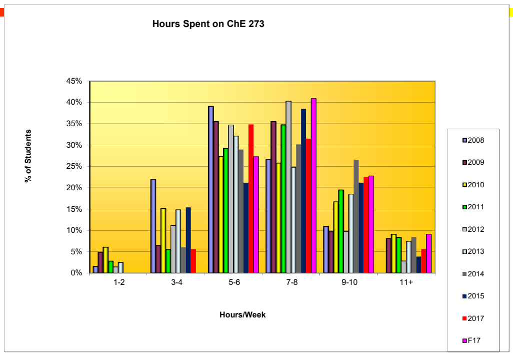
Survey Results



Chapters 5-6
(where we are going)

- Ideal gases and liquids (today)
  - Densities
  - Partial pressures
- Non-ideal gases (next time)
  - Eqns. of state
  - Reduced pressures and temperatures
  - Compressibility charts (z)
- Vapor-liquid systems (Ch. 6)
  - Vapor pressure
  - Humidity
  - Raoult's law
  - Bubble and dew points
  - Solid-solid & liquid-liquid systems

Class 15

- Properties of Single Phase Materials
  - Connection to Material Balances
  - Ideal Assumptions
  - Liquids- density of mixtures
  - Ideal Gases
  - Standard conditions

Is the following possible?

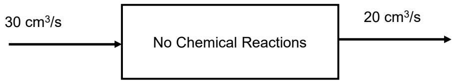
No!

Is the following possible?

Yes!

Only if reactions occur!

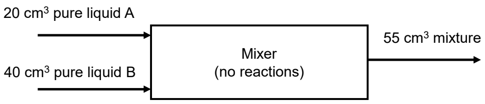
Is the following possible?



Yes!

Ideal Gas, change in temperature or pressure

Is the following possible?


20 cm^3 pure liquid A

40 cm^3 pure liquid B

Mixer
(no reactions)

55 cm^3 mixture

Yes!

Even for liquid systems!

Need Relationships Between Variables

- Not easy to measure molar flow rates
- What can we easily measure?
  - Mass flow rate
  - Volumetric flow rate
  - Composition
  - Pressure
  - Temperature
- Relate measured variables to desired quantities

Liquid Mixtures

- In general, liquid volume is not conserved

  $V = V_1 + V_2 + V^E$
- Contraction or expansion occurs because of the difference in interactions between like and unlike molecules
- V^E typically small. Assume $V^E = 0$ for this course.
- This implies that liquid volumes are additive

$$\frac{1}{\bar{\rho}} = \sum_{i=1}^{n} \frac{x_i}{\rho_i}$$

x_i = mass fraction of species i

Mass and Mole Fractions Have Units!

- $x_i = \frac{mass\ of\ species\ i}{mass\ of\ mixture}$ (same with moles)
- Look at units of density equation

$$\frac{1}{\bar{\rho}} = \sum_{i=1}^{n} \frac{x_i}{\rho_i}$$

- $\frac{1}{kg/m^3} = \frac{\frac{kg\ of\ i}{kg\ of\ mix}}{\frac{kg\ of\ i}{m^3}}$

Example

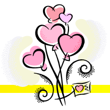
- What is the density of a mixture containing 20 wt% A (ρ_A = 1 g/cm^3) and the balance B (ρ_B = 2 g/cm^3)?

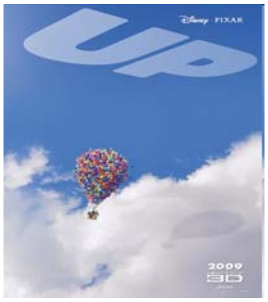
$$\frac{1}{\rho} = \frac{0.2}{\rho_A} + \frac{0.8}{\rho_B} = \frac{0.2}{1} + \frac{0.8}{2}$$

Therefore, ρ = 1.67 g/cm^3

If you used $\rho = \Sigma x_i \rho_i$, you would have calculated ρ = 0.2*1 + 0.8*2 = 1.8 g/cm^3 …. Oops!

Gases





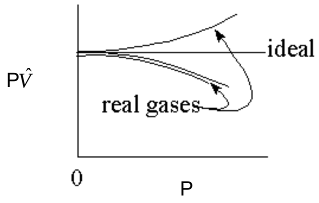
- **Equation of State** (EOS)
  - relates amount (moles) to V, T, P
- Many different equations of state
  - represent behavior of real systems
- **Ideal Gas Law**
  - Simplest equation of state
  - Most widely used

Ideal Gas

- Equation of State: **PV = nRT**
- Also $P\hat{V} = RT$ (i.e., $\hat{V} = V/n$)
- Assumptions
  - No interaction between molecules
  - Molecules have zero volume
- Valid at low concentration (n/V)
  - Best at high or low pressures?
  - Best at high or low temperatures?

$\hat{V}$= specific volume

Ideal vs. Real Gases



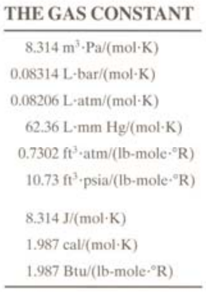
From p. 192, ideal when:

$$\hat{V}_{ideal} > 5L/mol \quad (diatomic\ \ gases)$$
$$\hat{V}_{ideal} > 20L/mol \quad (other\ \ gases)$$

Ideal Gas Constant

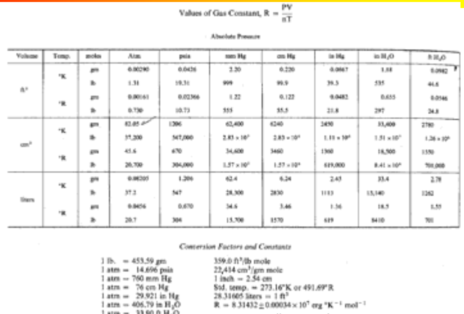
- In Chemistry and Chemical Engineering, ***R*** is universal (independent of species)
  - Nice table in the back cover of the book for different units
- In Mechanical Engineering, the MW of the species is included, so there is a different value of ***R*** for each species

Ideal Gas Constant



THE GAS CONSTANT	
8.314 m³·Pa/(mol·K) 0.08314 L·bar/(mol·K) 0.08206 L·atm/(mol·K) 62.36 L·mm Hg/(mol·K) 0.7302 ft³·atm/(lb-mole·°R) 10.73 ft³·psia/(lb-mole·°R)	For ideal gas eqn
8.314 J/(mol·K) 1.987 cal/(mol·K) 1.987 Btu/(lb-mole·°R)	For Energy

from CRC Handbook



Values of Gas Constant, $R = \frac{PV}{nT}$

Absolute Pressure

Volume	Temp.	moles	Atm.	psia	mm Hg	cm Hg	in Hg	in H_2O	ft H_2O
ft³	°K	gm	0.00290	0.0426	2.20	0.220	0.0867	1.18	0.0982
		lb	1.31	19.31	999	99.9	39.3	535	44.6
	°R	gm	0.00161	0.02366	1.22	0.122	0.0482	0.655	0.0546
		lb	0.730	10.73	555	55.5	21.8	297	24.8
cm³	°K	gm	82.05	1206	62,400	6240	2450	33,400	2780
		lb	37,200	547,000	2.83×10^7	2.83×10^6	1.11×10^6	1.51×10^7	1.26×10^6
	°R	gm	45.6	670	34,600	3460	1360	18,500	1550
		lb	20,700	304,000	1.57×10^7	1.57×10^6	619,000	8.41×10^6	701,000
liters	°K	gm	0.08205	1.206	62.4	6.24	2.45	33.4	2.78
		lb	37.2	547	28,300	2830	1113	15,140	1262
	°R	gm	0.0456	0.670	34.6	3.46	1.36	18.5	1.55
		lb	20.7	304	15,700	1570	619	8410	701

Conversion Factors and Constants

1 lb. = 453.59 gm
1 atm = 14.696 psia
1 atm = 760 mm Hg
1 atm = 76 cm Hg
1 atm = 29.921 in Hg
1 atm = 406.79 in H_2O
1 atm = 33.90 ft H_2O

359.0 ft³/lb mole
22,414 cm³/gm mole
1 inch = 2.54 cm
Std. temp. = 273.16°K or 491.69°R
28.31605 liters = 1 ft³
$R = 8.31432 \pm 0.00034 \times 10^7$ erg °K⁻¹ mol⁻¹

$8314.3\ \frac{N \cdot m}{kgmol \cdot K}$ or $\frac{J}{kgmol \cdot K}$ $\qquad$ $8.3143\ \frac{N \cdot m}{gmol \cdot K}$ or $\frac{J}{gmol \cdot K}$

Gas Concentration & Density

- Concentration = moles/volume = n/V

$$C = \frac{n}{V} = \frac{P}{RT} \qquad or \qquad C_i = \frac{y_i P}{RT}$$

- Density = mass/volume = n·MW/V = C·MW

$$\rho = \frac{n \cdot MW}{V} = \frac{P \cdot MW}{RT} \qquad or \qquad \rho_i = \frac{y_i P \cdot MW_i}{RT}$$

Application Example

- Suppose the tires on your car are inflated to 32 psig at 25°C (77°F). What is the tire pressure at -10°C (14°F)? Assume that you are at sea level. Would this make a difference in your answer?

Time Saver!

Concept: # moles do not change!

$$n = \frac{P_1V}{RT_1} = \frac{P_2V}{RT_2} \Rightarrow P_2/T_2 = P_1/T_1$$

Must use absolute P and T

P_1 = 32 psig + 14.7 psia =46.7 psia
$P_2 = P_1(T_2/T_1)$ = 46.7 psia * (263 K/298 K) = 41.2 psia
41.2 – 14.7 = 26.5 psig

If P_{atm} = 12.5, P_2 = 39.3 psia = 26.8 psig

Tom Brady & Deflate-Gate

Concepts: # moles do not change!
V constant

- T = 72°F indoors (532°R)
- T = 10°F Outdoors (470°R)
- V = constant
- Regulation: 12.5 to 13.5 psig
- $\frac{n}{V} = constant = \frac{P_1}{RT_1} = \frac{P_2}{RT_2}$
- $P_{out} = P_{indoor}\left(\frac{T_{out}}{T_{indoors}}\right)$

$$12.5\ psig = 27.2\ psia\left(\frac{470°R}{532°R}\right) = 24.0\ psia = 9.3\ psig$$

- 11.9 psig if starting pressure was 13.5 psig

Caution

- Only take ratios of values in absolute units
- **NEVER** take ratios of:
  - Temperatures in °C or °F (instead use K or °R)
  - Gauge pressures (instead use absolute pressures)

Standard Conditions

- Provide a reference point for reporting gas flows
- Convenient for use in calculations with ideal gas law
- Units generally reported by flow meters

SI
T_s = 0°C = 273K
P_s = 1 atm
V_s = 0.022415 m^3 (22.415 L/mol)
n_s = 1 gmol

American Engineering
T_s = 492°R (i.e., 32°F)
P_s = 1 atm
$\hat{V}_s$ = 359 ft^3/lb-mol
n_s = 1 lb-mol

Used frequently by author

Society of Petroleum Engineers (common industrial standard)
T_s = 60°F
P_s = 14.7 psia

Gas Flows under Standard Conditions

- **SCM**: standard cubic meters (m^3 STP)
- **SCF**: standard cubic feet (ft^3 STP)
- **SCFM**: standard cubic feet per minute (ft^3/min STP)
- **SCMH**: standard cubic meters per hour (m^3/hr STP)
- **SCFH**: standard cubic feet per hour (ft^3/hr STP)
- **SCCM**: standard cubic centimeters per minute (cm^3/min STP)
- **SLPM:** standard liters per minute (lit/min STP)

Gas Flows under Standard Conditions

- **SCM**: standard cubic meters (m^3 STP)
- **SCF**: standard cubic feet (ft^3 STP)
- **SCFM**: standard cubic feet per minute (ft^3/min STP)
- **SCMH**: standard cubic meters per hour (m^3/hr STP)
- **SCFH**: standard cubic feet per hour (ft^3/hr STP)
- **SCCM**: standard cubic centimeters per minute (cm^3/min STP)
- **SLPM:** standard liters per minute (lit/min STP)

Frequently used in Dr. Fletcher's experience

Standard Conditions and Ideal Gas Calculations

$PV = nRT$

Concepts: *n* does not change!
$\dot{n}$ does not change!

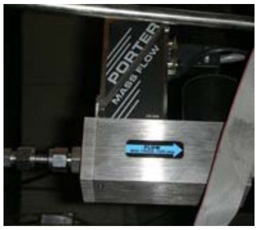
$P_s\hat{V}_s = RT_s$ (s = standard state)

$$\frac{P\hat{V}}{RT} = \frac{P_s\hat{V}_s}{RT_s} \quad \text{so} \quad \frac{P\hat{V}}{T} = \frac{P_s\hat{V}_s}{T_s} \qquad \frac{P\dot{V}}{T} = \frac{P_s\dot{V}_s}{T_s}$$

Given standard volume or volumetric flow rate, use ratios to convert to actual volume or volumetric flow rate

Flow Meters Often Report Standard Conditions

- Examples from my labs



Mass flow controller (slpm)

Rotameters (slpm or sccm)

Example

- The flow rate of a stream at 285°F and 1.3 atm is measured with an orifice meter. The calibration chart for the meter indicates that the flow is 3.95 x 10^5 SCFM. Calculate the molar flow rate and the true volumetric flow rate of the stream.

$$\dot{n} = \frac{P\dot{V}}{RT} = \frac{P_S\dot{V}_S}{RT_S} \quad \text{so}$$

Absolute T's

$$\dot{V} = \dot{V}_s\left(\frac{P_s}{P}\right)\left(\frac{T}{T_s}\right) = 3.95\times10^5\,SCFM\left(\frac{1\,atm}{1.3\,atm}\right)\left(\frac{745°R}{492°R}\right) = 4.60\times10^5\,ft^3/\min$$

Gas Mixtures

- **Partial pressure** of component A

$p_A = y_AP_{tot}$

- Dalton's Law

total P = sum of partial pressures

Example: At sea level, what is the partial pressure of O_2?

$p_{O2} = y_{O2}\ P_{tot} = 0.21*1.0\text{ atm} = 0.21\text{ atm}$

- Good for both ideal and non-ideal gases!

Gas Mixtures (cont.)

- In LaBarge, Wyoming, there is a natural gas well for ExxonMobil
- Gas composition coming from the well is:
  - $y_{CO2} = 0.70$
  - $y_{CH4} = 0.25$
  - $y_{H2S} = 0.05$
- If the total pressure in the well is 20 atm, what is the partial pressure of CH_4?

$P_{CH4} = y_{CH4}\ P_{tot}$
$= (0.25)(20\text{ atm})$
$= 5\text{ atm}$

Ideal Gas Mixtures

- Amagat's Law

partial volumes add up to total volume

$v_A + v_B + \ldots = V_{tot}$

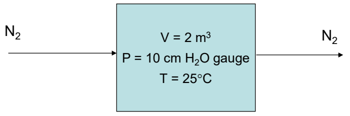
- Volume fraction = mole fraction

percent by volume = mole percent

$v_A = y_A\ V_{tot}$

Good only for ideal gases!

Problem 5.9 (purging a box)



N_2

$V = 2\ m^3$

$P = 10$ cm H_2O gauge

$T = 25°C$

N_2

Replace volume every 5 minutes

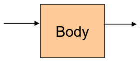
Find $\dot{m}_{N2}$

(a) Calculate $\dot{m}_{N2}$ using the ideal gas equation (easy)

(b) Calculate $\dot{m}_{N2}$ using 22.4 L/mol at standard conditions (this way is confusing)

HW Hints

- 5.15 (5.11) – gas cylinder
  - Total mass = $m_{tank} + m_{gas}$
  - $m_{gas} = n_{gas}\ MW_{gas}$
  - With constant volume at STP, n = constant
- 5.25 (5.19 – workbook)
- 5.34 (5.25) – Avg MW, mass fraction
- 5.36 (5.27) – breathing
  - Find $\dot{V}_{in}$, convert to $\dot{m}_{in}$
  - N_2 balance, find $\dot{m}_{out}$ and $\dot{V}_{out}$



Body