The Consultant Engineer

There was an engineer who had an exceptional gift for fixing all mechanical things. After serving his company loyally for over 30 years, he happily retired. Several years later his company contacted him regarding a seemingly impossible problem they were having with one of their multi-million dollar machines. They had tried everything and everyone else to get the machine fixed, but to no avail. In desperation, they called on the retired engineer who had solved so many of their problems in the past.

The engineer reluctantly took the challenge. He spent a day studying the huge machine. At the end of the day he marked a small X in chalk on a particular component of the machine and proudly stated, 'This is where your problem is!' The part was replaced and the machine worked perfectly again.

The company received a bill for $50,000 from the engineer for his services. They demanded an itemized accounting of his charges. The engineer responded briefly:

One chalk mark $1

Knowing where to put it $49,999

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Business

- This is lecture #18 out of 36
  - Half way!
- Exam next week
  - Available at review on Monday (Oct. 17)
  - Due Friday, Oct. 21 at 9 am
  - 3 hrs
  - Take home
  - Practice exam posted on Learning Suite
- Quiz

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Review/Quiz

- What is vapor pressure?
- What is partial pressure?
- What is the equation for Raoult’s law?

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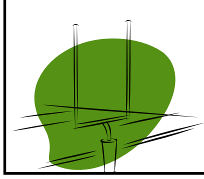
Goals

- Review: Vapor Pressure, Raoult’s Law
- Definitions for 1 liquid species, 2+ gas species
  - Dew Point
  - Boiling Point
  - Relative and Absolute Humidity
  - Degrees Superheat
- Examples



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Raoult's Law

$$y_iP = x_iP_i^*$$

Pure Component (1 species)	1 liquid species 2+ gas species	2+ liquid species 2+ gas species
Last Friday	Today	Wednesday
$y_i = 1$ $x_i = 1$ So: $P_{tot} = P_i^*$	Example: Air-water $y_i \neq 1$ $x_i = 1$ So: $y_iP_{tot} = P_i = P_i^*$	

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What is Saturation?

- Think of a sponge

- The maximum amount of water absorbed by the sponge is called saturation
- Any extra water after saturation runs off the sponge

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Saturated Air

- What happens when air becomes saturated with water vapor?
  - Any additional water starts to condense and form liquid water droplets
  - Point at which the first drop condenses is called the **dew point**
  - Saturation point (and hence dew point) is a function of temperature (related to vapor pressure)
    - Higher temperature air can hold more water vapor

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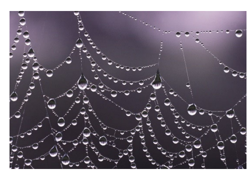
Dew Point Equations

- Dew point is when first drop condenses
  - Saturated Air
  - Occurs when $y_i P_{tot} = P_i^*$ $(x_i = 1)$
    - So air is saturated when $P_i = P_i^*$
    - P_i^* is sometimes called P_i^{sat}



- Examples:
  - If you know the temperature, you can calculate y_{H2O} from P_i^* and P_{tot}, or
  - If you know y_i and P_{tot}, you can calculate P_i^* and then calculate the corresponding temperature (T_{dp})

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What if you are not at the dew point?

- How do you quantify the amount of moisture in the air?
  - Mole or mass fraction of H_2O
  - **Relative Humidity** = $\frac{P_i}{P_i^*} = \frac{P_{H2O}}{P_{H2O}^*}$
    - Like the percent of saturation
    - 50% humidity = 50% of the moisture that the air can hold at that temperature
    - P_{H2O}^* is a function of temperature
    - Saturation is 100% relative humidity
  - **Absolute Humidity** = $\frac{mass\ of\ vapor}{mass\ of\ dry\ gas}$
    - Kind of like a weird mass fraction

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More Definitions

(1 liquid species, 2+ gas species)

- **Boiling Point**
  - First bubble of vapor appears in liquid
  - Essentially, $x_i = y_i = 1$ at interface
  - $P_{H2O}^* = P_{tot}$ (same as for 1 gas species)
- **Degrees Superheat**
  - Measure of how far you have to cool the gas to condense the first drop of liquid
  - Degrees superheat = $T - T_{dp}$

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More Definitions
(1 liquid species, 2+ gas species)

- **What if $P_i > P_i^*$**
  - Supersaturated (relative humidity > 100%)
  - Not at equilibrium
  - Liquid will condense out of the gas phase
  - Conditions will change back to the saturation point where $P_i = P_i^*$

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Examples

1. BYU Heating Plant
2. Boiling point in Provo
3. Relative humidity in Virginia
   1. P_{H2O}
   2. y_{H2O}
   3. Degrees superheat
4. Air conditioner with reheat

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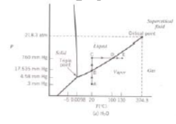
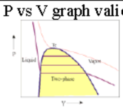
Raoult's Law

$y_i P_{tot} = x_i P_i^*$

$$y_i \hat{\phi}_i P = x_i \gamma \phi_i^* P_i^* \exp\left[\int_{P^*}^{P} \frac{V_i^L}{RT} dP\right]$$

Single Component	**Liquid = 1 component** **Gas = 2+ components (n_g)**	**Liquid = 2+ components (n_L)** **Gas = 2+ components (n_g)**
DF = 2 + 1 – 2 = 1	DF = 2 + n_{spec} – 2 = n_{spec}	DF = 2 + n_{spec} – 2 = n_{spec}
$y_i = 1.0$ $x_i = 1.0$	$y_i \neq 1.0$ $x_i = 1.0$	$y_i \neq 1.0$ $x_i \neq 1.0$
At vapor-liquid equilibrium, $P_i^* = P_{tot}$	At vapor-liquid equilibrium, $y_i P_{tot} = P_i^*$	At vapor-liquid equilibrium, $y_i P_{tot} = x_i P_i^*$
boiling T = condensing T	dew point occurs at T_{dp} i.e., when first liquid condenses - saturated vapor ($P_i = P_i^*$)	1st drop of liquid = dew point (saturated vapor)
	boiling when $P_{tot} = P_i^*$ (like single component, saturated liquid)	1st bubble of gas = bubble point (saturated liquid)
	Relative humidity = $y_i P_{tot}/P_i^*$ (or P_i/P_i^*) - saturated when R.H. = 100%	No boiling point defined - temperature changes as lighter component evaporates
P vs T graph valid 	Absolute humidity = $m_{steam}/m_{dry\,gas}$ $= \left(\frac{P_i MW_i}{RT}\right) \Big/ \left(\frac{(P_{tot} - P_i) MW_{dry}}{RT}\right)$ $= P_i MW_i / \left((P_{tot} - P_i) MW_{dry}\right)$	
P vs V graph valid 	Degrees superheat = T - T_{dp}	

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Upcoming HW problems

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17.1. Air at 90°C and 1.00 atm (absolute) contains 10.0 mole% water. A continuous stream of this air enters a compressor–condenser, in which the temperature is lowered to 15.6°C and the pressure is raised to 3.00 atm. The air leaving the condenser is then heated isobarically to 100°C. Calculate the fraction of water that is condensed from the air, the relative humidity of the air at 100°C, and the ratio of volumetric flow rates (i.e., m^3 outlet air at 100°C per m^3 feed air at 90°C).
Can ideal gas be used for this calculation?

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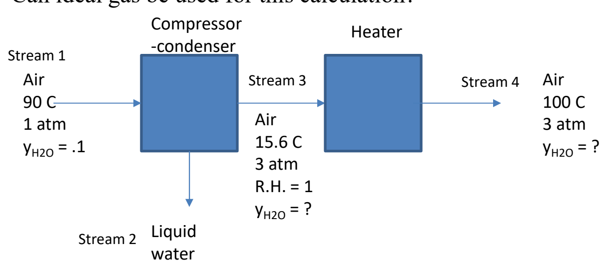
Isobarically = constant pressure



1. Use a basis of 100 moles of moist air entering compressor
2. Find $y_{H2O,3}$ from vapor pressure, RH_3, and definition of partial pressure
3. Note that $y_{H2O,3} = \frac{n_{H2O,3}}{n_{H2O,3}+n_{dry\ air}}$, so if you know $y_{H2O,3}$ and $n_{dry\ air}$, you can get $n_{H2O,3}$
4. Do the balances on moles of water in and out of compressor
5. Use ideal gas law to get ratios of volumetric flow rates

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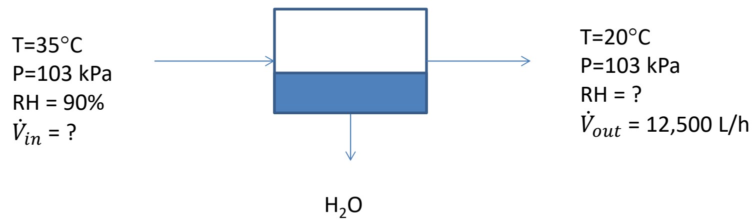
17.2. On a hot summer day the temperature is 35°C, barometric pressure is 103 kPa, and the relative humidity is 90%. An air conditioner draws in outside air, cools it to 20°C, and delivers it at a rate of 12,500 L/h. Calculate the rate of moisture condensation (kg/h) and the volumetric flow rate of the air drawn from the outside.



Strategy:
1. Find P* for inlet, then $y_{H2O,in}$
2. Recognize that outlet air is saturated with water (RH = 100%), so find P* for outlet and $y_{H2O,out}$
3. From outlet volumetric flow rate, find $n_{gas,out}$, then $n_{H2O,out}$
4. $n_{air,in} = n_{air,\ out}$, so find $n_{H2O,in}$
5. $n_{H2o,liq}$ by difference

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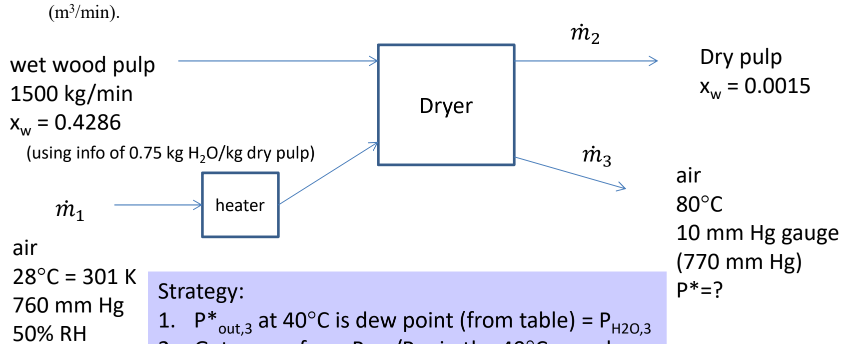
17.3. A hot-air dryer is used to reduce the moisture content of 1500 kg/min of wet wood pulp from 0.75 kg H_2O/kg dry pulp to 0.15 wt% H_2O. Air is drawn from the atmosphere at 28°C, 760 mm Hg, and 50% relative humidity, sent through a blower-heater, and then fed to the dryer. The air leaves the dryer at 80°C and 10 mm Hg (gauge). A sample of the exit air is drawn into a chamber containing a mirror and cooled slowly, keeping the gauge pressure at 10 mm Hg. A mist is observed to form on the mirror at a temperature of 40.0°C.

(a) What is the vapor pressure of H_2O at the conditions in the dryer exit?
(b) Calculate the partial pressure and mole fraction of H_2O in the air leaving the dryer.
(c) Calculate the mass of water removed from the pulp (kg/min) and the volumetric flow rate of air entering the system (m^3/min).



Strategy:
1. $P^*_{out,3}$ at 40°C is dew point (from table) = $P_{H2O,3}$
2. Get $y_{w,out,3}$ from P_{H2O}/P_{tot} in the 40°C sample
3. Get $y_{H2O,in,1}$ from RH_{in}
4. Balances on
   1. dry pulp mass
   2. moles of water
   3. moles of dry air

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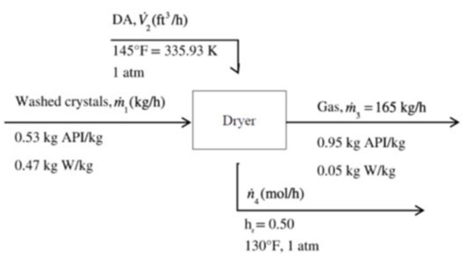
6.35 in 4th Edition



Strategy:
1. Find $\dot{m}_{API,3}$
2. API balance to find $\dot{m}_1$
3. Water balance to find $\dot{m}_{H2O,4}$
4. Use RH_{H2O} to find $y_{H2O,4}$
5. Find $\dot{n}_4$ and $\dot{n}_{air,4}$
6. Ideal gas law to find $\dot{V}_2$

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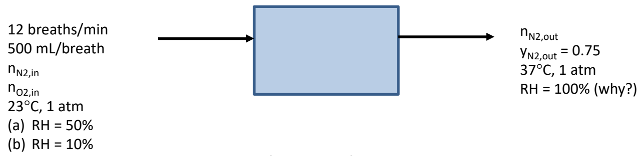
6.26 in 4th Edition

6.25. An adult takes roughly 12 breaths each minute, inhaling approximately 500 mL with each breath. Oxygen and carbon dioxide are exchanged in the lungs. The amount of nitrogen exhaled equals the amount inhaled, and the mole fraction of nitrogen in the exhaled air is 0.75. The exhaled air is saturated with water vapor at body temperature, 37°C. Estimate the increase in the rate of water loss (g/day) when a person breathing air at 23°C and a relative humidity of 50% enters an airplane in which the temperature is also 23°C but the relative humidity is 10%.



$n_{N2,out} = n_{N2,in}$

$y_{N2,in}$ = 0.79 on a dry basis

Find Δm_{H2O} for both inlet RH's

Strategy:

1. From P^*_{in} and P^*_{out} and RH's find $y_{H2O,in}$ and $y_{H2O,out}$
2. Find $y_{N2,in,wet\ basis}$
3. Find $n_{total,in}$
4. Balance on N_2, then get n_{total} out
5. $\Delta\ n_{H2O}$ using n_{total} and inlet and outlet y_{H2O}'s
6. Convert to Δm_{H2O}

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