Nov. 9

Air
50°C
$\phi = 0.40$
100 kPa
1 kg dry air

(a) $P_v = ?$ 40% of P_g.

$$P_v = \phi P_g = (0.4)(12.343\text{ kPa}) = 4.94\text{ kPa}$$

$\nearrow P_g$ @ 50°C

(b) $$\omega \overset{?}{=} \frac{0.622 P_{\cancel{g}v}}{P - P_{\cancel{g}v}} = \frac{0.622(4.94)}{100 - 4.94} = 0.0323 \frac{\text{kg H}_2\text{O}}{\text{kg dry air}}$$

(c) What would ω be is air were saturated?

$$\omega_{sat} = \frac{0.622 P_g}{P - P_g} = \frac{0.622(12.343)}{100 - 12.343} = 0.0876 \frac{\text{kg H}_2\text{O}}{\text{kg dry air}}$$

$\phi = \frac{\omega}{\omega_{sat}}$? No $\frac{0.0323}{0.0876} = 0.37$, not 0.40.

(d) If you cool the air, at which point does condensation begin?

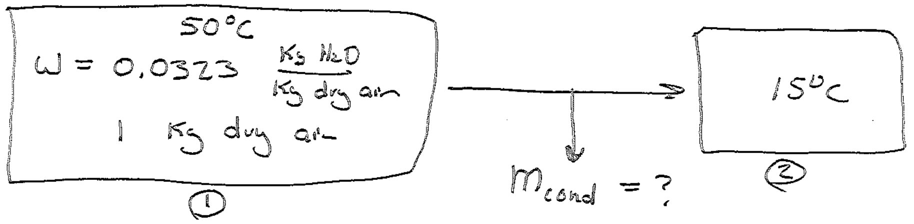
What changes as we cool?

ω - No
φ - Yes → 100%
P_v - No

$$P_v = \phi P_g$$

$$4.94 = (1.0)(P_g) \longrightarrow T_{sat} = 32.5°C \Rightarrow \boxed{\text{Dew Point}}$$

(e) Continue cooling to 15°C, how much condenses?



$$m_{v,1} = m_{v,2} + m_{cond}$$

- Approach is to figure out how much water the 15°C air can hold and look for difference

P_g @ 15°C

$$\omega_{sat} = \frac{0.622 P_g}{P - P_g} = \frac{0.622[1.7051\text{ kPa}]}{100 - 1.7051} = 0.0108 \frac{\text{kg H}_2\text{O}}{\text{kg dry air}}$$

$$m_{cond} = \Delta\omega = 0.0323 - 0.0108 = 0.0215 \frac{\text{kg H}_2\text{O condensed}}{\text{kg dry air}}$$

Last point: To get total mass in a box:

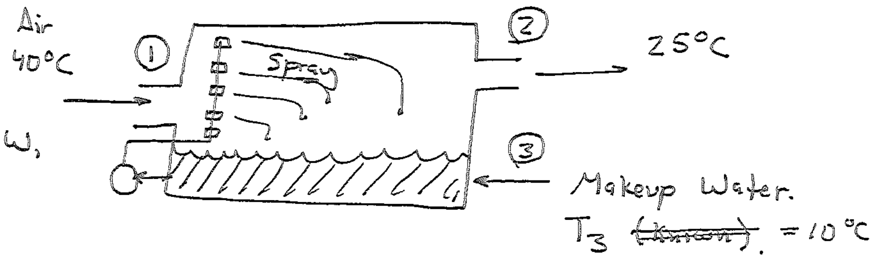
$$m = m_a + m_v = m_a\left[1 + \frac{m_v}{m_a}\right] = m_a[1 + \omega]$$

$$\Longrightarrow \boxed{\frac{\text{Total mass}}{\text{Mass Dry Air}} = 1 + \omega}$$

$\Rightarrow$ Total mass of original box = $1+\omega$ = $\underline{1.0323 \text{ Kg}}$

Now shift to energy equation:

Develop 1st law around an example: Adiabatic Humidifier. – [Swamp Cooler]



Notes: ⓐ Spray is so fine that exit air is saturated

ⓑ Globally

$$\boxed{\text{Energy Needed to Evap. Water}} \xrightarrow{\text{Comes from}} \boxed{\text{Energy Given up by air on cooling}}$$

ⓒ If incoming air is wet, no cooling!

ⓓ Set up and run, read $T_2 = 25°C \longrightarrow$ Get ω_1

Conservation of Mass – Do for air and water separately.

Air: $\dot{m}_{a,1} = \dot{m}_{a,2} = \dot{m}_a$ (constant),

Water: $\dot{m}_{v,1} + \dot{m}_3 = \dot{m}_{v,2}$

but $\dot{m}_v = \omega \dot{m}_a$ $\left[\frac{\text{Kg H}_2\text{O}}{\cancel{\text{Kg dry air}}}\right]\left[\frac{\cancel{\text{Kg dry air}}}{\text{s}}\right]$

$\omega_1 \dot{m}_a + \dot{m}_3 = \omega_2 \dot{m}_a$ or $\boxed{\dot{m}_3 = \dot{m}_a(\omega_2 - \omega_1)}$

First Law: Flow System: $\cancelto{0}{\dot{Q}} - \cancelto{0}{\dot{W}} = \dot{H}_2 - \dot{H}_1 - \dot{H}_3$

$$\Rightarrow \quad \Sigma \dot{m}_i h_i = \Sigma \dot{m}_e h_e$$

$$\dot{m}_a h_{a,1} + \dot{m}_{v,1} h_{v,1} + \dot{m}_3 h_3 = \dot{m}_a h_{a,2} + \dot{m}_{v,2} h_{v,2}$$

Divide by $\dot{m}_a$

$$h_{a,1} + \underbrace{\frac{\dot{m}_{v,1}}{\dot{m}_a}}_{\omega} h_{v,1} + \underbrace{\frac{\dot{m}_3}{\dot{m}_a}}_{\omega_2 - \omega_1} h_3 = h_{a,2} + \underbrace{\frac{\dot{m}_{v,2}}{\dot{m}_a}}_{\omega_2} h_{v,2}$$

$$\underline{\left[h_{a,1} + \omega_1 h_{v,1}\right]} + (\omega_2 - \omega_1) h_3 = \underline{\left[h_{a,2} + \omega_2 h_{v,2}\right]}$$

We will see later that the bracketed terms can by looked up on the psychrometric chart!

⇒ Since ΔT is small in these applications, it's OK to use $h_{a,1} = C_{p,a} T_1$

$$\left[C_{p,a} T_1 + \omega_1 h_{v,1}\right] + (\omega_2 - \omega_1) h_3 = \left[\dot{C}_{p,a} T_2 + \omega_2 h_{v,2}\right]$$

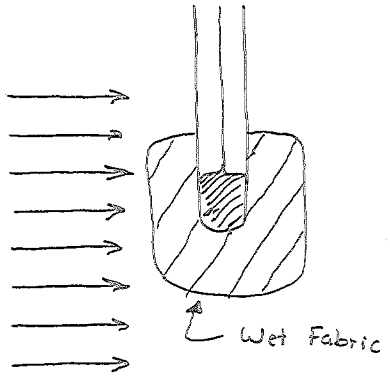
$$[1.005][40°C] + \omega_1 \underbrace{[2574.3]}_{\text{Sat vapor @ } T_1} + (\overset{\downarrow}{0.02036} - \omega_1)\underbrace{(42.01)}_{h_f \text{ @ } 10°C} = [1.005][25] + [0.02036][2547.2]$$

$$\omega_2 = \omega_{sat}(25°C) = \frac{0.622 P_g}{P - P_g} = \frac{(0.622)(3.169 \text{ KPa})}{100 - 3.169 \text{ KPa}} = 0.02036 \frac{\text{Kg H}_2\text{O}}{\text{Kg dry air}}$$

Solve: $\omega_1 = 0.01486 \frac{\text{Kg H}_2\text{O}}{\text{Kg dry air}}$

$$\Rightarrow \phi_1 = \frac{\omega_1 P}{(0.622 + \omega_1) P_{g,1}} = \frac{[0.01486][100]}{(0.622 + 0.01486)\underbrace{(7.384)}_{P_g \text{ @ } 40°C}} = \underline{\underline{31.6\%}}$$

How to get in practice? Wet bulb temperature:



- Water evaporates
- Cools liquid
- This reduces P_g, evap rate
  → Reach steady state

Heat supplied by air = heat lost by evaporation

Nov 14

Run @ 8:30 am.

$T_{WB} = 42°F = 5.6°C$

$T = 47°F = 8.3°C$

$$\left[C_{p,a} T_1 + \omega_1 h_{v,1}\right] + (\omega_2 - \omega_1) h_f = \left[C_{p,a} T_2 + \omega_2 h_{v,2}\right]$$

$$(1.005)(8.3) + \omega_1 (2516.7) + (0.00571 - \omega_1)(23.51) = [1.005][5.6] + [0.00571][2511.7]$$

$$\Rightarrow \omega_1 = 0.00461 \frac{\text{Kg H}_2\text{O}}{\text{Kg dry air}} \Rightarrow \phi_1 = 67\%$$

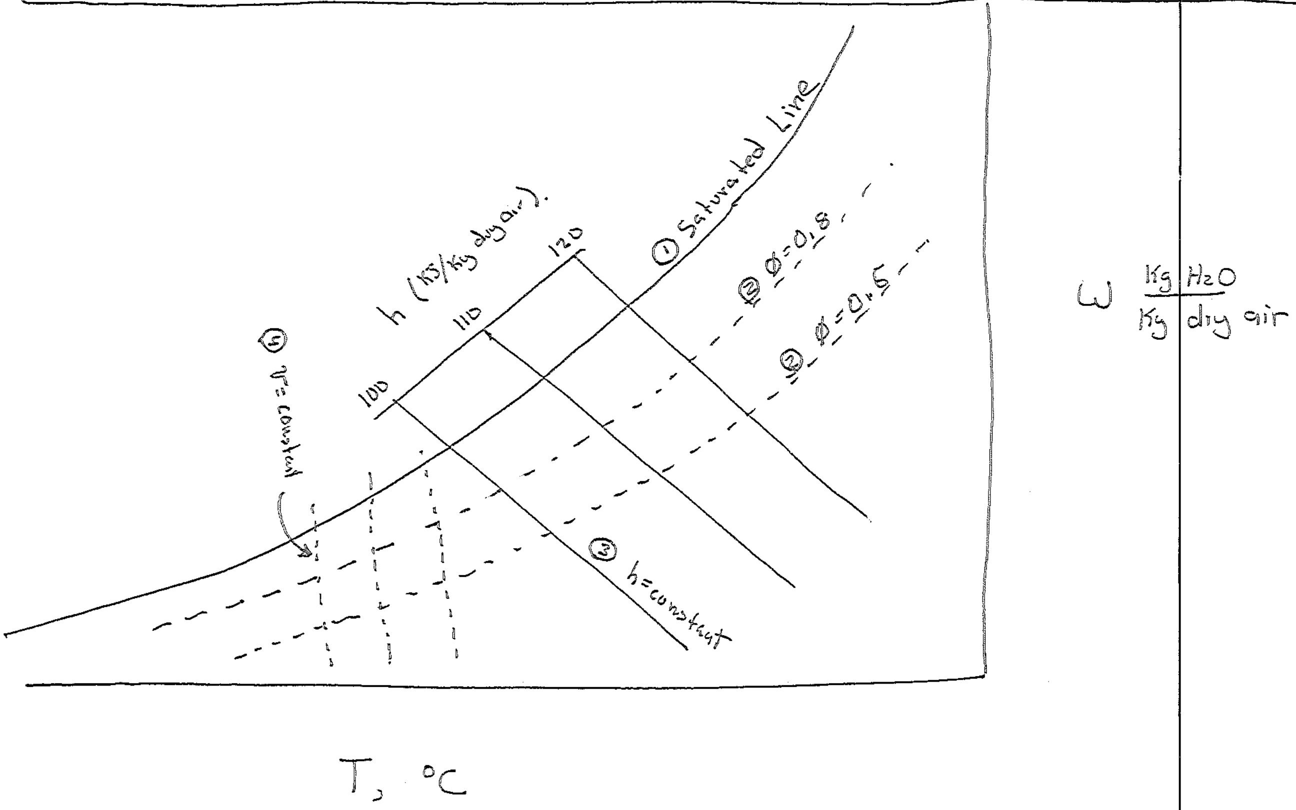
Next, run in my office: $T_{WB} = 57°F = 13.9°C$
$T = 74°F = 23.3°C$

$\omega_1 = 0.0062 \frac{Kg\ H_2O}{Kg\ dry\ air}$, $\phi_2 = 34\%$

⇒ Inside humidity ratio a little higher, & but relative humidity <u>much</u> lower.

Psychrometric Chart (Fig A-9) provides a tool to automate those calculations.

WORKS ONLY FOR 1 ATM = 101.325 KPa ⇒ OTHERWISE MUST USE EQUATIONS



Main Features

① Saturation Line: $T \longrightarrow P_g \Rightarrow \omega_{sat} = \frac{0.622 P_g}{101 - P_g}$

⇒ Choose a lot of T's, and draw line.

② Lines of constant φ:

$$\left.\begin{array}{c} T \longrightarrow P_g \\ \text{Vary } \phi\ (0.1, 0.2, \ldots) \end{array}\right\} \quad \omega = \frac{0.622 \phi P_g}{101 - \phi P_g}$$

For each T, pick φ = 0.1, 0.2, etc. and get corresponding ω.
⇒ Then plot.

③ Lines of constant h:

$$h = h_a + \omega h_v = C_{P,a} T + \omega h_v$$

Solve for $\omega = \frac{h - C_{P,a} T}{h_v}$

To draw line for h = 100 kJ/kg dry air, go

$$\omega = \frac{100 - c_{p,a} T}{h_v}$$

Pick T ⟶ h_v
⇒ Get ω that corresponds to this T
⇒ Draw h line.

④ v = constant lines - ideal gas:

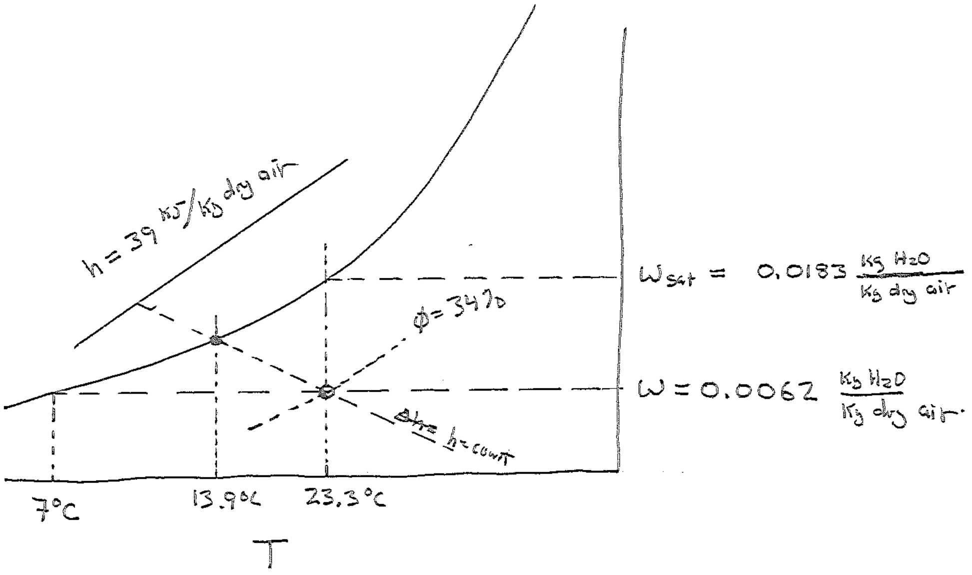
Chart has two roles:

① Given two ~~pro~~ independent properties, can get all others.
$T, T_{WB}, T_{DP}, \phi, h, v, \omega$

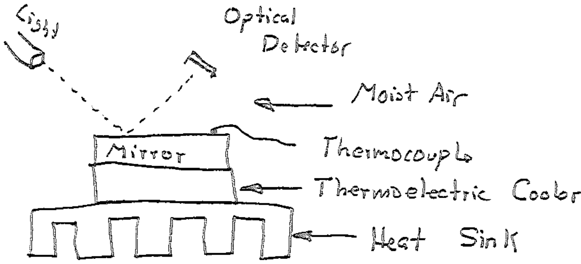
② Easy way to visualize processes

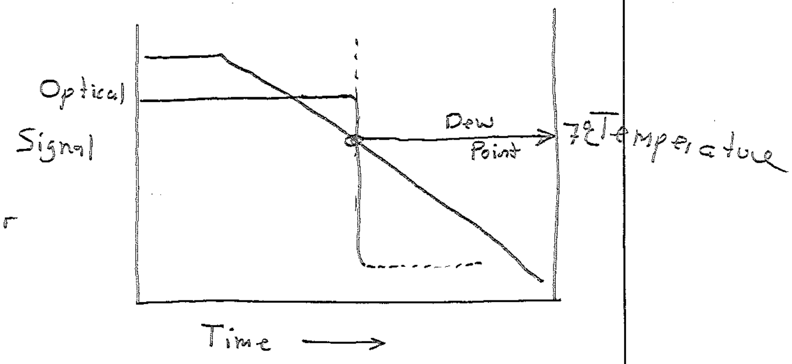
Must use equations if (a) $P \neq 1\,atm$
(b) Fall off chart.

Example: Ran sling psychrometer: $T = 23.3°C$
$T_{WB} = 13.9°C$



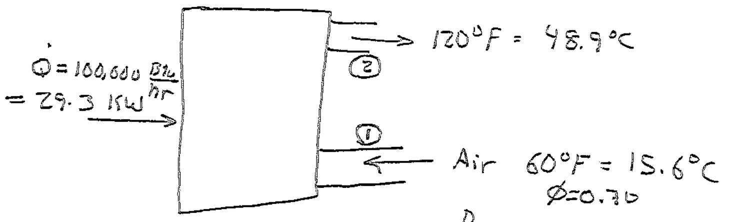
A different method:





Some examples of using the chart:

- Simple heating and cooling:



$\phi = ?$

$\dot m_a = ?$

First Law: ~~$\dot m_a h$~~ $\dot Q - \cancel{\dot W}^{\,0} = \Sigma \dot m_e h_e - \Sigma \dot m_i h_i$

$$\dot Q = \dot m_{a} h_{a,2} + \dot m_{v,2} h_{v,2} - \dot m_{a} h_{a,1} - \dot m_{v,1} h_{v,1}$$

here $\dot m_a$ is constant, ~~so~~ and $\dot m_v$ is constant

$$\dot Q = \dot m_a\left[\underbrace{\left(h_{a,2} + \underbrace{\frac{\dot m_{v,2}}{\dot m_a}}_{\omega} h_{v,2}\right)}_{h_2} - \underbrace{\left(h_{a,1} + \underbrace{\frac{\dot m_v}{\dot m_a}}_{\omega} h_{v,1}\right)}_{h_1}\right] \Longrightarrow \omega_1 = \omega_2$$

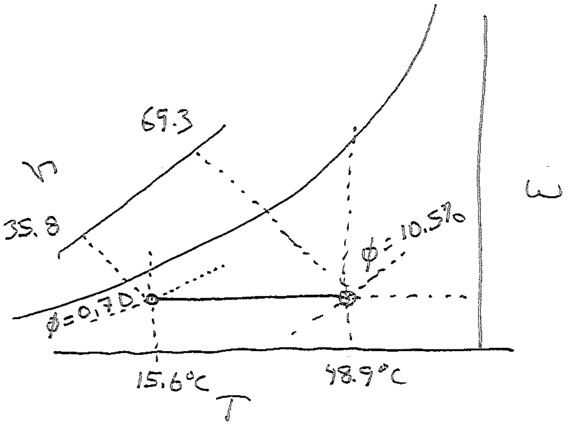
1) Via equation: $h_a = c_{p,a} T$ $h_v = h_g$ @ 48.9 and 15.6°C

$\Longrightarrow \dot m_a$

~~$\phi_2 = \frac{\omega P}{(0.622+\omega}$~~ $\omega = \dfrac{0.622\,\phi P_g}{P - \underset{\uparrow\ .7}{\phi} \underset{\nwarrow}{P_g}}$ @ 15.6°C

Then $\phi_2 = \dfrac{\omega P}{(0.622+\omega)P_g}$ ← @ 48.9°C

2) Via chart:

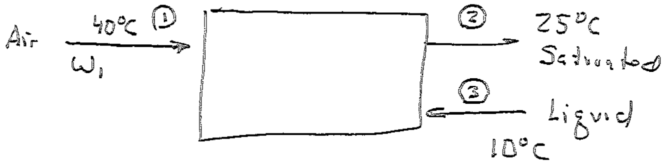


$\dot Q = \dot m_a (h_2 - h_1)$

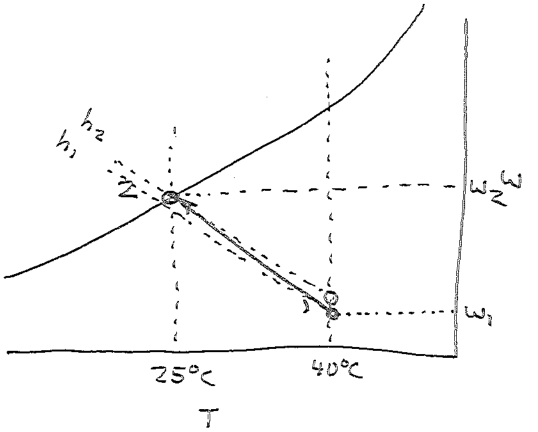
$29.3\ kW = \dot m_a \left(69.3 - 35.8\ \frac{kJ}{kg\ dry\ air}\right)$

$\dot m_a = 0.87\ \frac{kg\ dry\ air}{s}$

- Next, our adiabatic saturator:



First Law: $$\underbrace{\left[h_a + \omega h_v\right]_1}_{h_1} + (\omega_2-\omega_1)h_3 = \underbrace{\left[h_a+\omega h_v\right]_2}_{h_2}$$



Two approaches - Simple and tough but correct.

1) Simple: Neglect the h of the inlet liquid stream

$\Rightarrow h_2 = h_1$

2) Tough, but more correct. Iterate.

(a) Let $h_2 = h_1 \longrightarrow$ get ω_1

$\Rightarrow$ (b) $h_1 + (\omega_2-\omega_1)h_3 = h_2$

New, lower.

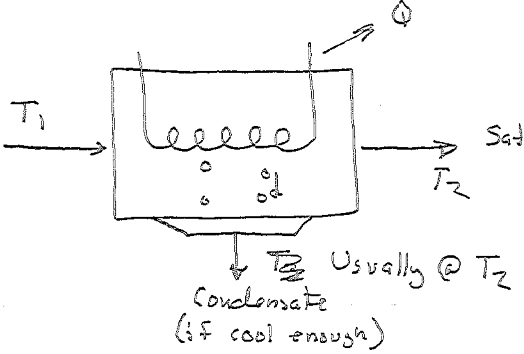
(c) New $h_1 \longrightarrow$ New ω_1

$\Rightarrow$ Repeat, but you shouldn't need to.

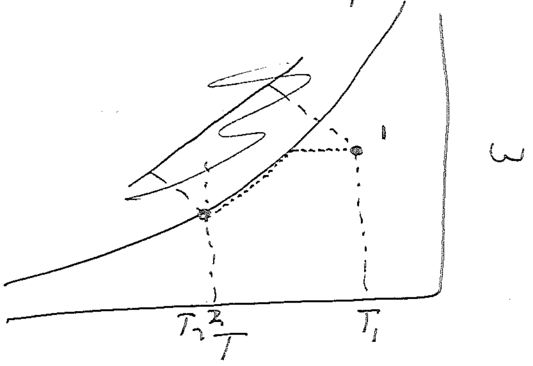
Nov ~~13~~ 15 - Power Plant

Nov 16

- Air conditioner:

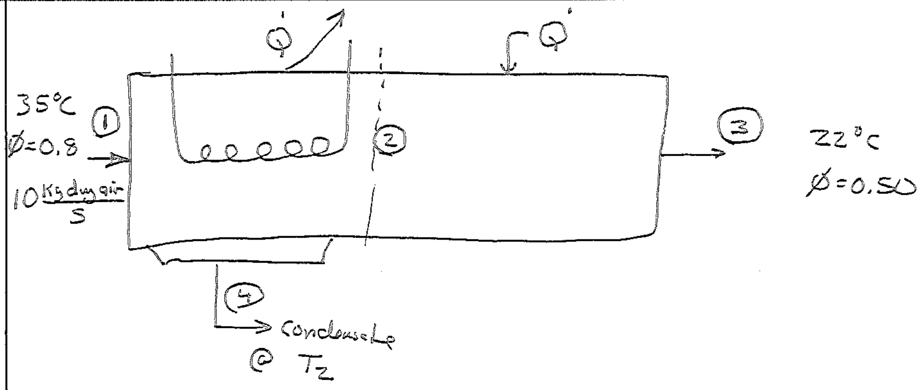


What path?

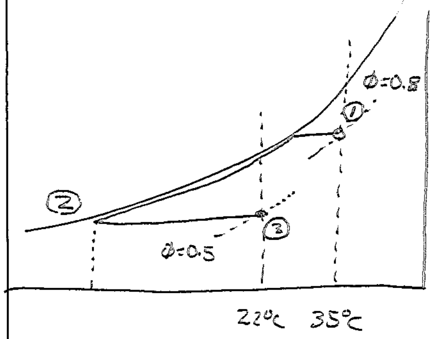


Problem is that air is now saturated - Outside of comfort zone.

Approach is to overcool, and then reheat.



First, visualize process on chart



1) Using equations:

$$\omega_1 = \frac{0.622\,\phi_1 P_{g,1}}{P - \phi_1 P_{g_1}}$$

$$\omega_3 = \frac{0.622\,\phi_3 P_{g,3}}{P - \phi_3 P_{g2}}$$

~~At point ③~~ $P_{v,3} = \phi_3 \underset{\substack{\uparrow \\ @\ 22°C}}{P_{g,3}}$

At point ② $P_{v,3} = P_{v,2} = P_{g,2} \xrightarrow{\text{Steam Table}} T_2$

First law for heater:

$$\dot Q = \cancel{(h_3 - h_2)} = \cancel{\dot m_a [h_3}$$
$$= \dot m_a h_{a,3} + \dot m_{v,3} h_{v,3} - [\dot m_a h_{a,2} + \dot m_{v,2} h_{v,2}]$$
$$= \dot m_a \left[\underbrace{(h_{a,3} + \omega_3 h_{v,3})}_{h_3} - \underbrace{(h_{a,2} + \omega_2 h_{v,2})}_{h_2}\right]$$

$C_{p,a}T_3$ $h_g @ T_3$ $C_{p,a}T_2$ h_{g,T_2}

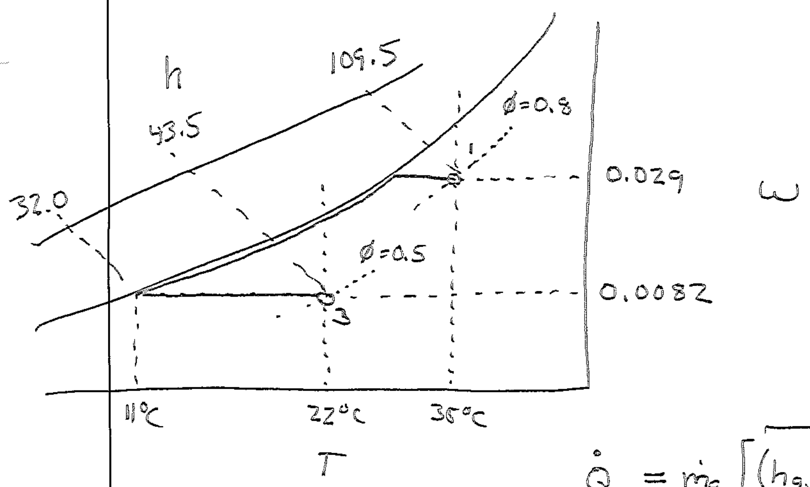
First Law for A/C:

$$\dot Q = \sum \dot m_e h_e - \sum \dot m_i h_i$$
$$= \dot m_a h_{a,2} + \dot m_{v,2} h_{v,2} + \dot m_4 h_4 - \dot m_a h_{a,1} - \dot m_{v,1} h_{v,1}$$

Conservation of water: $\dot m_{v,1} = \dot m_{v,2} + \dot m_4$ $\omega_1 - \omega_2 = \frac{\dot m_4}{\dot m_a}$

$$\dot Q = \dot m_a \left[[h_{a,2} + \omega_2 h_{v,2}] + (\omega_1 - \omega_2) \underset{\substack{\uparrow \\ h_f @ T_4 = T_2}}{h_4} - [h_{a,1} + \omega_1 h_{v,1}] \right]$$

2) Using Chart:



$$\dot{Q} = \dot{m}_a\left[\overbrace{(h_{a,3}+\omega_3 h_{v,3})}^{h_3}-\overbrace{(h_{a,2}-\omega_2 h_{v,2})}^{h_2}\right]$$

First Law on heater: $\dot{Q} = \dot{m}_a(h_3-h_2) = (10\frac{kg}{s})\left[43.5-32.0\,\frac{kJ}{kg_{dry\ air}}\right] = \boxed{115\ kW}$

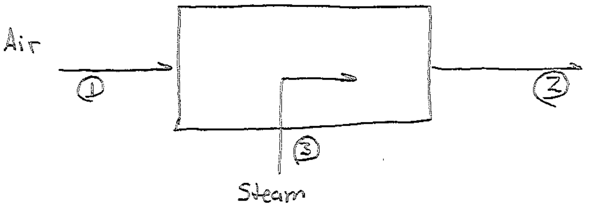
First Law on AC.

$$\dot{Q} = \dot{m}_a\left\{\underbrace{(h_{a,2}+\omega_2 h_{v,2})}_{h_2}+(\omega_1-\omega_2)h_4-\underbrace{(h_{a,1}+\omega_1 h_{v,1})}_{h_1}\right\}$$

$$= 10\,\frac{kg}{s}\left[32.0 + (.029-.0082)(46.21) - 109.5\right] = \boxed{-765.4\,kW}$$

Nov. 19

- Steam heating:



$\cancel{\dot{Q}}^{0} - \cancel{\dot{W}}^{0} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i$ $\qquad \dot{m}_a h_{a,1} + \dot{m}_{v,1} h_{v,1} + \dot{m}_3 h_3 = \dot{m}_a h_{a,2} + \dot{m}_{v,2} h_{v,2}$

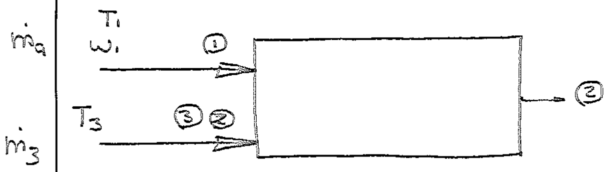
Conservation of Water: $\dot{m}_{v,1} + \dot{m}_3 = \dot{m}_{v,2}$

or $\dot{m}_a\left[\frac{\dot{m}_{v,2}}{\dot{m}_a} - \frac{\dot{m}_{v,1}}{\dot{m}_a}\right] = \dot{m}_3 = \dot{m}_a(\omega_2-\omega_1)$

$$\left[h_{a,1}+\omega_1 h_{v,1}\right] + (\omega_2-\omega_1)h_3 = \left[h_{a,2}+\omega_2 h_{v,2}\right]$$

~~or~~ $\boxed{h_1 + (\omega_2-\omega_1)h_3 = h_2}$

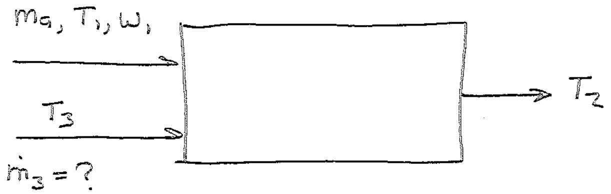
Say I know the steam and air flow rates.



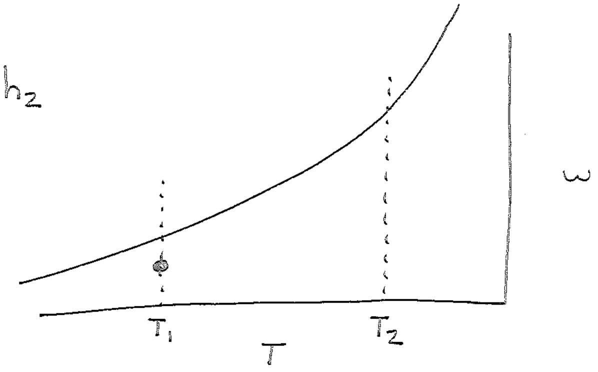
h_1 from chart $\quad \dot{m}_a[\omega_2 - \omega_1] = \dot{m}_3 \quad \Rightarrow \omega_2$

$\Rightarrow h_2, \omega_2 \Rightarrow T_2, \phi_2$, etc.

Now say I want to target a specific outlet T_2.



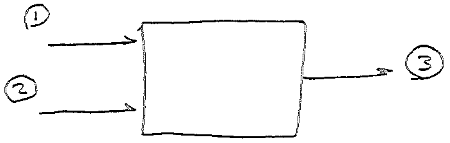
$$h_1 + (\omega_2 - \omega_1)h_3 = h_2$$



Iterate

$\dot{m}_3$ →	ω_2 →	h_2 →	T_2
–	–	–	–
–	–	–	–
–	–	–	–
–	–	–	–

- Adiabatic Mixing



air $\quad \dot{m}_{a,3} = \dot{m}_{a,1} + \dot{m}_{a,2}$

water: $\quad \dot{m}_{v,3} = \dot{m}_{v,1} + \dot{m}_{v,2}$

~~1st Law $\dot{m}_{a,3}h_3 = \dot{m}_{a,1}h_1 + \dot{m}_{a,2}h_2$~~

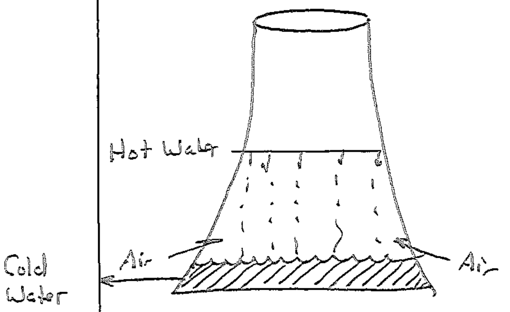
but $\quad \dot{m}_{v,3} = \dot{m}_{a,3}\omega_3, \quad \dot{m}_{v,2} = \dot{m}_{a,2}\omega_2, \quad \dot{m}_{v,1} = \dot{m}_{a,1}\omega_1$

so: $\quad \dot{m}_{a,3}\omega_3 = \dot{m}_{a,1}\omega_1 + \dot{m}_{a,2}\omega_2$

1st Law : $\quad \dot{m}_{a,3}h_3 = \dot{m}_{a,1}h_1 + \dot{m}_{a,2}h_2$

Know all inlet conditions: $\Longrightarrow \dot{m}_{a,3}, \omega_3, h_3$
$\Longrightarrow$ Chart $\quad T_3$, etc.

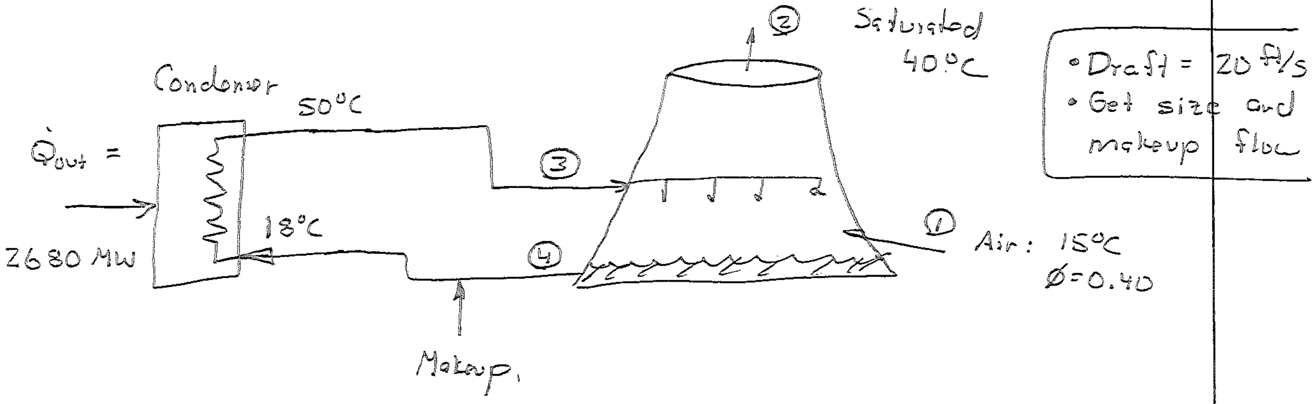
Last topic: $\boxed{\text{Wet Cooling Towers}}$



- Warm droplets evaporate (like wet bulb thermometer).
- Energy for h_{fg} comes from ΔT on drops.
- Cold water to process
- Warm air naturally updrafts (some units have fans, like UW).

Lets look at the design of the cooling tower for the Trojan plant.

$$\left.\begin{array}{l}\dot{W}_{elect} = 1150\ MW \\ \eta = 30\%\end{array}\right\}\quad \dot{Q}_{out} = 2680\ MW$$



- Draft = 20 ft/s
- Get size and makeup flow

Get total water flow via 1st law on condenser:

$$\dot{Q}_{out} = \dot{m}_3\, C_{P,H_2O}\,(T_3 - T_4)$$

$$2{,}680{,}000\ \tfrac{kJ}{s} = \dot{m}_3 \left(4.184\ \tfrac{kJ}{kg\text{-}K}\right)(50-18\ °C) \Rightarrow \underline{\dot{m}_3 = 20{,}017\ kg/s}$$

- Stop and think about this for a second. ~ 20 tons/s cooling water. for a condenser running > 50°C.
- We know we get better cycle η with cooler condenser.' 40°C $\Rightarrow \dot{m}_3 = 29$ tons/s $\Rightarrow$ Bigger exchanger, more cost.

Now do 1st law on tower: $\dot{Q} - \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i$

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

Water balance: $\dot{m}_{v,2} + \dot{m}_4 = \dot{m}_{v,1} + \dot{m}_3$

$$\Rightarrow \dot{m}_4 = \dot{m}_3 - (\dot{m}_{v,2} - \dot{m}_{v,1})$$

$$= \dot{m}_3 - m_a(\omega_2 - \omega_1)$$

So: $\dot m_a h_1 + \dot m_3 h_3 = \dot m_a h_2 + \left[\dot m_3 - \dot m_a(\omega_2 - \omega_1)\right] h_4$

Solve for $\dot m_a = \dfrac{\dot m_3 (h_3 - h_4)}{(h_2 - h_1) - (\omega_2 - \omega_1) h_4}$

$\dot m_3 = 20,017 \text{ Kg/s}$
$h_3 = h_f @ 50°C = 209.33 \text{ KJ/Kg}$
$h_4 = h_f @ 18°C = 75.57 \text{ KJ/Kg}$
h_2 = off chart !

$h_g @ 40°C = 2574.3$

$$h_2 = \underset{1.005}{C_p}\,\underset{40°C}{T_2} + \omega_2 h_{v,2} = 166.59 \text{ KJ/Kg}$$

$$\omega_2 = \omega_{sat} @ 40°C = \frac{0.622 P_g}{P - P_g} = \frac{0.622(7.384)}{101 - 7.384} = 0.0491 \frac{\text{Kg H}_2\text{O}}{\text{Kg dry}}$$

$h_1 \overset{\text{Chart}}{=} 24.5 \text{ KJ/Kg}$
$\omega_1 = 0.00425 \frac{\text{Kg H}_2\text{O}}{\text{Kg dry}}$

$$\dot m_a = \frac{\left[20,017 \frac{\text{Kg}}{\text{s}}\right]\left[209.33 - 75.57 \text{ KJ/Kg H}_2\text{O}\right]}{\left[166.59 - 24.5 \frac{\text{KJ}}{\text{Kg dry air}}\right] - \left[0.0491 - 0.00425 \frac{\text{Kg H}_2\text{O}}{\text{Kg dry air}}\right]\left[75.57 \frac{\text{KJ}}{\text{Kg dry a}}\right]}$$

$\boxed{\dot m_a = 19,300 \frac{\text{Kg dry air}}{\text{s}}}$ Volumetric Flow Rate $= \dot m_a v_1 = \frac{19,300 \text{ Kg dry}}{\text{s}} \bigg| \frac{0.821 \text{ m}^3}{\text{Kg dry}} = 15,850 \frac{\text{m}^3}{\text{s}}$

Mean draft velocity = 20 ft/s

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$$\text{Area} = \frac{15,830 \text{ m}^3}{\text{s}} \bigg| \frac{\text{s}}{20 \text{ ft}} \bigg| \frac{3.28 \text{ ft}}{\text{m}} = 2600 \text{ m}^2 \Rightarrow \boxed{D = 57.5 \text{ m}}$$

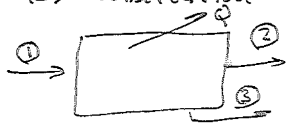
Makeup water: $\dot m_a(\omega_2 - \omega_1) = \left[19,300 \frac{\text{Kg dry}}{\text{s}}\right]\left[0.0491 - 0.00425 \frac{\text{Kg H}_2\text{O}}{\text{Kg dry}}\right]$
$= 866. \text{ Kg/s}$

⇒ If heat were directly put into river, would get a ~0.3°C temperature rise, but dispersion is poor down there.

Review main points

- Express all quantities on dry basis. $\dot m_a$ doesn't change during humidification / dehumidification processes.
- Know difference between P_v, P_g.
- Know how to convert between each of the 3 variables, P_v, ϕ, ω.
- Attack all problems via:
  (a) Conservation of dry air: $\sum \dot m_{a,in} = \sum \dot m_{a,out}$

  (b) Conservation of water: e.g. ac unit



Condensate

$\dot m_{v,1} = \dot m_{v,2} + \dot m_3$
or $\omega_1 = \omega_2 + \dot m_3 / \dot m_a$

(C) First Law:

$$\dot{m}_a h_{a,1} + \dot{m}_{v,1} h_{v,1} = \dot{m}_3 h_3 + \dot{m}_a h_{a,2} + \dot{m}_{v,2} h_{v,2}$$

or

$$\underbrace{h_{a,1} + \omega_1 h_{v,1}}_{h_1} = (\omega_1 - \omega_2) h_3 + \underbrace{h_{a,2} + \omega_2 h_{v,2}}_{h_2}$$

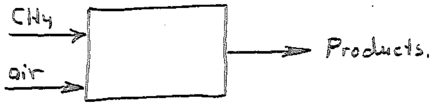
$$h_1 \longleftarrow \text{Chart} \longrightarrow h_2$$

- Chart: 1 atm only !
  - relate ω, ϕ
  - Get T_{DP}, ω_{sat}.
  - Get h's as above.

Chapter 13 – Chemical Reactions – Combustion

Overview of Issues –

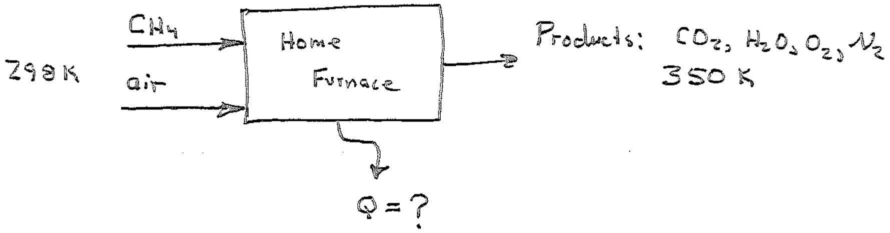
① Stoichiometry Calculations:



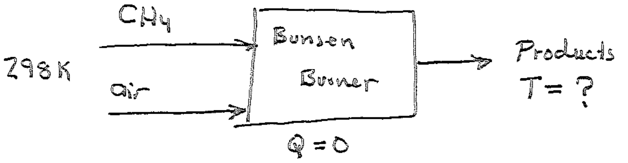
→ How much air exactly balances a given fuel?

→ Product composition: y_{H_2O}, y_{CO_2} ?

② First Law Balances:

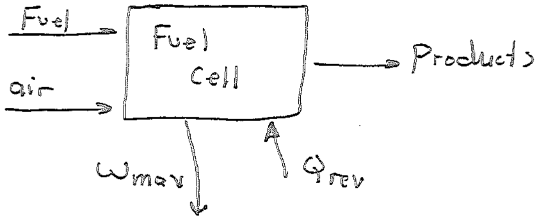


Or:



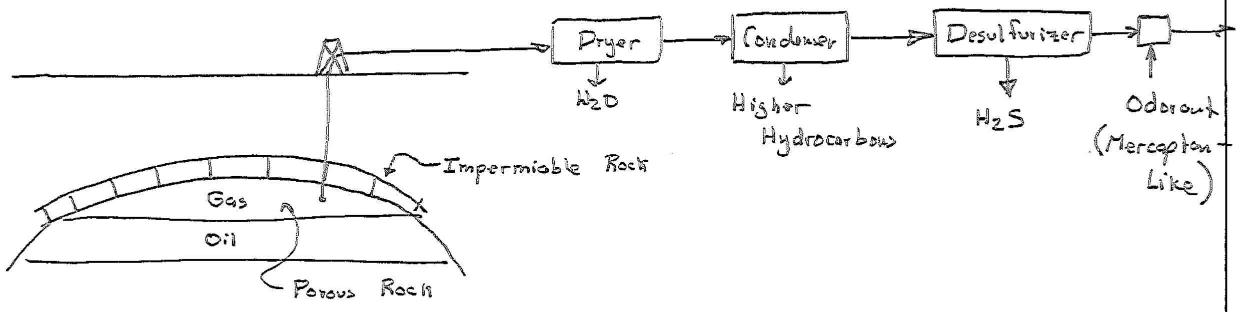
⇒ Adiabatic Flame Temperature

③ Second Law Issues (will not cover... see ME 430)



Briefly talk about fuel resources: ~90% of energy comes from combustion.

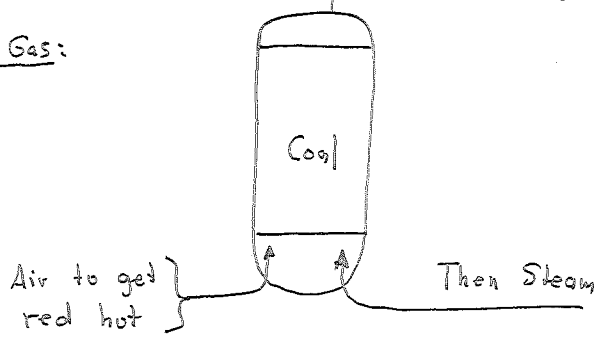
Natural Gas



Composition: 80-95% CH_4
Ethane, Ethylene, Propane.

Alternate Gases

Coal Gas:

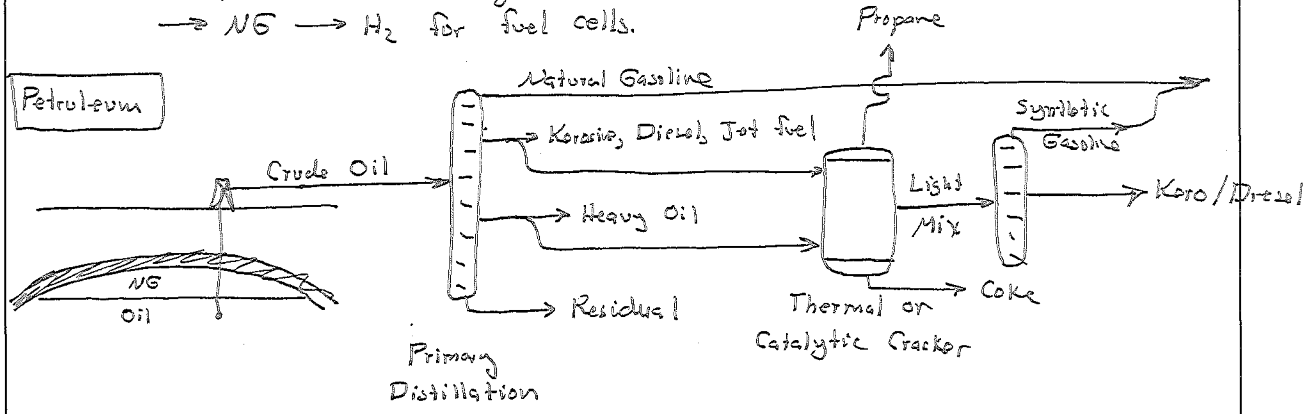


$C + H_2O \rightarrow CO + H_2$

$CO + H_2O \rightarrow CO_2 + H_2$
Water gas shift.

- This is how gasworks park worked
- Neglected technology, but seeing resurgance
  - → Biomass → Fuel gas.
  - → NG → H_2 for fuel cells.

Petroleum



- Before 1900- Wanted Kerosine for lamp oil, Gasoline a dangerous byproduct
- Now want gasoline, need to change refining to get better product match.

Coal

Explore by composition:

	(Mass %)	
Minerals	5	→ Slag on furnace walls (corrosion/heat transfer) → Waste problem (every 20 days have a unit train leaving) → Particulate matter → Toxics, As, Hg, Se, U, etc.
Sulfur	2	→ SO_2: Acid rain, sulfate particulate (visibility). → SO_3: → H_2SO_4 → plant corrosion
~~Nitrogen~~	.	
Nitrogen	1	→ NO, NO_2 → Smog.
Hydrogen	7	→ H_2O
Carbon	83	→ CO_2

→ Per 1 MJ → Coal gives: 0.102 Kg CO_2
NG gives: 0.049 Kg CO_2 due to more H, less C.

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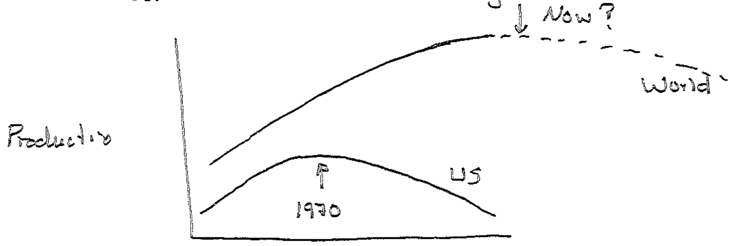
Quick Assessment:

Petroleum is exclusively a transportation fuel:
- → Only get 20-25% out of oil field; rest is trapped in rock
- → Used ~ 50% of world's easily recoverable oil.



- ⟹ In 10-30 years will begin to see costs rise due to scarsity of ~~cheap oil~~ easily recoverable oil.
- ⟹ EOR technologies can get lots more, but not at \$20-30/barrel
- ⟹ So issue is not running out, but economic impact of large increases in oil prices.

Coal US has more than anybody; ~500 year supply, but do we want to burn it all?

Natural Gas: No minerals, S, N, so cleanup is easy.
\$2.5/10^6 Btu vs. \$1.4 for coal due to less cleanup required.
- → In Northwest, we get from Canada → Combined cycles is where the action is.
- → Used 15% in world, 50% in US, Canada big supplier
  Last ~70-100 years?

First $\boxed{\text{Stoichiometry}}$

Start with 1 Kmole CH_4 + stoichiometric air.

$$[1]\ CH_4 + [a_{th}]\overbrace{[O_2 + 3.76 N_2]}^{\text{air}} \longrightarrow CO_2 + 2H_2O + 3.76 a_{th} N_2$$

$\uparrow$ 21% O_2 $\quad$ $\uparrow$ 79% N_2

(No O_2).

So!

- Stoichiometric: Just enough air to give
  - $C \rightarrow CO_2$
  - $H \rightarrow H_2O$
  - No left over O_2

- Get a_{th} via O-atom balance:

$$\text{In} = \text{Out}$$

$$2a_{th} = 2 + 2 \quad \Rightarrow \quad a_{th} = 2$$

a_{th} is a <u>stoichiometric air demand</u>, and is the same for each fuel.

$CH_4 = 2$

- So balanced equation becomes:

$$CH_4 + 2[O_2 + 3.76 N_2] \rightarrow CO_2 + 2H_2O + 7.52 N_2$$

- Now do some things:

  - Product composition: $n = \Sigma n_i = 1 + 2 + \cancel{3.76} = 7.52 = 10.52$

	n_i	$y_i = n_i/n$
CO_2	1	0.095
H_2O	2	0.190
N_2	7.52	0.715
$n = \Sigma n_i =$	10.52	

Dew Point: $P_v = y_{H_2O} P$

$= [0.19][100 \text{ KPa}]$

$= 19$ KPa.

Find place in steam table where $P_g = 19$ KPa $\Rightarrow$ <u>$T_{DP} = 58.8°C$</u>

- Definition: $\quad$ AF mass ratio $= \dfrac{m_a}{m_f}$

$$m_f = \frac{1 \text{ Kmole} \mid 16 \text{ Kg}}{\mid \text{Kmole}} = 16 \text{ Kg}$$

$$m_a = \frac{2\,[1 + 3.76] \text{ Kmoles air} \mid 29 \text{ Kg}}{\mid \text{Kmole}} = 276.1 \text{ Kg}.$$

$$AF = \frac{276.1}{16} = 17.3$$

Normally you burn with <u>extra air</u> to ensure all the fuel is burned.

Introduce a new parameter Φ_{AF} = Air/fuel stoichiometric ratio.
$\Phi = 1$ if stoichiometric, >1 if more air is present (called fuel lean or air rich).

Set up for a new fuel, ethane with $\Phi_{AF} = 1.2 \rightarrow$ 120% theoretical air
20% excess air

$$C_2H_6 + a_{th}\Phi_{AF}\left[O_2 + 3.76N_2\right] \rightarrow$$

1. Get a_{th} for C_2H_6 by <u>temporarily</u> assuming $\Phi_{AF} = 1$

$$C_2H_6 + a_{th}\left[O_2 + 3.76N_2\right] \rightarrow 2CO_2 + 3H_2O + 3.76\,a_{th}N_2$$

O-atom balance: $2a_{th} = 4 + 3 \Rightarrow a_{th} = 3.5$ [Will always be this for C_2H_6]

2. Now insert Φ_{AF}

$$C_2H_6 + 3.5\Phi_{AF}\left[O_2 + 3.76N_2\right] \rightarrow 2CO_2 + 3H_2O + (3.5)(3.76)\Phi_{AF}N_2 + zO_2$$

Get z via O-atom balance

$$(2)(3.5)\Phi = \cancel{z}\ 4 + 3 + 2z \Rightarrow z = 3.5(\Phi - 1)$$

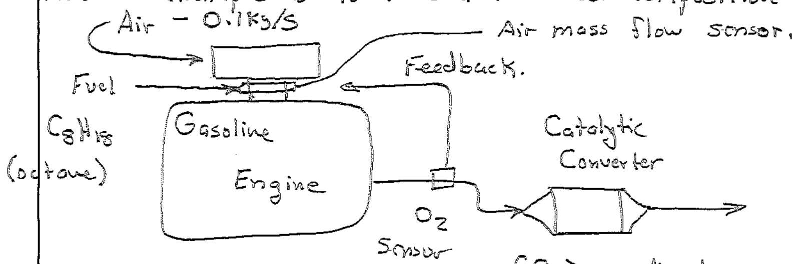
or $$\boxed{C_2H_6 + 3.5\Phi_{AF}\left[O_2 + 3.76N_2\right] \rightarrow 2CO_2 + 3H_2O + 13.16\Phi_{AF}N_2 + 3.5(\Phi_{AF} - 1)O_2}$$

$$\Phi = 1.2 \Rightarrow C_2H_6 + [3.5][1.2]\left[O_2 + 3.76N_2\right] \rightarrow 2CO_2 + 3H_2O + 15.79N_2 + 0.70\,O_2$$

3. Get product composition:

	n_i	$y_i = n_i/n$
CO_2	2	0.093
H_2O	3	0.140
N_2	15.79	0.735
O_2	0.70	0.033
$n =$	21.49	

Another example is to take a measured composition and work backwards to A/F.



$$\left.\begin{matrix} CO, \\ Fuel \end{matrix}\right\} \xrightarrow{\text{Oxidized}} CO_2$$
$$NO \xrightarrow{\text{Reduced}} N_2$$

Both work only if y_{O_2} is controlled tightly!

e.g. $\Rightarrow y_{O_2} = \cancel{0.05}$ 0.5%

$\Rightarrow$ Find ~~AF~~. $\dot{m}_{fuel}$

$C_8H_{18} + a_{th}\Phi_{AF}[O_2+3.76N_2] \rightarrow$

① Temporarily assume $\Phi=1$ to get a_{th}

$$C_8H_{18} + a_{th}[O_2+3.76N_2] \rightarrow 8CO_2 + 9H_2O + 3.76a_{th}N_2$$

O-atom balance: $2a_{th} = 16+9 \Rightarrow a_{th} = 12.5$

② Now insert Φ_{AF}

$$C_8H_{18} + 12.5\phi[O_2+3.76N_2] \rightarrow 8CO_2+9H_2O + (12.5)(3.76)\phi N_2 + zO_2$$

Get z via O-atom balance: $(2)(12.5)\phi = 16+9+2z \Rightarrow$
$z = 12.5(\phi-1)$

or $C_8H_{18} + 12.5\phi[O_2+3.76N_2] \rightarrow 8CO_2+9H_2O + 47\phi N_2 + 12.5(\phi-1)O_2$

Know $y_{O_2} = 0.005$, want ϕ; How?

$$y_{O_2} = \frac{n_{O_2}}{n} = \frac{12.5(\phi-1)}{8+9+47\phi+12.5(\phi-1)} = 0.005$$

$\Rightarrow \Phi_{AF} = 1.0262 \Rightarrow$ 102.62% Theoretical Air
$\Rightarrow$ 2.62% Excess Air

Now get: $AF = \frac{m_a}{m_f}$

$m_f = [1\text{ Kmole}][114\ \text{Kg/Kmole}] = 114$ Kg.

$m_a = [\text{Kmoles air}][M_{air}]$

$= [12.5][1.0262][1+3.76][29\ \text{Kg/Kmole}] = 1771$ Kg.

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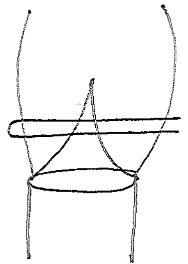
$AF = \frac{1771}{114} = 15.53\ \frac{\text{Kg air}}{\text{Kg fuel}}$

so: $\frac{0.1\text{ Kg air}}{\text{s}}\left|\frac{\text{Kg fuel}}{15.53\text{ Kg air}}\right. = \underline{\underline{6.44\ \frac{\text{grams fuel}}{\text{s}}}}$

A couple of combustion-related topics:

① Completeness of combustion:



For stoichiometric: $CH_4 + 2[O_2+3.76N_2] \longrightarrow CO_2 + 2H_2O + 7.52N_2$

Quench $\longrightarrow 0.75CO_2 + 0.25CO + 2H_2O + 7.52N_2$
$+ 0.125O_2$

→ Not all $C \rightarrow CO_2$, some stops @ CO

→ Means you have some left over O_2

→ This is why cars emit CO → Not always enough time to finish combustion
→ Cylinder walls are cold.

② Substoichiometric Combustion

CH_4 + 90% Theoretical Air.

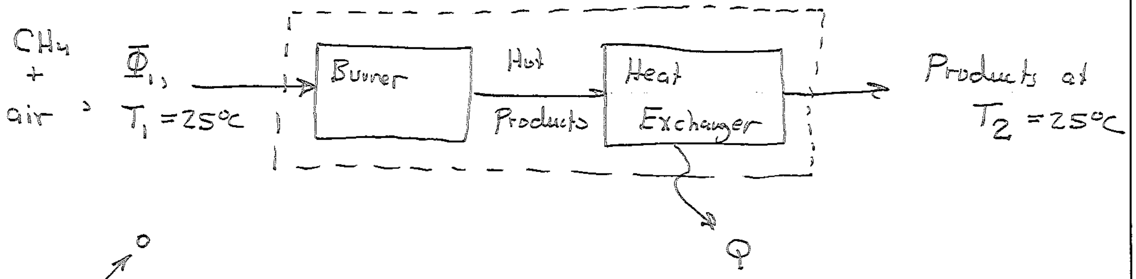
$$CH_4 + 2[0.9][O_2+3.76N_2] \rightarrow 2H_2O + 0.6CO_2 + 0.4CO + 6.77N_2$$

$$\Rightarrow \; y_{CO} = 4.09\% \; ; \quad \underset{\uparrow}{y_{CO}} = 0.0035\%$$

ambient air standard

So you can see why a malfunctioning Kerosine heater (i.e., blocked air passages) is so dangerous.

First Law on Reacting Systems



$$\dot{Q} - \cancel{\dot{W}}^{\,0} = \sum \dot{n}_e h_e - \sum \dot{n}_i h_i$$

Since both reactants and products are at 25°C, the $\Delta h \, (=Q)$ is due to the change in chemical form (i.e., potential energy in bonds becomes thermal energy upon reaction).

We need a new definition of $h = 0$ to express this.

$$\Rightarrow \; \boxed{h = 0 \text{ for } \underline{\text{elements}} \text{ in their } \underline{\text{standard state}} \text{ at } 25°C}$$

Note that this is (as usual) arbitrary. The only thing that is important is to be consistent.

Elements in standard state H_2, O_2, N_2, C-graphite.

Not in standard state H-atoms, O_3, C-diamond

$$\text{i.e.,} \quad \underset{\uparrow}{\text{C-graph}} \xrightarrow{\Delta h} \text{C-diamon}$$

Arbitrarily call this zero.

Looking ahead:

h (any compound, any T_1) $=$ Δh elements @ 25°C → compound @ 25°C $+$ Δh compound at 25°C → compound at T_1

$\equiv \bar{h}_f^\circ$ - enthalpy of formation.

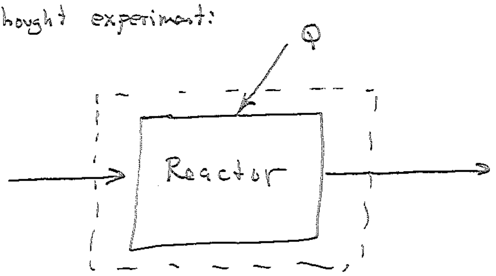
Table, each compound has its own value (A-25)

$$\Delta h = \int_{25°C}^{T_1} c_p\, dT$$

$= h_{T_1} - h_{25°C}$ from ideal gas tables. (A-23)

Get $\bar{h}_f^\circ$ via thought experiment:

- Elements
- Standard state
- 25°C



1 Kmole Product 25°C

for e.g. CO_2

1 Kmole graphite

1 Kmole O_2

1 Kmole CO_2

First Law on box: $$Q = \left[\sum n_i \bar{h}_i\right]_P - \cancel{\left[\sum n_i \bar{h}_i\right]_R}$$ 0 by definition

$$\Rightarrow \quad Q = \bar{h}^\circ_{f,CO_2} = -393,520 \frac{kJ}{kmole\ CO_2}$$

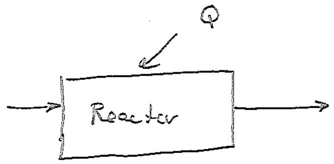
So burn $C + O_2$ in calorimeter, get heat out (⇒ minus sign) ⇒ This becomes $\bar{h}_{f,CO_2}$ in table. A-

Special case for water:

1 Kmole H_2

0.5 Kmole O_2

25°C



1 Kmole H_2O 25°C

$Q = \bar{h}^\circ_{f,H_2O}$, but you have two values:

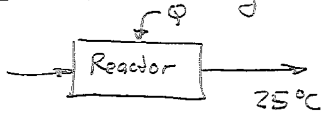
if f. $-285,830$ kJ/Kmole H_2O

if g $-241,820$ kJ/Kmole H_2O

$\Delta =$ h_{fg} @ 25°C.

Enthalpy of Reaction: Looks at any reactant/product combo.

R 25°C



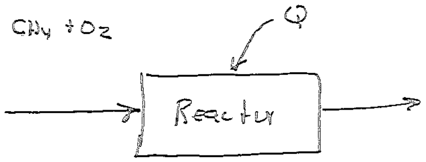
P 25°C

Can always get from $\bar{h}_f^\circ$ table. A-25

e.g. Stoichiometric $CH_4 + O_2$

CH_4

$2O_2$ 25°C



$CO_2 + 2H_2O\,(f)$ 25°C