

IDEAL MIXING . IDEAL GASES

Ideal Gas $p_i = \frac{m_i R_i T}{V}$ $p_i = \frac{n_i \bar{R}_i T}{V}$

Ideal Mixing - Daltons Law $p_{\text{mix}} = \sum_i p_i(T_{\text{mix}}, V_{\text{mix}})$ (13-6)

$$\boxed{p_1}_{(T, V)} + \boxed{p_2}_{(T, V)} + \tilde{0} + \boxed{p_n}_{(T, V)} = \boxed{p_{\text{mix}}}_{(T, V)}$$

Ideal Gas $V_i = \frac{m_i R_i T}{p}$ $V_i = \frac{n_i \bar{R}_i T}{p}$

Ideal Mixing - Agamats Law $V_{\text{mix}} = \sum_i V_i(T_{\text{mix}}, p_{\text{mix}})$ (13-7)

$$\boxed{V_1}_{(T, p)} + \boxed{V_2}_{(T, p)} + \tilde{0} + \boxed{V_n}_{(T, p)} = \boxed{V_{\text{mix}}}_{(T, p)}$$

MIXTURES

$$m = \sum_i m_i \quad (13.1)$$

$$\text{mass fraction} = \frac{m_i}{m} = \frac{m_i}{\sum_i m_i}$$

mass = moles \times MWT

$$m = n \times \text{MWT} \quad (12.3)$$

$$\text{mole fraction, } y = \frac{n_i}{n} = \frac{n_i}{\sum_i n_i} \quad (13.2)$$

1 mole CO₂ + 1 mole N₂

	moles	molar analysis	MWT	weight	gravimetric analysis
CO ₂	1	50%	44	44 lbs	61.1%
N ₂	1	50%	28	28 lbs	38.9%
	2	100%		72lbs	

$$pV = nRT$$

$$n_i = \frac{p_i V_i}{RT_i}$$

$$\frac{n_i}{n} = \frac{p_i V_i}{RT_i} \frac{RT}{pv} = \frac{p_i}{p} \frac{V_i}{V} \frac{R T}{R T}$$

$$\frac{n_i}{n} = \frac{p_i}{p}$$

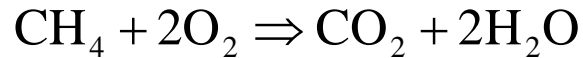
$$p_i v_i = RT_i$$

$$\frac{n_i}{n} = \frac{p_i}{p} = \frac{RT_i}{v_i} \frac{v}{RT}$$

$$\frac{n_i}{n} = \frac{v}{V_i}$$

COMBUSTION

Chemical Equation Balance is a Mass Balance



Mass Reactants = Mass Products

Mass Fuel + Mass Oxidizer = Mass Products of Combustion

Mass Reactant Carbon = Mass Product Carbon

$$\text{C} = \text{C}$$

Mass Reactant Hydrogen = Mass Product Hydrogen

$$\text{H}_4 = 2\text{H}_2$$

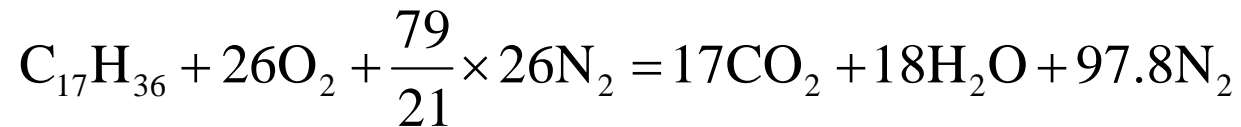
Mass Reactant Oxygen = Mass Product Oxygen

$$2\text{O}_2 = \text{O}_2 + 2\text{O}$$

Mass = moles \times Molecular Weight

Balance the equation for complete combustion of $C_{17}H_{36}$ in theoretical air.

Determine the the ratio of theoretical air per pound of $C_{17}H_{36}$.



assume 1 mole of fuel as the basis of calculation

$$\text{Carbon Balance} \quad 1C_{17} = 17C$$

$$\text{Hydrogen Balance} \quad H_{36} = 18H_2$$

$$\text{Oxygen Balance} \quad 26O_2 = 17O_2 + 18O$$

$$\text{Air Mass} = \text{moles} \times \text{Molecular Weight} = 26 \times 32 + 97.8 \times 28 = 3570 \text{ lbs/ lb mole fuel}$$

$$\text{Fuel Mass} = 17 \times 12 + 36 \times 1 = 240 \text{ lbs/lb mole fuel}$$

$$\text{Air Fuel Ratio} = \frac{3570}{240} = 14.87 \text{ lb air/lb fuel}$$

Overall Balance

$$\text{Mass Fuel} + \text{Mass Air} = \text{Mass Products}$$

$$240 + 3570 = 17 \times 44 + 97.8 \times 28 + 18 \times 18$$

$$3810. \text{ lbs} = 3810.4 \text{ lbs}$$

COMPLETE COMBUSTION - STOICHIOMETRIC COMBUSTION

All fuel is consumed and no oxidant remains

Only Theoretical Oxygen (Theoretical Air) is supplied

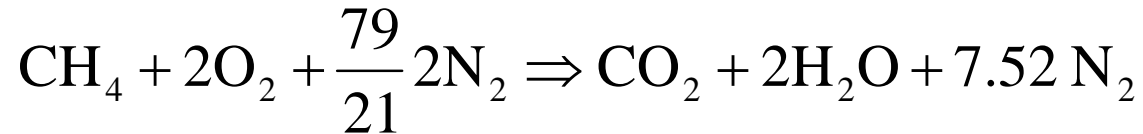
$$\% \text{ Theoretical Air} = \frac{\text{Actual Combustion Air}}{\text{Theoretical Combustion Air}}$$

$$\% \text{ Excess Air} = \frac{\text{Actual Combustion Air} - \text{Theoretical Air}}{\text{Theoretical Air}}$$

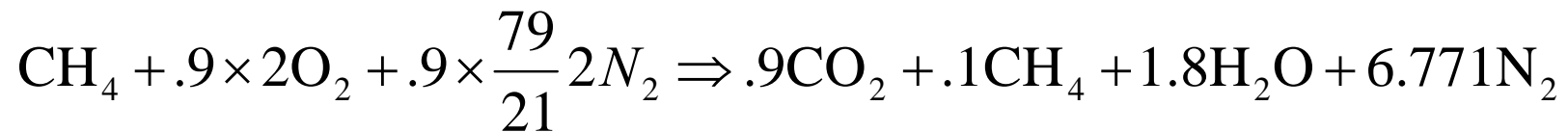
$$\% \text{ Excess Air} = \% \text{ Theoretical Air} - 100\%$$

Methane is burned with 90% Theoretical Air

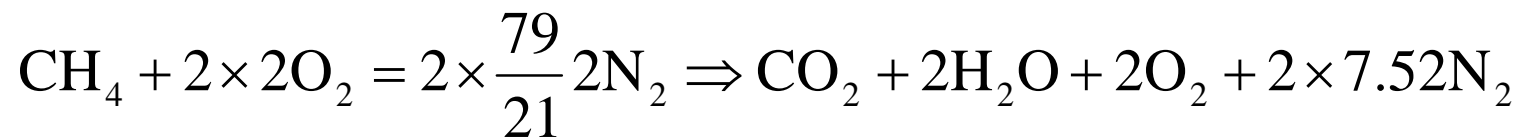
THEORETICAL AIR



90% THEROETICAL AIR (-10% EXCESS AIR)

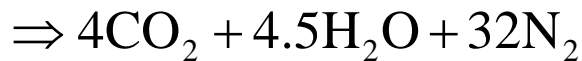


100% EXCESS AIR (200% THEORETCAL AIR)



What is the dew point temperature of the following products of combustion at 100 kPa?

How much water condenses if the products are cooled to 35 C?



$$36 \text{ moles} + 4.5 \text{ moles H}_2\text{O} = 40.5$$

$$y_v = \frac{n_v}{n} = \frac{p_v}{p}$$

$$p_v = \frac{4.5}{40.5} \times 100 = 11.11 \text{ kPa}$$

at $\phi = 100\%$

$$p_v = p_g = 11.11 \text{ kPa}$$

$$T(@ p_g = 11.11 \text{ kPa}) = T_{dp} = 47.74 \text{ C}$$

Cooled to 35C

$$y_v = \frac{n_v}{n} = \frac{p_v}{p}$$

$$\frac{n_v}{n + n_v} = \frac{p_v}{p}$$

at condensation $\phi = 100\%$

$$p_v = p_g$$

$$\frac{n_v}{n + n_v} = \frac{p_g @ 35 \text{ C}}{100 \text{ kPa}}$$

$$\frac{n_v}{36 + n_v} = \frac{5.6291}{100}$$

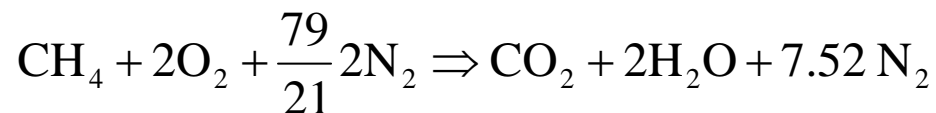
$$100 n_v = 5.6291 \times 36 + 5.6291 n_v$$

$$n_v = 2.147 \text{ moles vapor}$$

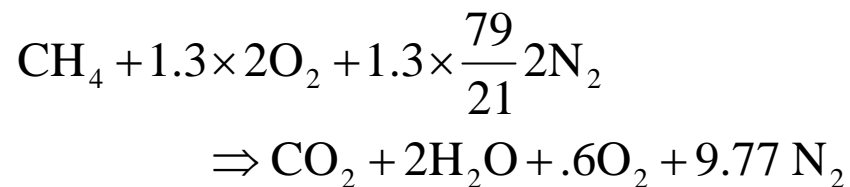
$$n_l = 4.5 - 2.147 = 2.35 \text{ moles liquid}$$

Determine the volumetric analysis of the gaseous products of combustion of methane burning with 30 % excess air After the products of combustion have cooled to 90 F.

THEORETICAL AIR



130% THEROETICAL AIR (30% EXCESS AIR)



at 90 F $p_v = p_g = .69904$ psia

$$y_{\text{H}_2\text{O}} = \frac{p_v}{p_{\text{products}}} = \frac{\text{moles vapor}}{\text{moles gas} + \text{moles vapor}}$$

$$\frac{p_v}{p_{\text{products}}} = \frac{m_v}{m_{\text{dry gas}} + m_v}$$

$$m_{\text{dry gas}} = 11.376 \text{ moles}$$

$$m_v = \frac{p_v \times m_{\text{dry gas}}}{p_{\text{products}} - p_v} = \frac{.69904 \times 11.376}{14.7 - .69904}$$

$$m_v = .568 \text{ moles vapor}$$

$$m_{\text{liquid}} = 2 - .568 = 1.432 \text{ moles}$$

$$\% = \frac{m_i}{m_{\text{gas}}} = \frac{m_i}{11.376 + .568}$$

$$\% \text{CO}_2 = 1/11.943 = 8.37\%$$

$$\% \text{H}_2\text{O} = .568/11.943 = 4.75\%$$

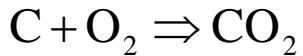
$$\% \text{O}_2 = .6/11.943 = 5.02\%$$

$$\% \text{N}_2 = 9.776/11.943 = 81.8\%$$

ENTHALPY OF FORMATION

heat absorbed or given off when a compound is formed from its elements

\bar{h}_f° , Table A – 26, A – 26E



$\bar{h}_f^\circ = -393,520 \text{ kJ/kmole}$ with, CO_2 @25 C

$\bar{h}_f^\circ = -169,300 \text{ BTU/lbmole}$, CO_2 @77 F

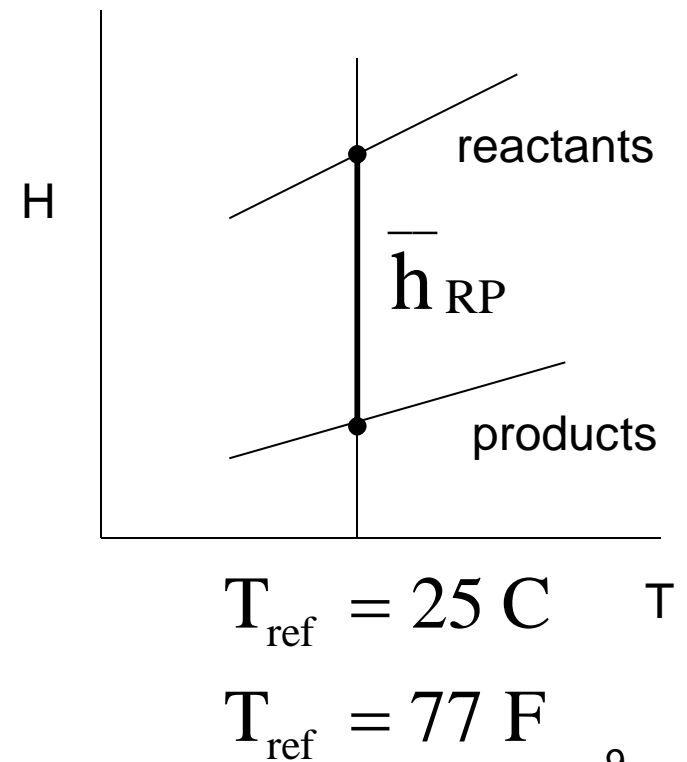
ENTHALPY OF COMBUSTION

$$\bar{h}_{\text{RP}} = \sum n \times \bar{h}_f^\circ_{\text{REACTANTS}} - \sum n \times \bar{h}_f^\circ_{\text{PRODUCTS}},$$

\bar{h}_f° Table A – 26

For the CO_2 reaction,

$$\bar{h}_{\text{RP}} = (1 \times 0 + 1 \times 0) - 1 \times (-393,300) = 393,300 \text{ kJ/kmole}$$

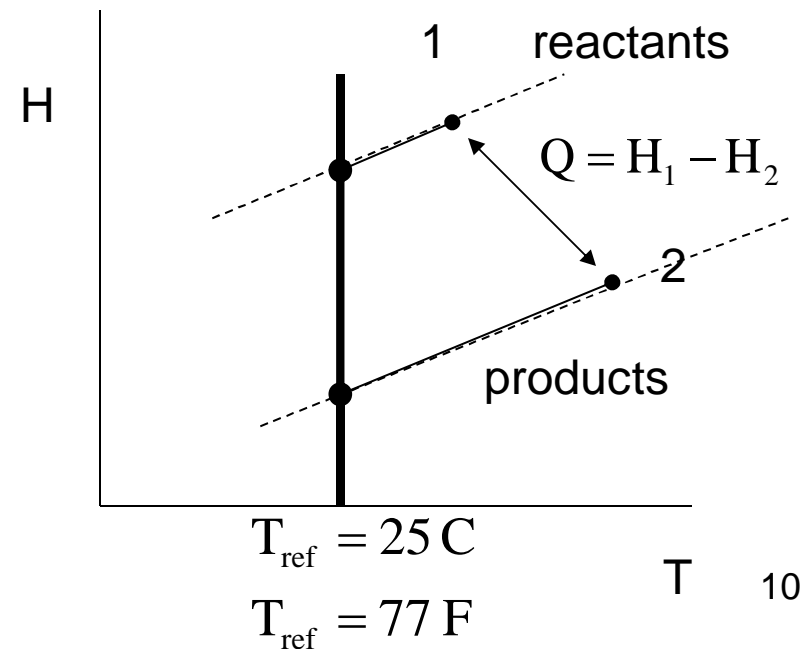
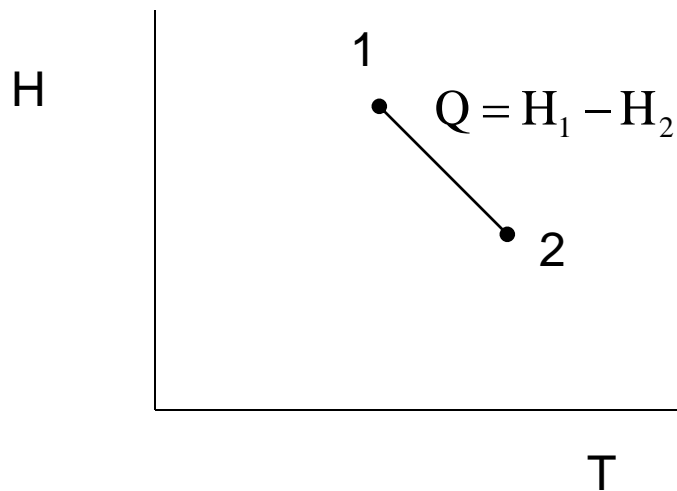


COMBUSTION ENERGY BALANCE

$$Q = H_{\text{reactants}} - H_{\text{products}}$$

$$Q = \sum_{\text{products}} \bar{n} \left(\bar{h}_f^{\circ} + \bar{h} \right) - \sum_{\text{reactants}} \bar{n} \left(\bar{h}_f^{\circ} + \bar{h} \right) \quad (13.19), \quad \bar{h}, \text{ Table A-23, A-23E}$$

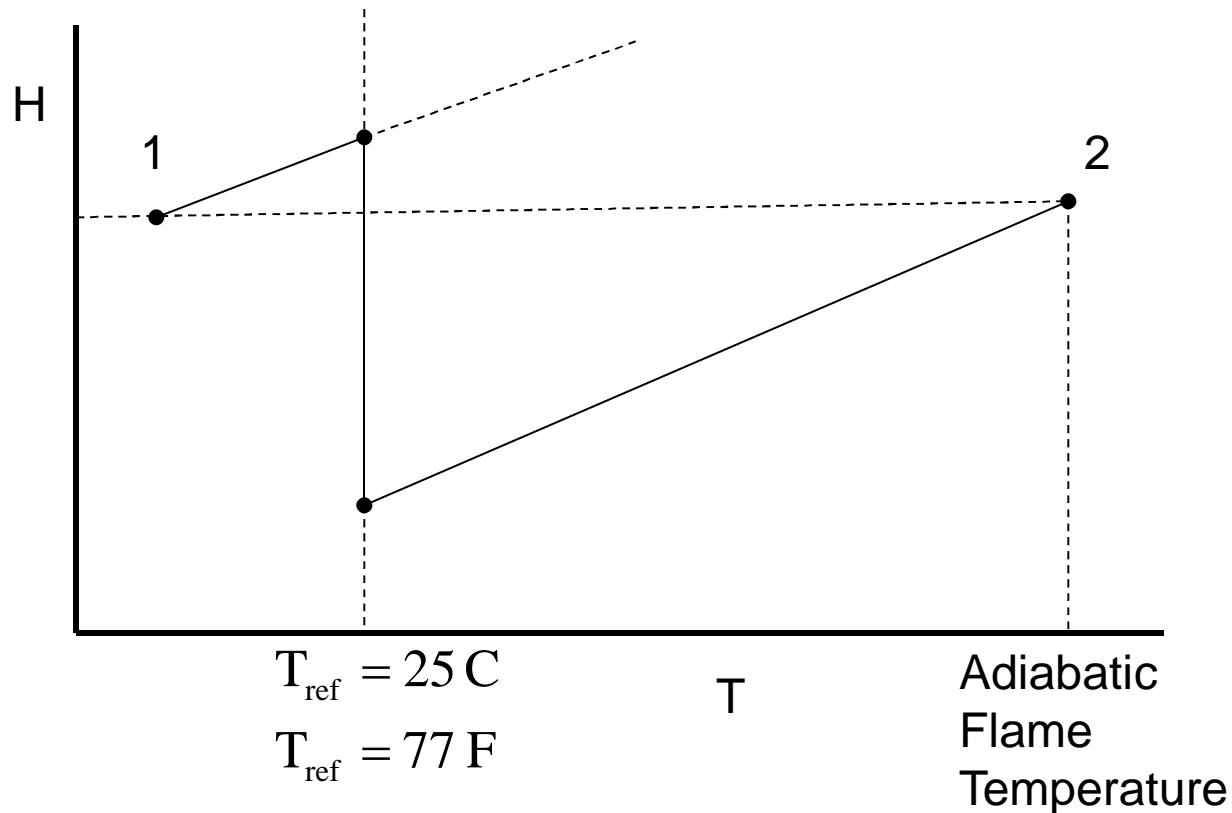
$$Q = \bar{h}_{\text{RP}} + \sum_{\text{products}} \bar{n} \left(\bar{h}_2 - \bar{h} @ T_{\text{ref}} \right) - \sum_{\text{reactants}} \bar{n} \left(\bar{h}_1 - \bar{h} @ T_{\text{ref}} \right)$$



ADIABATIC FLAME TEMPERATURE

$$Q = 0 = \bar{h}_{RP} + \sum_{\text{products}} \bar{n} \left(\bar{h}_2 - \bar{h} @ T_{\text{ref}} \right) - \sum_{\text{reactants}} \bar{n} \left(\bar{h}_1 - \bar{h} @ T_{\text{ref}} \right)$$

all the combustion energy remains in the products of combustion



Propane is burned in air at 25 C and 100. kPa. Combustion is complete. Products of combustion are at at 87 C. Determine the heat supplied and in kJ/ kmole and the adiabatic flame temperature ?

$$p_g @ 80C = 47.416 \text{ kPa}$$

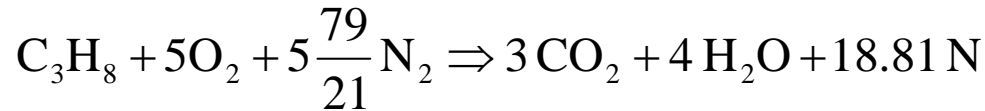
$$\frac{p_v}{p_{\text{atm}}} = \frac{n_v}{n}$$

$$p_v = 100 \times \frac{4}{25.81}$$

$$p_v = 15.49 \text{ kPa}$$

$$T_{\text{dp}} \cong 55 \text{ C}$$

no condensation



$$\bar{h}_{\text{RP}} = \sum n \times \bar{h}_f^{\circ} \text{ REACTANTS} - \sum n \times \bar{h}_f^{\circ} \text{ PRODUCTS}, \bar{h}_f^{\circ} \text{ Table A - 26}$$

React.	n	\bar{h}_f°	$n \times \bar{h}_f^{\circ}$	\bar{h}_{87C}	\bar{h}_{25C}	$n \times \bar{h}$
C_3H_8	1	-103,850	-103,850			
Prod.	n	\bar{h}_f°	$n \times \bar{h}_f^{\circ}$	\bar{h}_{87C}	\bar{h}_{25C}	$n \times \bar{h}$
CO_2	3	-393,520	-1,180,560.	11,748	9364	7152
$\text{H}_2\text{O}_{\text{gas}}$	4	-241,820	-967,280.	11,992	9904	8352
N_2	18.81	0	0	10,471	8669	33,896

$$\sum n = 25.81 \quad \bar{h}_{\text{RP}} = -2,043,990. \quad \sum \bar{h} = 49,400$$

$$Q = \bar{h}_{\text{RP}} + \sum \bar{h}$$

$$Q = -2,043,990. + 49,400 = 1,994,590. \text{ kJ/kmole}$$

Adiabatic Flame Temperature

@ 1020 K to 1040 K

$$\bar{c}_{p\text{CO}_2} = \frac{43,859 - 42,769}{20} = 54.5 \text{ kJ/kmole C}$$

$$\bar{c}_{p\text{H}_2\text{O}} = \frac{36,709 - 35,882}{20} = 41.35 \text{ kJ/kmole C}$$

$$\bar{c}_{p\text{N}_2} = \frac{30,784 - 30,124}{20} = 33 \text{ kJ/kmole C}$$

For adiabatic, $Q = 0$, all \bar{h}_{RP} goes into heating the products of combustion

$$\bar{h}_{\text{RP}} = \sum n \times \bar{h} = \sum n_i \bar{c}_{pi} \times (T - 25 \text{ C})$$

$$2,043,990 = (3 \times 54.5 + 4 \times 41.35 + 18.81 \times 33) \times (T_{\text{ad}} - 25 \text{ C})$$

$$2,043,990 = 949.63(T_{\text{ad}} - 25 \text{ C})$$

$$T_{\text{adiabatic}} = 2177.4 \text{ C}$$

Assuming initial atmospheric conditions (1 bar and 20 °C), the following table list the adiabatic flame temperature for various gases under constant pressure conditions. The temperatures mentioned here are for a stoichiometric fuel-oxidizer mixture (i.e. [equivalence ratio](#)). Note this is a theoretical flame temperature produced by a flame that loses no heat (i.e. closest will be the hottest part of a flame) where the combustion reaction is quickest. And where complete combustion occurs, so the closest flame temperature to this will be a non-smokey, commonly bluish flame

1. [^] The temperature equal to ≈ 3200 K corresponds to 50 % of [chemical dissociation](#) for CO_2 at pressure 1 atm. The latter one stays [invariant](#) for adiabatic flame and the carbon dioxide constitutes 97 % of total gas output in the case of [anthracite](#) burning in [oxygen](#). Higher temperatures will occur for reaction output while it going under higher pressure (up to 3800 K and above, see e.g. [Jongsup Hong a et](#))

Adiabatic flame temperature (constant pressure) of common gases/Materials			
Fuel	Oxidizer	T_{ad} (°C)	T_{ad} (°F)
Acetylene (C₂H₂)	air	2500	4532
Acetylene (C₂H₂)	Oxygen	3480	6296
Butane (C₄H₁₀)	air	1970	3578
Cyanogen (C₂N₂)	Oxygen	4525	8177
Dicyanoacetylene (C₄N₂)	Oxygen	4990	9010
Ethane (C₂H₆)	air	1955	3551
Hydrogen (H₂)	air	2210	4010
Hydrogen (H₂)	Oxygen	3200	5792 ^[1]
Methane (CH₄)	air	1950	3542
Natural gas	air	1960	3562 ^[2]
Propane (C₃H₈)	air	1980	3596
Propane (C₃H₈)	Oxygen	2526	4579
MAPP gas			
Methylacetylene (C₃H₄)	air	2010	3650
MAPP gas			
Methylacetylene (C₃H₄)	Oxygen	2927	5301
Wood	air	1980	3596
Kerosene	air	2093 ^[3]	3801
Light fuel oil	air	2104 ^[3]	3820
Medium fuel oil	air	2101 ^[3]	3815
Heavy fuel oil	air	2102 ^[3]	3817
Bituminous Coal	air	2172 ^[3]	3943
Anthracite	air	2180 ^[3]	3957
Anthracite	Oxygen	¹ 2900 ^[see 1]	¹ 5255

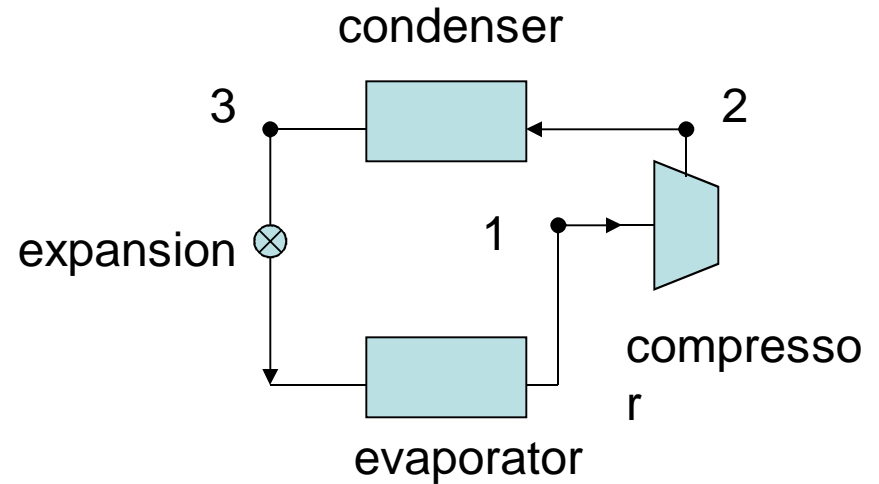
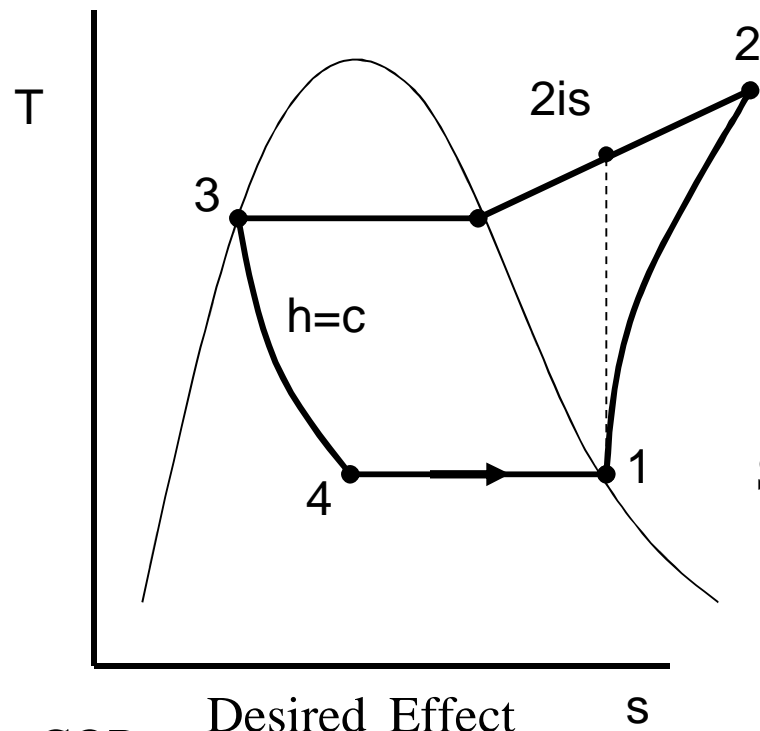
REVIEW

Chapters 10,11,12,13

All the review notes are
also given in the original
Chapter notes

Vapor Compression Refrigeration Cycle

Open systems, Steady flow



Steady Flow, Open System - region in space

Steady Flow Energy Equation

$$Q = m \times \left(u + pv + \frac{V^2}{2} + gh \right) + W_{\text{shaft}}$$

Compression Process, $1 \Rightarrow 2$, $Q = 0$, $W_{\text{in}} = m(h_2 - h_1)$

Condenser Process, $2 \Rightarrow 3$, $W = 0$, $Q_{\text{out}} = m(h_2 - h_3)$

Expansion Process, $3 \Rightarrow 4$, $Q = 0$, $W = 0$, $h_3 = h_4$

Evaporator Process, $4 \Rightarrow 1$, $W = 0$, $Q_{\text{in}} = m(h_1 - h_4)$

$$Q_{\text{in}} = m(h_1 - h_3)$$

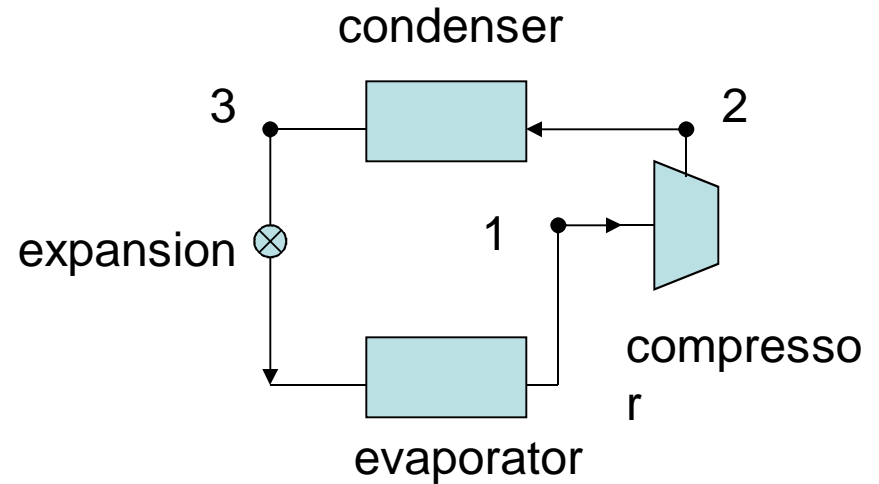
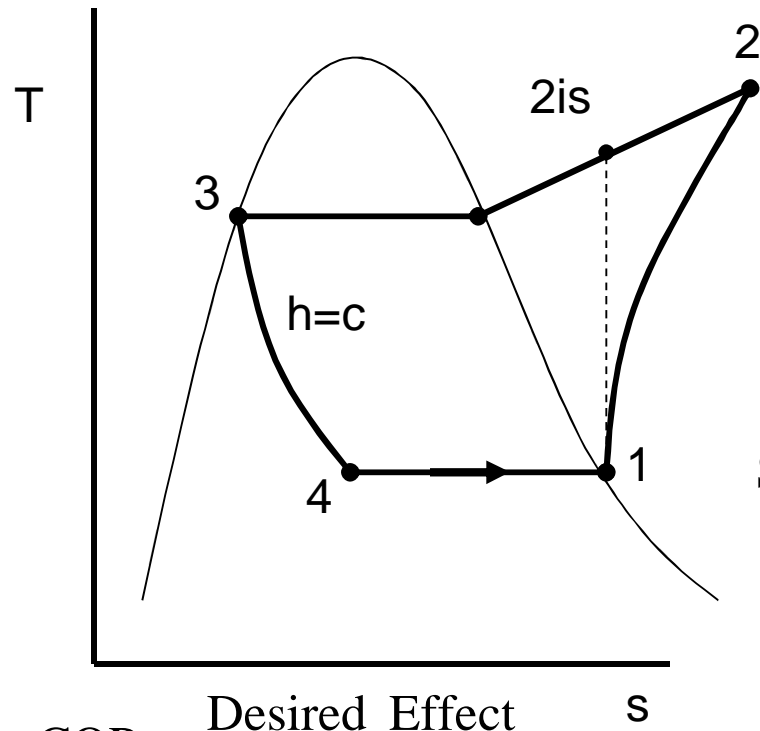
$$\text{COP} = \frac{\text{Desired Effect}}{\text{Effort Required}}$$

$$\text{COP}_{\text{ref}} = \frac{Q_{\text{in}}}{W}$$

$$\text{COP}_{\text{heat pumo}} = \frac{Q_{\text{out}}}{W}$$

Vapor Compression Refrigeration Cycle

Open systems, Steady flow



Steady Flow, Open System - region in space

Steady Flow Energy Equation

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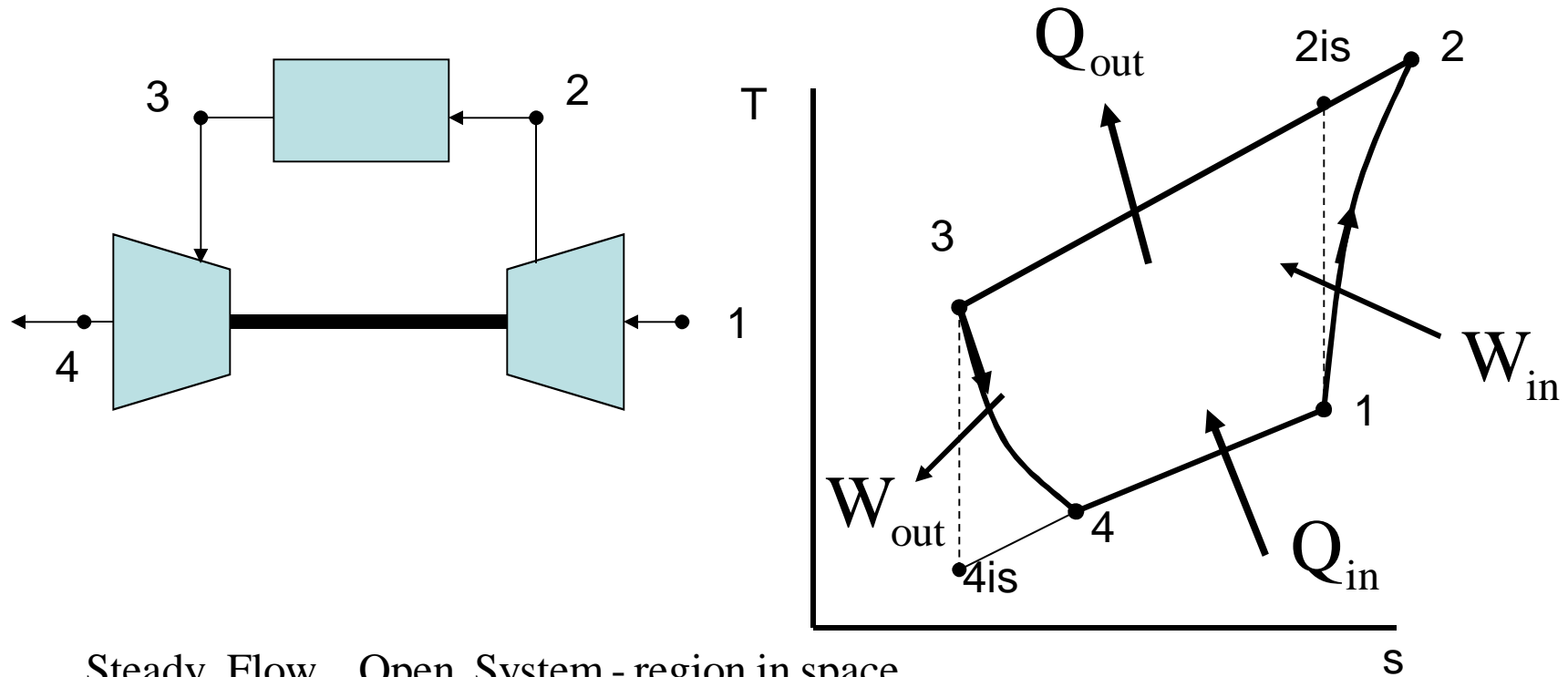
$$Q_{\text{in}} = m(h_1 - h_3)$$

$$\text{COP} = \frac{\text{Desired Effect}}{\text{Effort Required}}$$

$$\text{COP}_{\text{ref}} = \frac{Q_{\text{in}}}{W}$$

$$\text{COP}_{\text{heat pumo}} = \frac{Q_{\text{out}}}{W}$$

Reverse Brayton Refrigeration Cycle



Steady Flow, Open System - region in space

Steady Flow Energy Equation

$$Q = m \times \left(u + pv + \frac{V^2}{2} + gh \right) + W_{shaft}$$

Compression Process, $1 \Rightarrow 2$, $Q = 0$, $W_{in} = m(h_2 - h_1)$

Heat Rejection Process, $2 \Rightarrow 3$, $W = 0$, $Q_{out} = m(h_2 - h_3)$

Expansion Process, $3 \Rightarrow 4$, $Q = 0$, $W_{out} = m(h_3 - h_4)$

Heat Absorption Process, $4 \Rightarrow 1$, $W = 0$, $Q_{in} = m(h_1 - h_4)$

100 kPa, 270 K air is compressed with a pressure ratio of 4 in a 10.49 regenerated reversed Brayton Cycle. Air enters the regenerator at 300 K and leaves at 280 K. Find: a) the low temperature b) work/kg, c) capacity/kg, and d) COP.

$$T_3 = T_1 \left(\frac{p_2}{p_1} \right) = 270(4)^{.2857} = 369.55 \text{ K}$$

$$\text{a) } T_5 = T_4 \left(\frac{p_5}{p_4} \right) = 280 \left(\frac{1}{4} \right)^{.2857} = 204.57 \text{ K}$$

Regenerator Heat Balance

$$h_3 - h_4 = h_1 - h_6$$

$$c_p(T_3 - T_4) = c_p(T_1 - T_6)$$

$$T_6 = 270 - 310 + 280 = 240 \text{ K}$$

$$\text{b) } Q_{\text{out}} = c_p(T_2 - T_3)$$

$$Q_{\text{out}} = 1.005 \times (369.55 - 310) = 59.85 \text{ kJ/kg}$$

$$\text{c) } Q_{\text{in}} = c_p(T_6 - T_5)$$

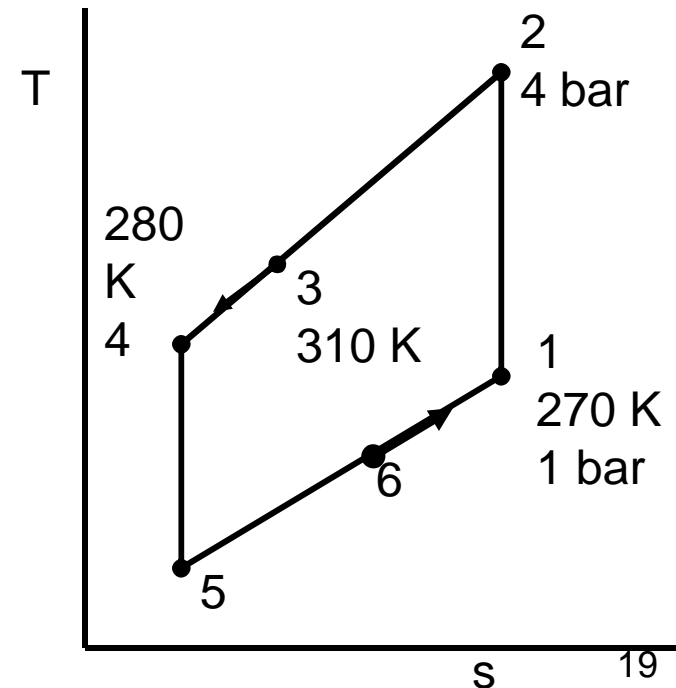
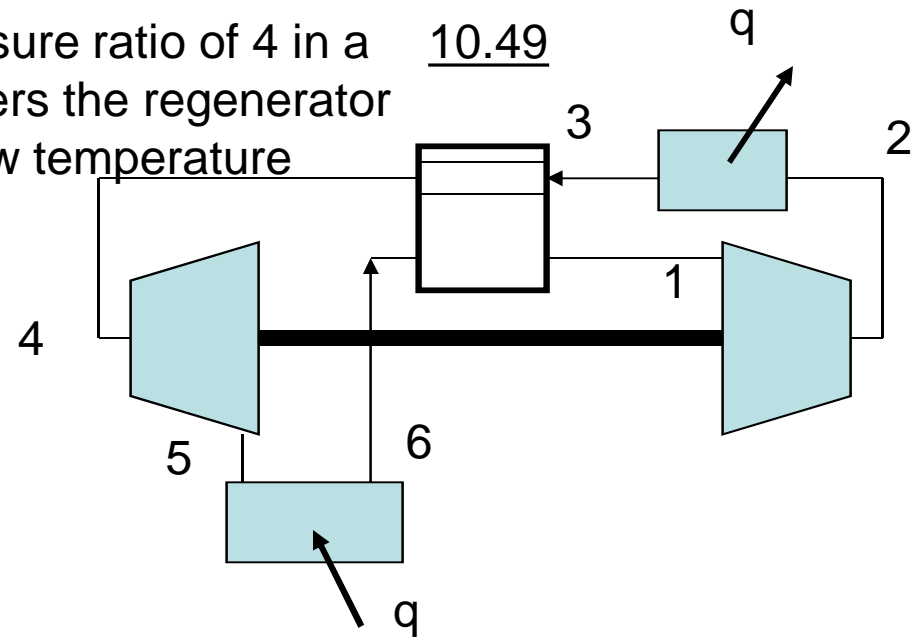
$$Q_{\text{in}} = 1.005 \times (240 - 204.57) = 35.61 \text{ kJ/kg}$$

$$\text{b) } w_{\text{net}} = w_c - w_t = c_p(T_2 - T_1) - c_p(T_4 - T_5)$$

$$w_{\text{net}} = 1.005(369.55 - 270) - 1.005(280 - 204.57)$$

$$w_{\text{net}} = 24.12 \text{ kJ/kg}$$

$$\text{d) } \text{COP}_{\text{ef}} = \frac{q_{\text{in}}}{w_{\text{net}}} = \frac{35.61}{24.12} = 1.48$$



100 kPa, 270 K air is compressed with a pressure ratio of 4 in a 10.49 regenerated reversed Brayton Cycle. Air enters the regenerator at 300 K and leaves at 280 K. Find: a) the low temperature b) work/kg, c) capacity/kg, and d) COP.

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$$T_6 = 270 - 310 + 280 = 240 \text{ K}$$

$$\text{b) } Q_{\text{out}} = c_p(T_2 - T_3)$$

$$Q_{\text{out}} = 1.005 \times (369.55 - 310) = 59.85 \text{ kJ/kg}$$

$$\text{c) } Q_{\text{in}} = c_p(T_6 - T_5)$$

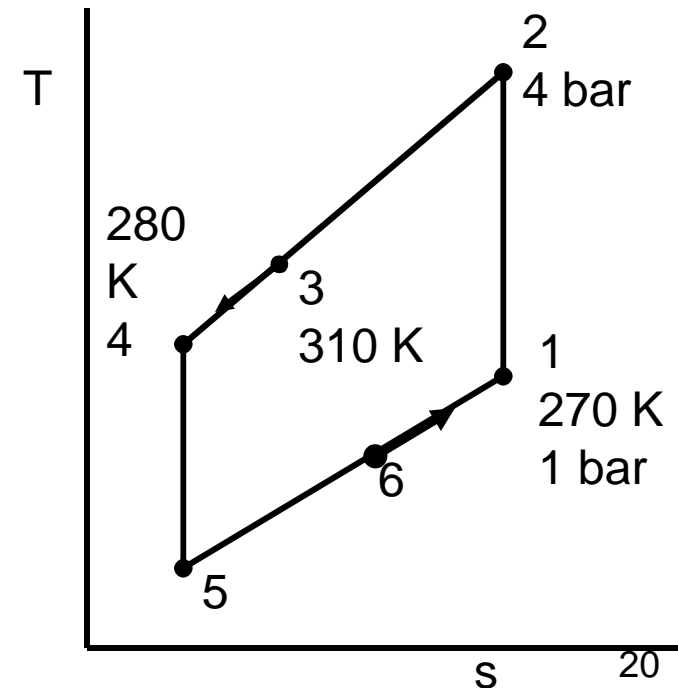
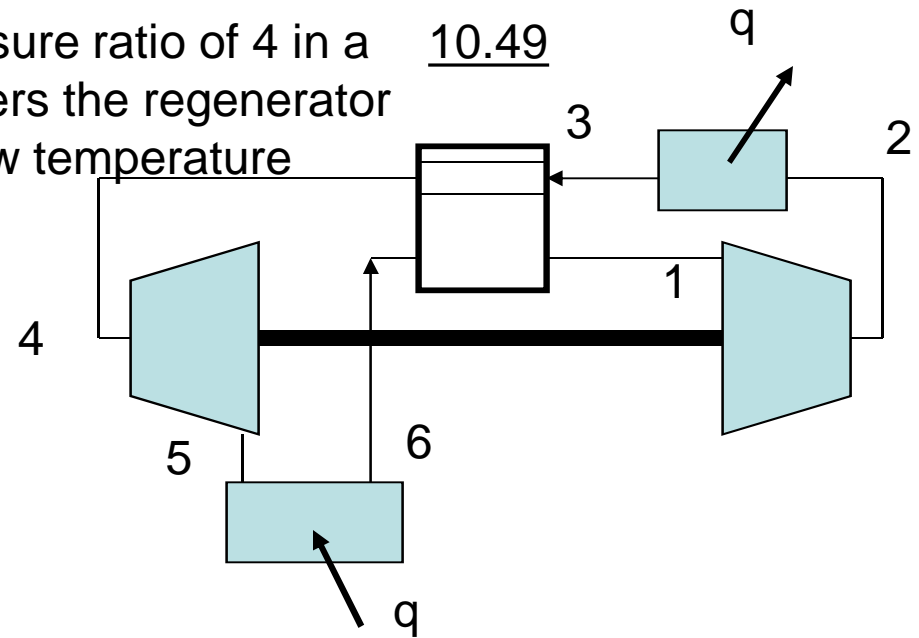
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$$\text{b) } w_{\text{net}} = w_c - w_t = c_p(T_2 - T_1) - c_p(T_4 - T_5)$$

$$w_{\text{net}} = 1.005(369.55 - 270) - 1.005(280 - 204.57)$$

$$w_{\text{net}} = 24.12 \text{ kJ/kg}$$

$$\text{d) } \text{COP}_{\text{ef}} = \frac{q_{\text{in}}}{w_{\text{net}}} = \frac{35.61}{24.12} = 1.48$$



Maxwell Relation Derivation

$$q = du + pdv \quad \text{First Law}$$

$$q = Tds \quad \text{Second Law}$$

Combining,

$$du = [T]ds + [-p]dv$$

Since u is a property, independent of path

and a function of any two other properties,

$u = u(s, v)$, du is an exact differential.

$$du = \left[\left(\frac{\partial u}{\partial s} \right)_v \right] ds + \left[\left(\frac{\partial u}{\partial v} \right)_s \right] dv$$

comparing the quantities in bracket,

$$T = \left(\frac{\partial u}{\partial s} \right)_v \quad (11.24) \quad \text{and} \quad -p = \left(\frac{\partial u}{\partial v} \right)_s \quad (11.25)$$

differentiating again,

$$\left(\frac{\partial T}{\partial v} \right)_s = \frac{\partial}{\partial v} \left(\frac{\partial u}{\partial s} \right)_v \quad \text{and}$$

$$\left(-\frac{\partial p}{\partial s} \right)_v = \frac{\partial}{\partial s} \left(\frac{\partial u}{\partial v} \right)_s$$

order does not affect the result of differentiation and,

$$\frac{\partial}{\partial v} \left(\frac{\partial u}{\partial s} \right)_v = \frac{\partial}{\partial s} \left(\frac{\partial u}{\partial v} \right)_s$$

substituting,

$$\left(\frac{\partial T}{\partial v} \right)_s = - \left(\frac{\partial p}{\partial s} \right)_v \quad (11.23)$$

12.65

a) $T_{db} = 24\text{ C}$, $T_{wb} = 16\text{ C}$

$$\omega(T_{wb}) = .622 \frac{p_g @ T_{wb}}{1.01325 - p_g @ T_{wb}}$$

$$\omega(T_{wb}) = .622 \frac{.01818}{1.01325 - .01818} = .0113$$

$$\omega(T_{db}) = \frac{\omega(T_{wb}) \times h_{fg}(T_{wb}) + c_p(T_{wb} - T_{db})}{h_g(T_{db}) - h_f(T_{wb})}$$

$$\omega(T_{db}) = \frac{.0113 \times (2530.8 - 67.19) + 1.005(16 - 24)}{2545.4 - 67.19}$$

$$\omega(T_{db}) = \frac{27.84 - 8.04}{2478.21} = .008$$

$$\omega = .622 \frac{p_v}{p - p_v}$$

$$.008 = .622 \frac{p_v}{1.01325 - p_v}$$

$$p_v = .0129$$

$$\phi = \frac{p_v}{p_g @ T_{db}} = \frac{.0129}{.02985} = 43.1\%$$

b) $T_{db} = 75\text{ F}$, $T_{wb} = 60\text{ F}$

$$\omega(T_{wb}) = .622 \frac{p_g @ T_{wb}}{14.7 - p_g @ T_{wb}}$$

$$\omega(T_{wb}) = .622 \frac{.2563}{14.7 - .2563} = .01104$$

$$\omega(T_{db}) = \frac{\omega(T_{wb}) \times h_{fg}(T_{wb}) + c_p(T_{wb} - T_{db})}{h_g(T_{db}) - h_f(T_{wb})}$$

$$\omega(T_{db}) = \frac{.01104 \times (1059.6) + .24(60 - 75)}{1094.25 - 28.08}$$

$$\omega(T_{db}) = \frac{11.69 - 3.6}{1066.17} = .00759$$

$$\omega = .622 \frac{p_v}{p - p_v}$$

$$.00759 = .622 \frac{p_v}{14.7 - p_v}$$

$$p_v = .1772$$

$$\phi = \frac{p_v}{p_g @ T_{db}} = \frac{.1772}{.4302} = 41.3\%$$

Specific and Relative Humidity

Basis of calculation - 1 lb_m dry air, 1 kgm dry air

Specific Humidity, Mass Fraction, $= \frac{\text{mass water vapor}}{\text{mass dry air}}$

$$\begin{aligned}
 &= \frac{\text{mass water vapor}}{\text{mass dry air}} = \frac{\left(\frac{pV}{RT}\right)_{\text{water}}}{\left(\frac{pV}{RT}\right)_{\text{air}}} = \frac{p_{\text{water}} \text{ MW } T_{\text{water}}}{p_{\text{air}} \text{ MW } T_{\text{air}}} \\
 &= \frac{18 p_w}{29(p_{\text{ambient}} - p_w)} \quad (12.43)
 \end{aligned}$$

Relative humidity $= \phi = \frac{\text{actual mass water vapor}}{\text{mass water vapor at saturation}}$

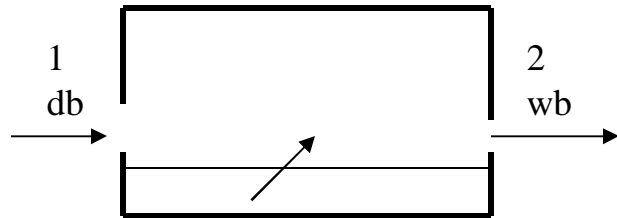
$$\phi = \frac{\text{actual mass water vapor}}{\text{mass water vapor at saturation}} = \frac{\left(\frac{pV}{RT}\right)}{\left(\frac{pV}{RT}\right)_{\text{saturation}}}$$

$$\phi = \frac{p_w}{p_g} = \frac{v_g}{v_w} \quad (12.44)$$

$$H = H_{\text{air}} + H_w \quad \text{BTU/lb}_{\text{dryair}}, \text{kJ/kg}_{\text{dryair}}$$

$$h = h_a + h_v = c_p T + h_v = c_p T + c_{pv} T$$

Adiabatic Saturation



basis of calculation 1 mass unit dry air

Steady Flow Energy Equation

$$E_{\text{air+vapor in}} + E_{\text{water added}} = E_{\text{air+vapor out}}$$

$$h_{a1} + h_{v1} + (h_{f2} - h_{f1}) = h_{a2} + h_{v2}$$

substituting,

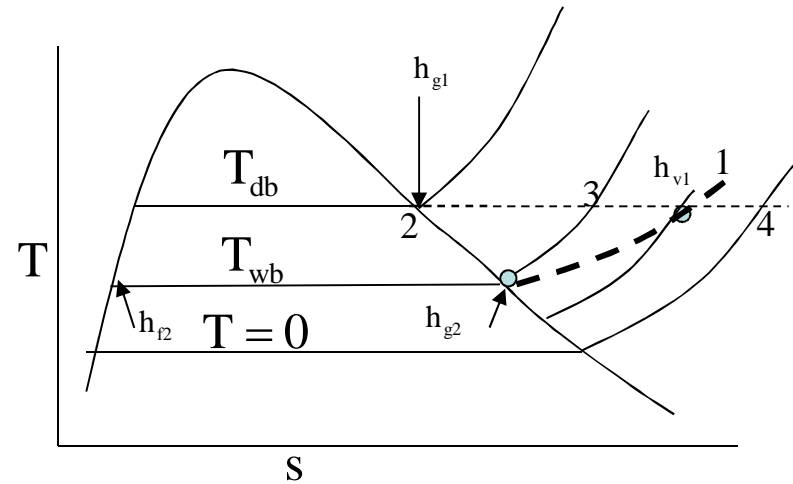
$$(h_{a1} - h_{a2}) = c_p (T_1 - T_2)$$

$$(h_{v2} - h_{f2}) = h_{fg}$$

$$c_p (T_2 - T_1) + (h_{v1} + h_{f2}) = h_{fg2}$$

$$1 = \frac{h_{fg2} - c_p (T_2 - T_1)}{(h_{v1} - h_{f2})}$$

$$= \frac{h_{fg2} - c_p (T_{db} - T_{wb})}{(h_{v db} - h_{f wb})}$$

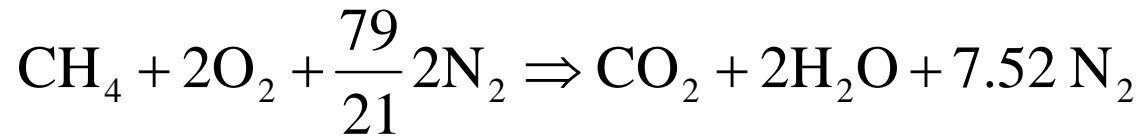


- 1) $h_{v1} = \text{saturation vapor enthalpy @ } (T = T_{db}, p = p_v)$
- 2) $h_{v1} = h_g @ T_{db}$
- 3) $h_{v1} = h_g @ T_{wb} + .45 * (T_{db} - T_{wb})$
- 4) $h_{v1} = h_g @ 0 F + .44(T_{db} - T_{wb}) = 1061.8 + .44(T_{db})$

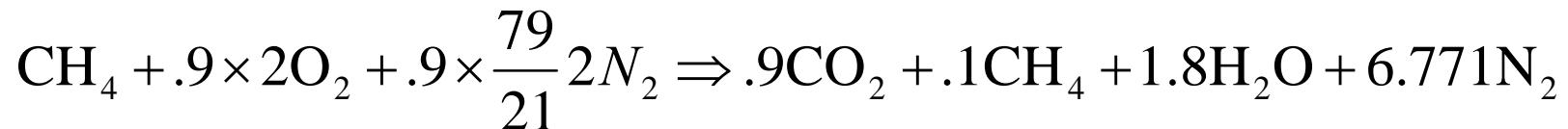
for 75F db, 70F wb

- | | |
|--|----------------|
| 1) $h_{v1} = 1094.07 \text{ BTU/lb dry air}$ | Exact |
| 2) $h_{v1} = 1093.83 \text{ BTU/lb dry air}$ | easiest to use |
| 3) $h_{v1} = 1093.91 \text{ BTU/lb dry air}$ | most accurate |
| 4) $h_{v1} = 1094.80 \text{ BTU/lb dry air}$ | |

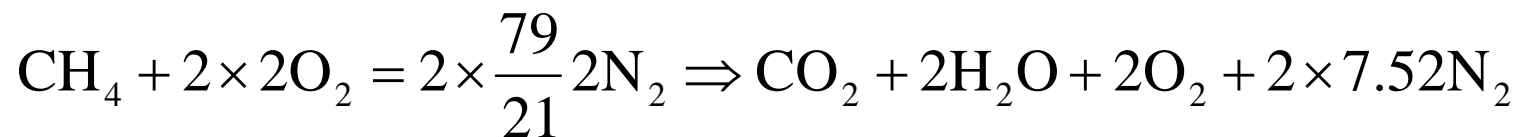
Methane is burned with 90% Theoretical Air
THEORETICAL AIR



90% THEROETICAL AIR (-10% EXCESS AIR)



100% EXCESS AIR (200% THEORETICAL AIR)



OPEN CYCLE ANALYSIS TOOL KIT

1. Properties

Ideal Gas

Gas Tables

Fluid Properties- steam, refrigerant tables

2. Processes

3. Energy Balances (First Law)

4. Component Performance

Turbine Efficiency

Compressor Efficiency

Heat Exchanger Effectiveness

Approach Temperature

5. Cycle Performance

Cycle Efficiency

Carnot Efficiency

Cycle COP

Carnot COP

IDEAL GAS $v = \frac{RT}{p}$, $V = m \frac{RT}{p}$ pg 107

$u = c_v \int dT = c_v (T_2 - T_1)$ pg 107

$h = c_p \int dT = c_p (T_2 - T_1)$

$s_2 - s_1 = c_v \ln \left(\frac{T_2}{T_1} \right) + R \ln \left(\frac{v_2}{v_1} \right)$ pg 231

$s_2 - s_1 = c_p \ln \left(\frac{T_2}{T_1} \right) - R \ln \left(\frac{p_2}{p_1} \right)$

GAS TABLE, A-22, A-22E

$v = \frac{RT}{p}$, $V = m \frac{RT}{p}$

h, u, s^o, p_r, v_r as functions of Temperature pg 112

$\frac{p_{r1}}{p_{r2}} = \frac{p_1}{p_2}$, $\frac{v_{r1}}{v_{r2}} = \frac{v_1}{v_2} = \frac{V_1}{V_2}$ pg 407

$s_2 - s_1 = s^o(T_2) - s^o(T_1) + R \ln \left(\frac{v_2}{v_1} \right)$ pg 230

$s_2 - s_1 = s^o(T_2) - s^o(T_1) - R \ln \left(\frac{p_2}{p_1} \right)$

1. PROPERTIES

FLUID PROPERTIES- steam, R-134a

Pressure Table-

v, u, h, s, T as functions of Pressure

Temperature Table-

v, u, h, s, P as functions of Temperature

$= v_f + x \times v_{fg}$, $x = \frac{v - v_f}{v_{fg}}$ pg 89

where v can be v, u, h or s

quality, $x = \frac{m_g}{m}$

Superheat Table-

$v, u, h,$ and s , as functions of T and p

Compressed Liquid Table-

$v, u, h,$ and s , as functions of T and p

2. PROCESSES

ISENTROPIC PROCESS –

Adiabatic, $Q = 0$, $S = 0$, Reversible

Ideal Gas – $pv^k = \text{constant}$

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} \quad \text{pg 257, 258, 417}$$

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

$$\frac{p_2}{p_1} = \left(\frac{v_1}{v_2}\right)^k$$

Real Gas

$$s_1 = s_2$$

3. ENERGY BALANCES

Open Systems

Steady Flow Equation form of First Law

$$Q = m \times \left(u + pv + \frac{V^2}{2} + gh \right) + W_{\text{shaft}} \quad \text{pg 142}$$

Open systems with $Q = 0$,

turbines, compressors pg 349

$$H_{\text{in}} = H_{\text{out}} + W, \quad W = m \times (h_1 - h_2)$$

pumps pg 270, 352

$$W = m \times (h_1 - h_2) = v(p_2 - p_1)$$

Open systems with $W = 0$,

heat exchangers, boiler, condensers,

feed water heaters pg 350

$$H_{\text{in}} = H_{\text{out}} + Q, \quad Q = m \times (h_1 - h_2)$$

Open systems with W and $Q = 0$,

throttling process, valves pg 158

$$H_{\text{in}} = H_{\text{out}}, \quad h_1 = h_2$$

Heat Exchangers

$$Q_{\text{cold fluid}} = Q_{\text{hot fluid}}$$

$$m_{\text{cold}} \times (h_{\text{cold out}} - h_{\text{cold in}}) = m_{\text{hot}} \times (h_{\text{hot out}} - h_{\text{hot in}})$$

Mixing

$$m_1 + m_2 = m_3$$

$$m_1 h_1 + m_2 h_2 = m_3 h_3$$

For Cycle

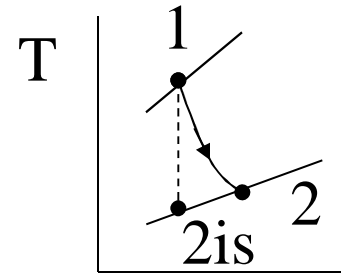
$$\sum_{\text{cycle}} Q = \sum_{\text{cycle}} W \quad \text{cycle} = \frac{W_{\text{net}}}{Q_{\text{in}}}$$

4. COMPONENT PERFORMANCE

TURBINE EFFICIENCY

$$\text{TURBINE} = \frac{W_{\text{actual}}}{W_{\text{isentropic}}} \quad \text{pg 261,262,358,433}$$

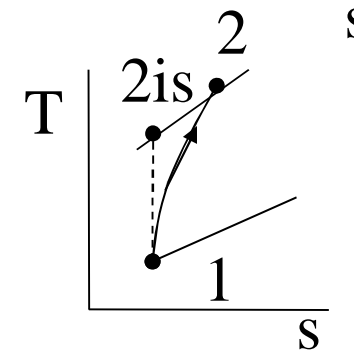
$$\text{TURBINE} = \frac{h_1 - h_2}{h_1 - h_{2\text{ isentropic}}}$$



COMPRESSOR AND PUMP EFFICIENCY

$$\text{COMPRESSOR} = \frac{W_{\text{isentropic}}}{W_{\text{actual}}} \quad \text{pg 263,359,433}$$

$$\text{COMPRESSOR} = \frac{h_{2\text{ isentropic}} - h_1}{h_2 - h_1}$$



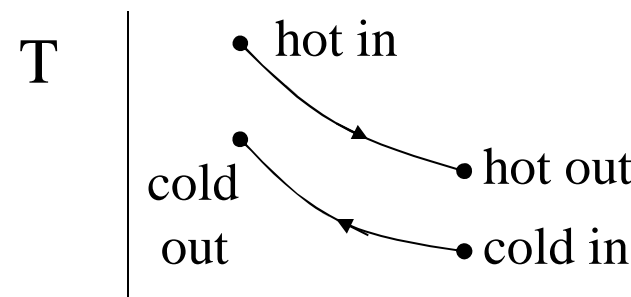
HEAT EXCHANGER EFFECTIVENESS

$$= \frac{\text{Actual } Q}{\text{Maximum } Q} \quad \text{pg 425,426}$$

$$= \frac{h_{\text{hot in}} - h_{\text{hot out}}}{h_{\text{hot in}} - h_{\text{cold in}}} = \frac{h_{\text{cold out}} - h_{\text{cold in}}}{h_{\text{hot in}} - h_{\text{cold in}}}$$

APPROACH TEMPERATURE

$$T_{\text{hot in}} - T_{\text{cold out}} \quad \text{and} \quad T_{\text{hot out}} - T_{\text{cold in}}$$



5. CYCLE PERFORMANCE

CYCLE EFFICIENCY

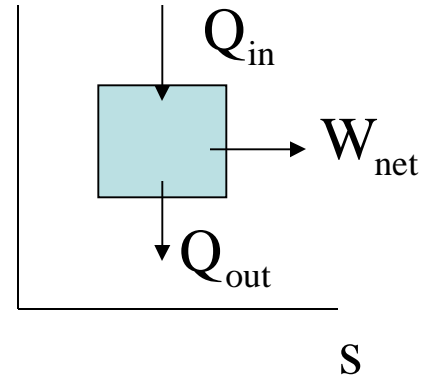
$$W = Q_{in} - Q_{out}$$

$$CYCLE = \frac{W_{net}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} \quad \text{pg 63, 350}$$

$$CYCLE = 1 - \frac{Q_{out}}{Q_{in}}$$

$$CARNOT \text{ CYCLE} = \frac{T_H - T_L}{T_H} = 1 - \frac{T_L}{T_H} \quad \text{pg 205}$$

T



CYCLE COEFFICIENT OF PERFORMANCE

$$COP_{refrigeration} = \frac{Q_{in}}{W} = \frac{Q_{in}}{Q_{in} - Q_{out}} \quad \text{pg 206}$$

$$COP_{heatpump} = \frac{Q_{out}}{W} = \frac{Q_{out}}{Q_{in} - Q_{out}}$$

$$COP_{CARNOT \text{ refrigeration}} = \frac{T_L}{T_H - T_L}$$

$$COP_{CARNOT \text{ heat pump}} = \frac{T_H}{T_H - T_L}$$

T

