, 80m/s and exit conditions are 10KPa, 92% quality, 50m/s. The mass flow rate of the steam is 12kg/s. Determine a) Δke b) power output c) turbine inlet area



a) $\Delta ke = \frac{V_2^2 - V_1^2}{2}$

$= \frac{50^2 - 80^2}{2}$

9.582

W'

$\left.\begin{array}{l}10MPa \\ 450°C\end{array}\right\}$ $h_1 = 3243.6$, $v_1 = 0.029742\ m^3/kg$

$10kPa \}$ ~~$h_f =$~~ $h_f = 191.77$ $h_{fg} = 2392.93$

$h = h_f + xh_{fg}$

$= 191.77 + (0.92 \times 2392.93)$

$= 2393.26 kJ/kg$

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

$W = 12\left[(3243.6 - 2393.26) + 1.95\right]$

$= 10227.48$

$= 10.23 MW$

c) $\dot{m} = \frac{1}{v_1} V_1 A_1$ $A_1 = \frac{12 \times 0.029742}{80} = 4.46 \times 10^{-3} m^2$

Air at 10°C and 80kPa enters the diffuser of a jet engine steadily with a velocity of 200m/s. Inlet area of the diffuser is 0.4m². Air leaves the diffuser with a velocity that is very small compared with the V_1. Determine a) mass flow rate of air b) Temperature of air leaving the diffuser

$PV = \frac{m}{M}RT$ $\rho = \frac{P}{RT}$ $\rho = \frac{80}{0.287 \times (283.15)}$

$\rho = 0.984\ kg/m^3$

$\dot{m} = \rho V A$

$= 0.984 \times 200 \times 0.4$

$= 78.76 kg/s$

$\dot{m}\left[(h_2 - h_1) + \frac{\cancel{V_2^2}^{0} - V_1^2}{2}\right] = 0$

$h_2 - h_1 - \frac{V_1^2}{2} = 0$ $\Delta h = \frac{V_1^2}{2}$

$\Delta h = C_p \Delta T = C_p(T_2 - T_1)$ $= \frac{200^2}{2}$

$C_p = 1.005 kJ/kg.K$ $= 20000\ J/kg$

$T_2 = \frac{\Delta h}{C_p} + T_1$ $= 20kJ/kg$

$T_2 = \frac{20}{1.005} + 283.15 = 303.1K = 29.9°C$

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$\cancel{m = \frac{RT_1}{V}}$ $m = \frac{P_1V_1}{RT_1}$ $m = \frac{130 \times 0.07}{0.2968 \times 393}$

$= 0.078\,kg$

$T_2 = 100°c$; $P_2 = 100kPa$

$V_2 = \frac{mRT_2}{P_2} = \frac{0.078 \times 0.2968 \times 373}{100}$

$= 0.0864 m^3$ when T_2 is given

$P_1V_1^n = P_2V_2^n$

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

$n = 1.248$

$Q - W = \Delta U + \cancel{\Delta KE}^{0} + \cancel{\Delta PE}^{0}$ Assumptions; ΔKE, ΔPE, steady state

$Q - W = \Delta U$

$W = P(V_2 - V_1)$

$Q - P(V_2 - V_1) = \Delta U$

$Q = U_2 - U_1 + PV_2 - PV_1$

$Q = U_2 + PV_2 - (U_1 + PV_1)$

But $H = U + PV$

$Q = H_2 - H_1$

$Q = \Delta H$

$h_1 = 306.88\,kJ/kg$ $h_2 = 72.34\,kJ/kg$ $m = 5kg$

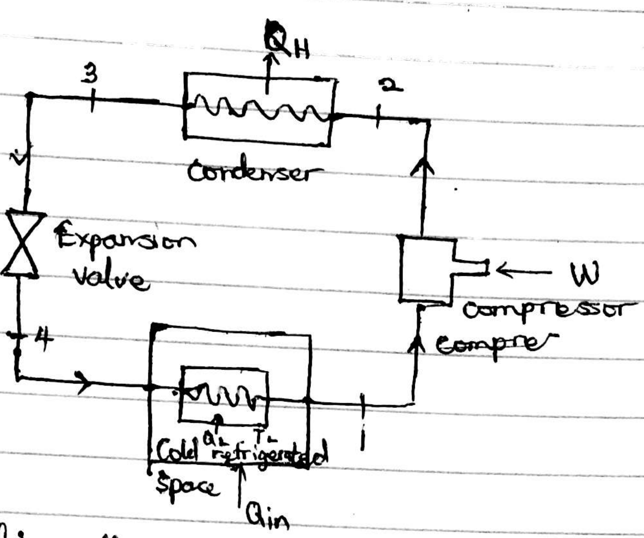
$Q = m(h_2 - h_1)$

$= 5(72.34 - 306.88)$

$= -1172.7kJ$

REFRIGERATION

A common refrigerator is based on a vapor compression cycle. This is a rankine cycle in the reverse



One can outline the vapour-compression refrigeration cycle are as follows

1-2 : Isentropic compression in a compressor

2-3 : Isobaric heat rejection in a condenser

3-4 : Throttling in an expansion device (adiabatic expansion in throttling valve)

4-1 : Isobaric heat transfer from low temperature reservoir

All 4 processes associated with the vapour-compression refrigeration cycle are steady flow ~~dev~~ processes. They make up the cycle and can ~~ea~~ be analysed as steady flow processes. K.E and P.E changes are usually small, relative to the work and heat transfer terms can be neglected. The ~~state~~ steady state flow ~~eq~~ energy equation on unit mass basis reduces to

$$(q_{in} - q_{out}) + (W_{in} - W_{out}) = (h_{exit} - h_{inlet}) \quad — (57)$$

Coefficient of ~~R~~ Performance

The compressor ~~in~~ and evaporator do not involve any work and the compressor can be approximated as adiabatic. The performance of refrigerators can be expressed as coefficient of performance (COP) or (β)

$$\beta = \frac{\text{What one wants}}{\text{what one pays for}} \quad — (58)$$

$$\left.\begin{aligned} &= \frac{\text{Desired output}}{\text{Required input}} \\ &= \frac{\text{Cooling effect}}{\text{Work input}} \end{aligned}\right\} — (59)$$

$\beta = \frac{Q_L}{W_{in}}$ — (60) $\quad \beta = \frac{h_1 - h_4}{h_2 - h_1}$

NB: Generally β or COP is the measure of ~~refrig~~ efficiency of the refrigerator or air conditioner. The higher β, the higher the efficiency of the equipment. Eg. If $\beta = 3.0$ indicates that 1W of motor power will produce 3W of ~~c~~ cooling

A common refrigerant (R-134a) enters a compressor at $x = 1$ $T = -15°C$ at the compressor inlet. The volume flow rate is $1 m^3/min$. The R-134a leaves the condenser at $T_3 = 35°C$ $P_3 = 1000 kPa$. Analyze the system

Solution

- Compressor power

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

- The refrigeration capacity

$\dot{Q}_{in} = \dot{m}(h_1 - h_4)$

- How much heat exits the back side

$Q_H = \dot{m}(h_2 - h_3)$

- Coefficient of performance (β)

$$\beta = \frac{\dot{Q}_{in}}{\dot{W}}$$

For State 1, $x_1 = 1$ $T_1 = -15°C$ $h_1 = 389.2 kJ/kg$ $s_1 = 1.7354 kJ/kgK$

$v_1 = 0.1200 m^3/kg$

For state 2-3, $P_2 = P_3 = 1000 kPa$ $\left.\begin{matrix} P_2 \\ s_1 = s_2 \end{matrix}\right\}$ $h_2 = 426.771 kJ/kg$

Expansion value, $h_3 = h_4 = 249.10 kJ/kg$

$$\dot{m} = \frac{\dot{V}_1}{v_1} = \frac{\frac{1}{60}}{0.1200} = 0.1389 kg/s$$

$\dot{W} = 0.1389(426.771 - 389.2)$

$= 5.2186 kW$

$\dot{Q}_{in} = 0.1389(\overset{389.2}{\cancel{426.771}} - 249.1)$

$= 19.460 kW$

Energy Conservation

$\dot{Q}_H = \dot{Q}_{in} + \dot{W}$

$24.678 = 19.460 + 5.2186$

An air conditioner with R-134a as the working fluid is used to keep the room at 26°C by rejecting the waste heat to the outdoor air at 34°C. The room gains heat through the walls and windows at a rate of 250 kJ/min while the heat generated by the computer, TV and light amounts to 900W. The refrigerant enters the compressor at 500kPa as a saturated vapour at a rate 100 l/min and leaves at ~~1000~~ 1200 kPa and 50°C. Determine
a) The actual COP b) the maximum COP c) the minimum volume flow rate of the refrigerant at the compressor inlet for the same compressor inlet and exit conditions

Solution

$T_L = 26°C$ $\dot{Q}_{wall+window} = 250\,kJ/min$ $\dot{Q}_{co,TV,Light} = 900W$

S1

$P_1 = 500kPa$ $\dot{V}_1 = 100 l/min = \frac{1}{600}\frac{m^3}{s}$

S2

$P_2 = 1200kPa$

$T_2 = 50°C$

$Q_{in} = Q_{wall+wind} + \dot{Q}_{co,TV,Lght}$

$= \frac{250kJ}{60s\,min} + \frac{900J}{s} = 5.067kW$

$W_{in} = \dot{m}_R(h_2 - h_1)$

$\left.\begin{matrix} P_1 = 500kPa \\ x_1 = 1 \end{matrix}\right\} \begin{matrix} h_1 = 259.3kJ/kg \\ v_1 = 0.04112m^3/kg \end{matrix}$ $\left.\begin{matrix} P_2 = 1.2MPa \\ T_2 = 50°C \end{matrix}\right\} h_2 = 278.27kJ/kg$

$\dot{m}_R = \frac{\frac{1}{600}}{0.04112} = 0.04053\,kg/s$

$W_{in} = 0.04053(278.27 - 259.3)$

$= 0.7689kW$

$COP_{actual} = \frac{Q_{in}}{W_{in}} = \frac{5.067}{0.7689} = 6.589$

$$COP_{max} = \frac{1}{\left(\frac{T_H}{T_L}\right) - 1} = \frac{1}{\left(\frac{34+273}{26+273}\right) - 1} = 37.375$$

$$COP = \frac{Q_{in}}{W_{in}} \qquad W_{in} = \frac{Q_{in}}{COP} = \frac{5.067}{37.375} = 0.13557\,kW$$

$$W_{min} = \dot{m}_{Rmin}(h_2 - h_1)$$

$$\dot{m}_{Rmin} = \frac{W_{min}}{h_2 - h_1} = \frac{0.13557}{278.27 - 259.3}$$

$$= 0.00715\,kg/s$$

$$\dot{m}_{Rmin} = \frac{\dot{V}_{min}}{v_1} \qquad \dot{V}_{min} = 0.00715 \times 0.04112$$

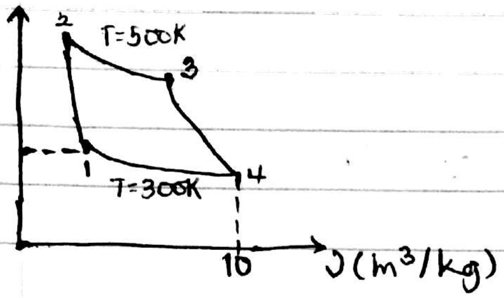
$$= 0.000294\,m^3/s$$

The ideal refrigeration cycle is used in the operation of an actual refrigerator. It experiences the following real effects. The refrigerant leaving the evaporator is superheated to -10°C. The refrigerant leaving the condenser is subcooled to 40°C. The compressor is 80% efficient. Calculate the actual rate of refrigeration and the coefficient of performance.

$h_3 = 74.5\,kJ/kg$ $\quad h_1 = 185\,kJ/kg$

$s_1 = 0.732\,kJ/kg\cdot K$ $\quad h_2' = 220\,kJ/kg$

A carnot engine operates with air using the cycle shown below



Determine the thermal efficiency under work output for each cycle of operation

$\eta = 1 - \frac{T_L}{T_H}$ $T_L = 300K$ $T_H = 500K$

$\eta = 1 - \frac{300}{500} = 0.4$ or 40%

$\eta = \frac{W}{Q_H}$ $W = \eta Q_H$

$w = \eta q_H$

$q - w = \Delta e = 0$

$q = w$

$q_H = W_{2-3} = \int_2^3 P dv$ From $Pv = RT$

$P = \frac{RT}{v}$

$W_{2-3} = \int_2^3 \frac{RT}{v} dv$

$= RT_H \int_2^3 \frac{1}{v} dv$

$= RT_H \ln \frac{v_3}{v_2}$

$k = 1.4$ for air

$P_1 v_1 = RT_1$

$v_1 = \frac{0.287(300)}{80}$

$= 1.076 m^3/kg$

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

$v_2 = 1.076 \left(\frac{300}{500}\right)^{\frac{1}{1.4-1}}$

$= 0.3 m^3/kg$

$v_3 = v_4 \left(\frac{T_4}{T_3}\right)^{\frac{1}{k-1}}$

$= 10 \left(\frac{300}{500}\right)^{\frac{1}{1.4-1}}$

$v_3 = 2.789 m^3/kg$

$W_{2-3} = q_H = 0.287(500) \ln \frac{2.789}{0.3}$

$= 319.96 kJ/kg$

$W = \eta q_H$

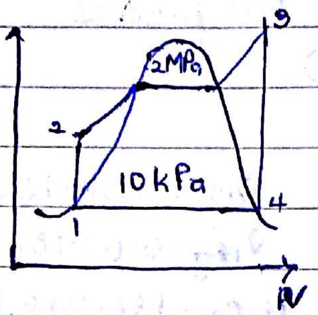
$= 0.4 \times 319.96$

$= 127.98 kJ/kg$

A steam power plant is proposed to operate between the pressures of 10kPa and 2MPa with a maximum temperature of 400°C as shown below. What is the maximum efficiency from the power cycle.

Sat. Liquid

$h_1 = h_f = 191.8 kJ/kg$



Superheated

$h_3 = 3248 kJ/kg$

$S_3 = 7.1279 kJ/kg.K$

$\eta = \dfrac{W_T - W_P}{Q_{in}}$

$\rho = 1000 kg/m^3$

$v = \dfrac{1}{1000} = 0.001 m^3/kg$

$W_P = h_2 - h_1$

$W_P = v(P_2 - P_1)$

$W_P = 0.001(2000 - 10)$

$= 1.99 kJ/kg$

$W_T = h_3 - h_4$

$S_3 = S_4 = 7.1279 kJ/kgK$

$h_4 = h_{4f} + x h_{4fg}$

$S_4 = S_{4f} + x S_{4fg}$

$x = \dfrac{S_4 - S_{4f}}{S_{4fg}}$ $\quad x = \dfrac{7.1279 - 0.6491}{\cancel{0.86}\,7.50019}$

$= 0.864$

$h_{4f} = 192 kJ/kg$ $\quad h_{4fg} = 2393 kJ/kg$

$h_4 = 192 + 0.864(2393)$

$= 2259.552 kJ/kg$

$W_T = 3248 - 2259.552$

$= 988.448 kJ/kg$

$q_{in} = h_3 - h_2$

$W_P = h_2 - h_1$

$h_2 = W_P + h_1$

$= 1.99 + 191.8$

$= 193.79 kJ/kg$

$q_{in} = 3248 - 193.79$

$= 3054.21 kJ/kg$

$\eta = \dfrac{988 - 1.99}{3054.21}$

$= 0.32$

A $0.5 m^3$ rigid tank contains R-134a initially at 200kPa and 0.4 quality Heat is transferred from a source to refrigerant at 34°C until pressure rises to 400kPa. Determine a) the entropy of refrigerant b) entropy change of heat source c) total entropy change for this process

$\Delta S_{T} \quad \Delta S_{ref} = m(S_2 - S_1)$

State 1

$P_1 = 200kPa$ }
$x_1 = 0.4$ }

$S_{1f} = 0.15457 kJ/kgK \qquad v_{1f} = 0.0007533$

$S_{1fg} = 0.78316 kJ/kgK \qquad v_{1fg} = 0.099867$

$u_{1f} = 38.28 kJ/kg \qquad u_{1fg} = 186.21 kJ/kg$

$S_1 = S_{1f} + x S_{1fg}$
$= 0.15457 + 0.4(0.78316)$
$S_1 = 0.4678 kJ/kgK$

$v_1 = v_{1f} + x v_{fg}$
$= 0.0007533 + 0.4(0.099867 - 0.0007533)$
$= 0.0404 m^3/kg$

$m = \frac{V}{v_1} = \frac{0.5}{0.0404} = 12.38 kg$

$P_2 = 400kPa$ }
$v_2 = v_1$ }

$v_f = 0.0007907 m^3/kg \qquad u_f = 63.62 kJ/kg$

$v_{fg} = 0.051201 m^3/kg \qquad u_{fg} = 171.45 kJ/kg$

$S_f = 0.24761 kJ/kgK \qquad S_{fg} = 0.67929 kJ/kgK$

$x_2 = \frac{0.0404 - 0.0007907}{0.051201 - 0.0007907}$

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