

# EVALUATING PROPERTIES FOR A PURE SUBSTANCES

# Outlines

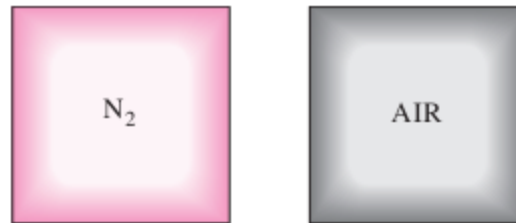
- TV, PV, PT, PVT Diagram
- Property Tables
- Introduction to Enthalpy
- Reference State & Reference Values
- Ideal Gas Equation of State
- Compressibility Factor
- Other Equation of State

# Phase, Pure Substances

- **PHASE** refers to a quantity of matter that is homogeneous throughout in both chemical composition and physical structure
- **PURE SUBSTANCE** is one that is uniform and invariable in chemical composition

# Pure Substances

- A pure substance does not have to be of a single chemical element or compound
- A mixture of various chemical elements or compounds also qualifies as a pure substance as long as the mixture is homogeneous, example : Air

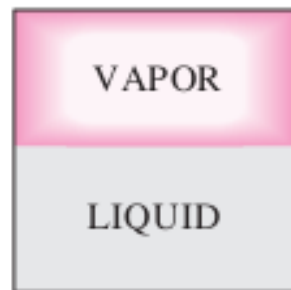


**FIGURE 3-1**

Nitrogen and gaseous air are pure substances.

# Pure Substance on Different Phases

- A mixture of two or more phases of a pure substance is still a pure substance as long as the chemical composition of all phases is the same.  
For example:
  - A mixture of ice and liquid water, is a pure substance
  - A mixture of liquid air and gaseous air, however, is not a pure substance

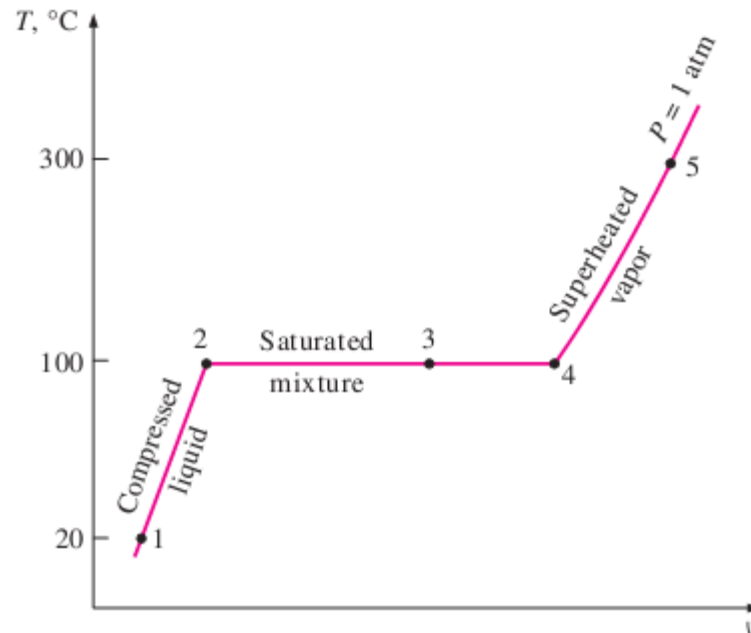
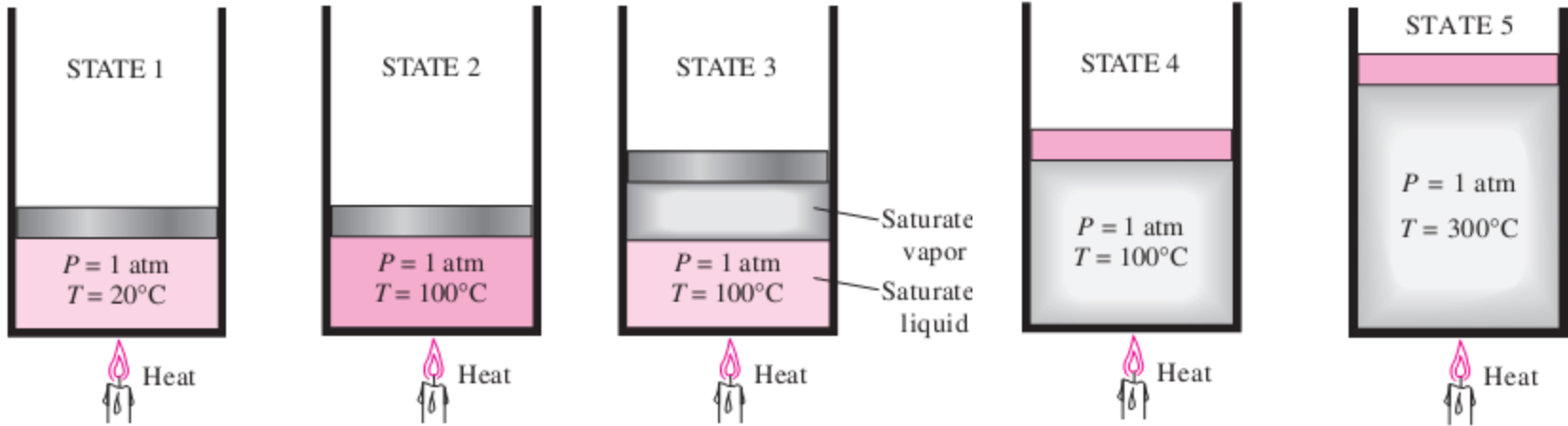


(a) H<sub>2</sub>O

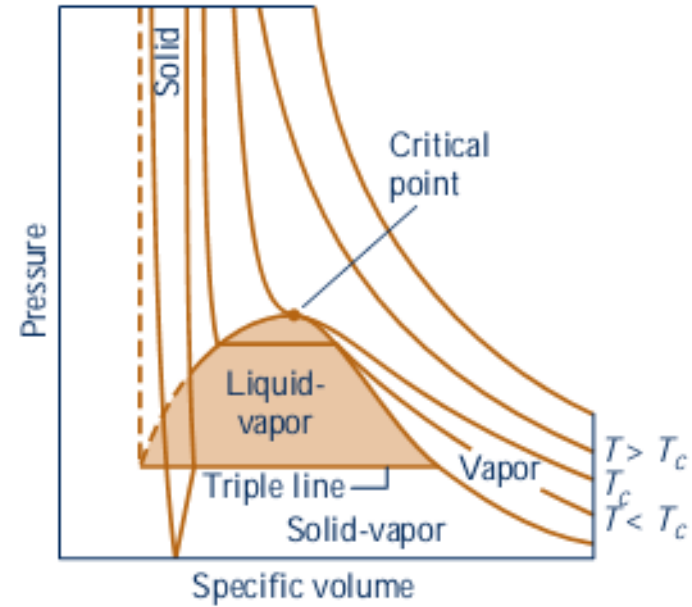
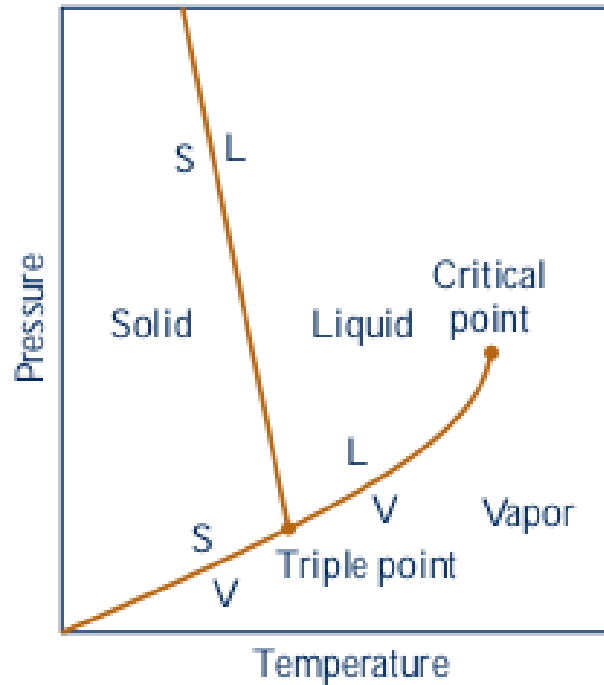
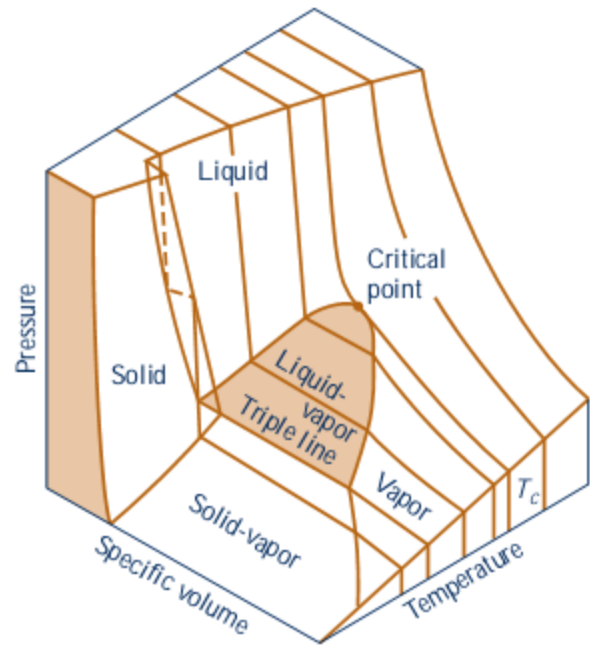


(b) AIR

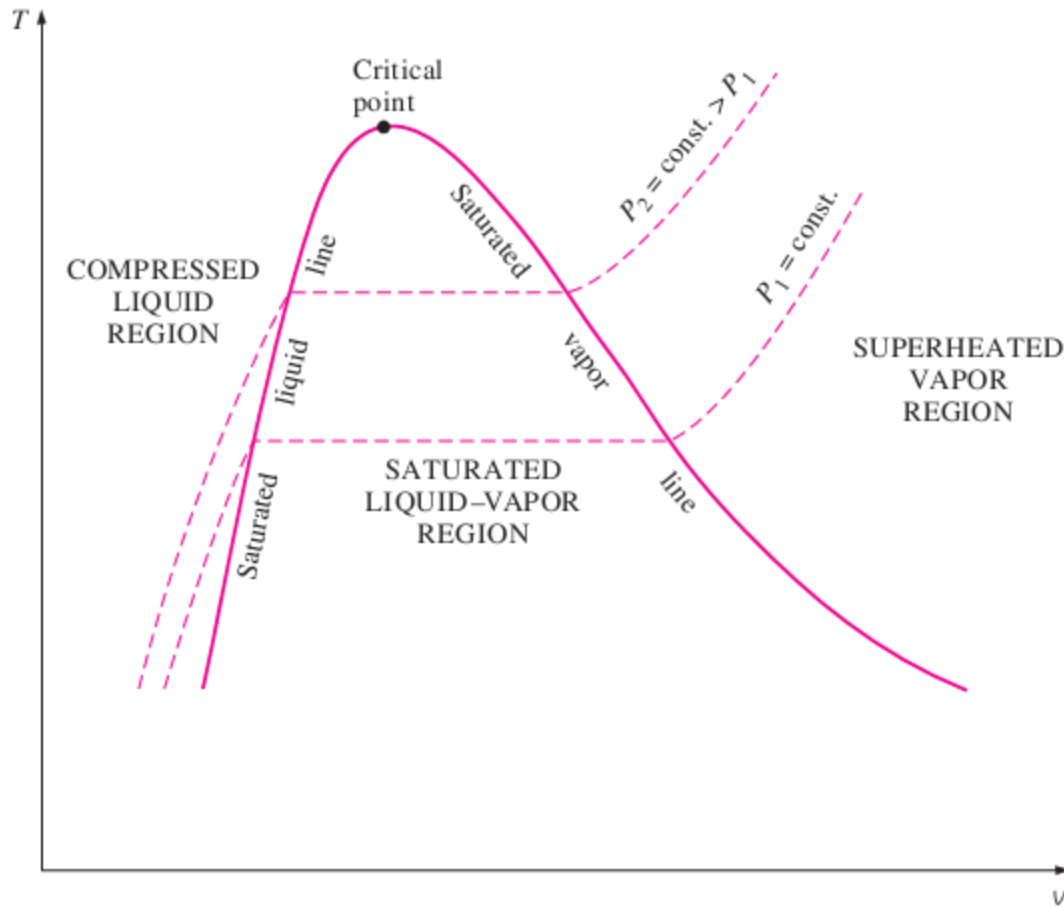
# Sub-cooled, Saturated, Superheated



# PVT diagram

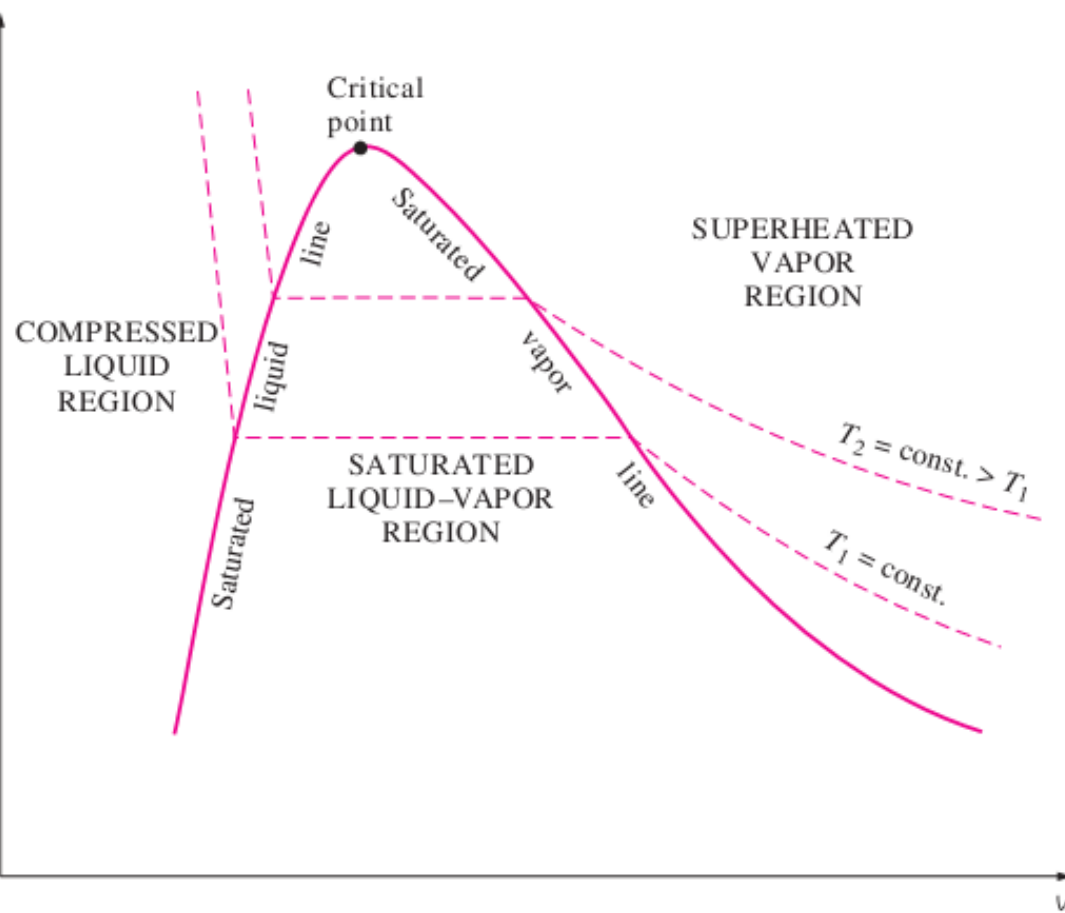


# T-V Diagram





# P-V diagram



# Superheated vs Saturated vs. Subcooled

Compared to saturated vapor, superheated vapor is characterized by

Lower pressures ( $P < P_{sat}$  at a given  $T$ )

Higher temperatures ( $T > T_{sat}$  at a given  $P$ )

Higher specific volumes ( $v > v_g$  at a given  $P$  or  $T$ )

Higher internal energies ( $u > u_g$  at a given  $P$  or  $T$ )

Higher enthalpies ( $h > h_g$  at a given  $P$  or  $T$ )

In general, a compressed liquid is characterized by

Higher pressures ( $P > P_{sat}$  at a given  $T$ )

Lower temperatures ( $T < T_{sat}$  at a given  $P$ )

Lower specific volumes ( $v < v_f$  at a given  $P$  or  $T$ )

Lower internal energies ( $u < u_f$  at a given  $P$  or  $T$ )

Lower enthalpies ( $h < h_f$  at a given  $P$  or  $T$ )

# Property Tables, Evaluating P, V, T Vapor & Liquid Tables

- Moran, Table A-4 → Superheated Water Vapor

Properties of Superheated Water Vapor

$T$ °C	$v$ m <sup>3</sup> /kg	$u$ kJ/kg	$h$ kJ/kg	$s$ kJ/kg · K	$v$ m <sup>3</sup> /kg	$u$ kJ/kg	$h$ kJ/kg	$s$ kJ/kg · K
$p = 0.06 \text{ bar} = 0.006 \text{ MPa}$ ( $T_{\text{sat}} = 36.16^\circ\text{C}$ )					$p = 0.35 \text{ bar} = 0.035 \text{ MPa}$ ( $T_{\text{sat}} = 72.69^\circ\text{C}$ )			
Sat.	23.739	2425.0	2567.4	8.3304	4.526	2473.0	2631.4	7.7158
80	27.132	2487.3	2650.1	8.5804	4.625	2483.7	2645.6	7.7564
120	30.219	2544.7	2726.0	8.7840	5.163	2542.4	2723.1	7.9644
160	33.302	2602.7	2802.5	8.9693	5.696	2601.2	2800.6	8.1519
200	36.383	2661.4	2879.7	9.1398	6.228	2660.4	2878.4	8.3237
240	39.462	2721.0	2957.8	9.2982	6.758	2720.3	2956.8	8.4828
280	42.540	2781.5	3036.8	9.4464	7.287	2780.9	3036.0	8.6314
320	45.618	2843.0	3116.7	9.5859	7.815	2842.5	3116.1	8.7712
360	48.696	2905.5	3197.7	9.7180	8.344	2905.1	3197.1	8.9034
400	51.774	2969.0	3279.6	9.8435	8.872	2968.6	3279.2	9.0291
440	54.851	3033.5	3362.6	9.9633	9.400	3033.2	3362.2	9.1490
500	59.467	3132.3	3489.1	10.1336	10.192	3132.1	3488.8	9.3194

# Property Tables, Evaluating P, V, T Vapor & Liquid Tables

- Moran, Table A-5 → Sub-cooled Liquid Water

**TABLE A-5**

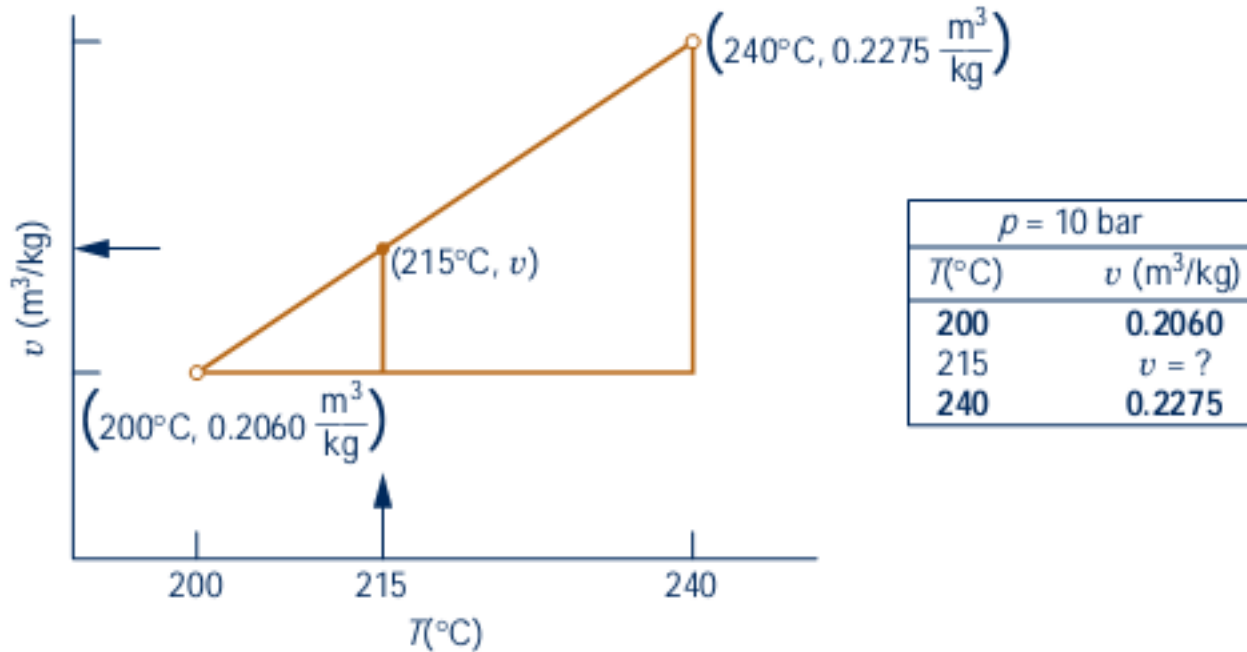
**Properties of Compressed Liquid Water**

$T$ °C	$v \times 10^3$ m <sup>3</sup> /kg	$u$ kJ/kg	$h$ kJ/kg	$s$ kJ/kg · K	$v \times 10^3$ m <sup>3</sup> /kg	$u$ kJ/kg	$h$ kJ/kg	$s$ kJ/kg · K
$p = 25 \text{ bar} = 2.5 \text{ MPa}$ ( $T_{\text{sat}} = 223.99^\circ\text{C}$ )					$p = 50 \text{ bar} = 5.0 \text{ MPa}$ ( $T_{\text{sat}} = 263.99^\circ\text{C}$ )			
20	1.0006	83.80	86.30	.2961	.9995	83.65	88.65	.2956
40	1.0067	167.25	169.77	.5715	1.0056	166.95	171.97	.5705
80	1.0280	334.29	336.86	1.0737	1.0268	333.72	338.85	1.0720
100	1.0423	418.24	420.85	1.3050	1.0410	417.52	422.72	1.3030
140	1.0784	587.82	590.52	1.7369	1.0768	586.76	592.15	1.7343
180	1.1261	761.16	763.97	2.1375	1.1240	759.63	765.25	2.1341
200	1.1555	849.9	852.8	2.3294	1.1530	848.1	853.9	2.3255
220	1.1898	940.7	943.7	2.5174	1.1866	938.4	944.4	2.5128
Sat.	1.1973	959.1	962.1	2.5546	1.2859	1147.8	1154.2	2.9202

# Exercise

- Find the following:
  - Saturation Temperature of Water at 10 MPa
  - Specific Volume of Water Vap. at 10 MPa, 600 °C
  - Specific Volume of Liq. Water at 10 MPa, 100 °C
  - Specific Volume of Water Vap. at 10 Bar, 215 °C

# Linear Interpolation



3.7 The following table lists temperatures and specific volumes of water vapor at two pressures:

$p = 1.0 \text{ MPa}$		$p = 1.5 \text{ MPa}$	
$T \text{ (}^\circ\text{C)}$	$v \text{ (m}^3\text{/kg)}$	$T \text{ (}^\circ\text{C)}$	$v \text{ (m}^3\text{/kg)}$
200	0.2060	200	0.1325
240	0.2275	240	0.1483
280	0.2480	280	0.1627

Data encountered in solving problems often do not fall exactly on the grid of values provided by property tables, and *linear interpolation* between adjacent table entries becomes necessary. Using the data provided here, estimate

- the specific volume at  $T = 240^\circ\text{C}$ ,  $p = 1.25 \text{ MPa}$ , in  $\text{m}^3\text{/kg}$ .
- the temperature at  $p = 1.5 \text{ MPa}$ ,  $v = 0.1555 \text{ m}^3\text{/kg}$ , in  $^\circ\text{C}$ .
- the specific volume at  $T = 220^\circ\text{C}$ ,  $p = 1.4 \text{ MPa}$ , in  $\text{m}^3\text{/kg}$ .

# Enthalpy

- Energy Balance :  $U = Q + W$
- At constant Pressure :  
 $U = Q - PdV \rightarrow Q = U + PdV$
- At constant Volume :  
 $U = Q - PdV \rightarrow Q = U$
- For convenience, we define a new variable:  
Enthalpy ( $H$ ) =  $U + PV$  (in Energy Unit)  
Per unit mass:  
 $h = u + Pv \rightarrow$  easier to tabulate



# Property Tables, Evaluating P, V, T Saturation Tables

- Moran, Table A-2 → Temperature Table

**TABLE A-2**

**Properties of Saturated Water (Liquid–Vapor): Temperature Table**

Pressure Conversions:  
1 bar = 0.1 MPa  
= 10<sup>2</sup> kPa

Temp. °C	Press. bar	Specific Volume m <sup>3</sup> /kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg · K		Temp. °C
		Sat. Liquid $v_f \times 10^3$	Sat. Vapor $v_g$	Sat. Liquid $u_f$	Sat. Vapor $u_g$	Sat. Liquid $h_f$	Evap. $h_{fg}$	Sat. Vapor $h_g$	Sat. Liquid $s_f$	Sat. Vapor $s_g$	
.01	0.00611	1.0002	206.136	0.00	2375.3	0.01	2501.3	2501.4	0.0000	9.1562	.01
4	0.00813	1.0001	157.232	16.77	2380.9	16.78	2491.9	2508.7	0.0610	9.0514	4
5	0.00872	1.0001	147.120	20.97	2382.3	20.98	2489.6	2510.6	0.0761	9.0257	5
6	0.00935	1.0001	137.734	25.19	2383.6	25.20	2487.2	2512.4	0.0912	9.0003	6
8	0.01072	1.0002	120.917	33.59	2386.4	33.60	2482.5	2516.1	0.1212	8.9501	8
10	0.01228	1.0004	106.379	42.00	2389.2	42.01	2477.7	2519.8	0.1510	8.9008	10
11	0.01312	1.0004	99.857	46.20	2390.5	46.20	2475.4	2521.6	0.1658	8.8765	11
12	0.01402	1.0005	93.784	50.41	2391.9	50.41	2473.0	2523.4	0.1806	8.8524	12
13	0.01497	1.0007	88.124	54.60	2393.3	54.60	2470.7	2525.3	0.1953	8.8285	13
14	0.01598	1.0008	82.848	58.79	2394.7	58.80	2468.3	2527.1	0.2099	8.8048	14
15	0.01705	1.0009	77.926	62.99	2396.1	62.99	2465.9	2528.9	0.2245	8.7814	15
16	0.01818	1.0011	73.333	67.18	2397.4	67.19	2463.6	2530.8	0.2390	8.7582	16
17	0.01938	1.0012	69.044	71.38	2398.8	71.38	2461.2	2532.6	0.2535	8.7351	17
18	0.02064	1.0014	65.038	75.57	2400.2	75.58	2458.8	2534.4	0.2679	8.7123	18
19	0.02198	1.0016	61.293	79.76	2401.6	79.77	2456.5	2536.2	0.2823	8.6897	19

# Property Tables, Evaluating P, V, T Saturation Tables

- Moran, Table A-3 → Pressure Table

**TABLE A-3**

**Properties of Saturated Water (Liquid–Vapor): Pressure Table**

Pressure Conversions:  
1 bar = 0.1 MPa  
= 10<sup>2</sup> kPa

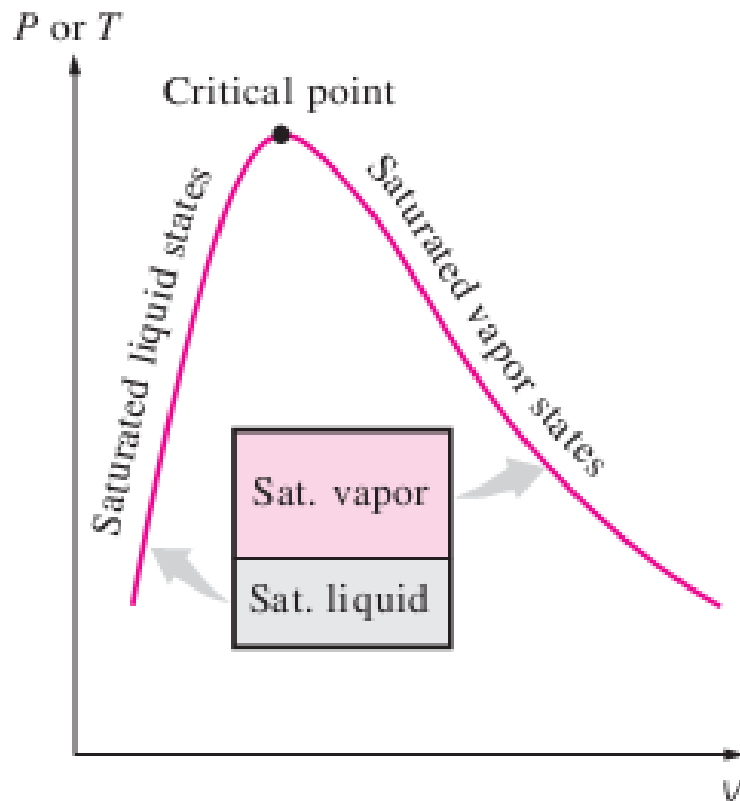
Press. bar	Temp. °C	Specific Volume m <sup>3</sup> /kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg · K		Press. bar
		Sat. Liquid $v_f \times 10^3$	Sat. Vapor $v_g$	Sat. Liquid $u_f$	Sat. Vapor $u_g$	Sat. Liquid $h_f$	Evap. $h_{fg}$	Sat. Vapor $h_g$	Sat. Liquid $s_f$	Sat. Vapor $s_g$	
0.04	28.96	1.0040	34.800	121.45	2415.2	121.46	2432.9	2554.4	0.4226	8.4746	0.04
0.06	36.16	1.0064	23.739	151.53	2425.0	151.53	2415.9	2567.4	0.5210	8.3304	0.06
0.08	41.51	1.0084	18.103	173.87	2432.2	173.88	2403.1	2577.0	0.5926	8.2287	0.08
0.10	45.81	1.0102	14.674	191.82	2437.9	191.83	2392.8	2584.7	0.6493	8.1502	0.10
0.20	60.06	1.0172	7.649	251.38	2456.7	251.40	2358.3	2609.7	0.8320	7.9085	0.20
0.30	69.10	1.0223	5.229	289.20	2468.4	289.23	2336.1	2625.3	0.9439	7.7686	0.30
0.40	75.87	1.0265	3.993	317.53	2477.0	317.58	2319.2	2636.8	1.0259	7.6700	0.40
0.50	81.33	1.0300	3.240	340.44	2483.9	340.49	2305.4	2645.9	1.0910	7.5939	0.50
0.60	85.94	1.0331	2.732	359.79	2489.6	359.86	2293.6	2653.5	1.1453	7.5320	0.60
0.70	89.95	1.0360	2.365	376.63	2494.5	376.70	2283.3	2660.0	1.1919	7.4797	0.70

Table A.3-A.5 is also known as **Steam Tables**

# Example

**3.9** Determine the volume change, in  $\text{ft}^3$ , when 1 lb of water, initially saturated liquid, is heated to saturated vapor while pressure remains constant at 1.0, 14.7, 100, and 500, each in  $\text{lb}/\text{in.}^2$  Comment.

# Mixture of Vapor & Liquid



Quality / Vapor Fraction:

$$x = \frac{m_{\text{vapor}}}{m_{\text{total}}}$$

$$v = (1 - x)v_f + xv_g$$

$$u = (1 - x)u_f + xu_g$$

$$h = (1 - x)h_f + xh_g$$

# Example

**3.16** Two kg of a two-phase, liquid–vapor mixture of carbon dioxide ( $\text{CO}_2$ ) exists at  $-40^\circ\text{C}$  in a  $0.05 \text{ m}^3$  tank. Determine the quality of the mixture, if the values of specific volume for saturated liquid and saturated vapor  $\text{CO}_2$  at  $-40^\circ\text{C}$  are  $v_f = 0.896 \times 10^{-3} \text{ m}^3/\text{kg}$  and  $v_g = 3.824 \times 10^{-2} \text{ m}^3/\text{kg}$ , respectively.

**3.17** Each of the following exercises requires evaluating the quality of a two-phase liquid–vapor mixture:

(a) The quality of a two-phase liquid–vapor mixture of  $\text{H}_2\text{O}$  at  $40^\circ\text{C}$  with a specific volume of  $10 \text{ m}^3/\text{kg}$  is

(i) 0, (ii) 0.486 (iii) 0.512, (iv) 1.

(b) The quality of a two-phase liquid–vapor mixture of propane at 20 bar with a specific internal energy of  $300 \text{ kJ/kg}$  is (i) 0.166, (ii) 0.214, (iii) 0.575, (iv) 0.627

(c) The quality of a two-phase liquid–vapor mixture of Refrigerant 134a at  $90 \text{ lbf/in.}^2$  with a specific enthalpy of  $90 \text{ Btu/lb}$  is (i) 0.387, (ii) 0.718, (iii) 0.806, (iv) 0.854.

(d) The quality of a two-phase liquid–vapor mixture of ammonia at  $-20^\circ\text{F}$  with a specific volume of  $11 \text{ ft}^3/\text{lb}$  is (i) 0, (ii) 0.251, (iii) 0.537 (iv) 0.749.

# Reference state & reference values

- $u$  ,  $h$  , and  $s \neq$  direct measurement
- $u$  ,  $h$  , and  $s =$  calculated from experiment
- When applying the energy balance, it is differences in internal, kinetic, and potential energy between two states that are important, and not the values of these energy quantities at each of the two states.
- Remember to check what is the reference state & reference values used by the data tables

# Energy Balance using Property Tables

- Water contained in a piston–cylinder assembly undergoes two processes in series from an initial state where the pressure is 10 bar and the temperature is 400°C.
  - Process 1–2 : The water is cooled as it is compressed at a constant pressure of 10 bar to the saturated vapor state.
  - Process 2–3: The water is cooled at constant volume to 150°C.
- a) Sketch both processes on T–v and p–v diagrams.
- b) For the overall process determine the work, in kJ/kg.
- c) For the overall process determine the heat transfer, in kJ/kg.

# Specific Heat ( $C_v$ & $C_p$ )

$$c_v = \left( \frac{\partial u}{\partial T} \right)_v \longrightarrow \text{Constant Volume}$$

$$c_p = \left( \frac{\partial h}{\partial T} \right)_p \longrightarrow \text{Constant Pressure}$$

Units:  
kJ/kg K or kJ/kmol K

Specific Heat Ratio (dimensionless)

$$k = \frac{c_p}{c_v}$$



# Incompressible Substance Model

- Incompressible : applicable for liquids, solids

$$h(T, p) = u(T) + pv$$

## TAKE NOTE...

For a substance modeled as incompressible,

$$v = \text{constant}$$

$$u = u(T)$$

differentiating Eq. above with respect to temperature while holding pressure fixed obtains:

$$\left(\frac{\partial h}{\partial T}\right)_p = \frac{du}{dT}$$

$$c_p = c_v \quad (\text{incompressible})$$

$$u_2 - u_1 = c(T_2 - T_1)$$

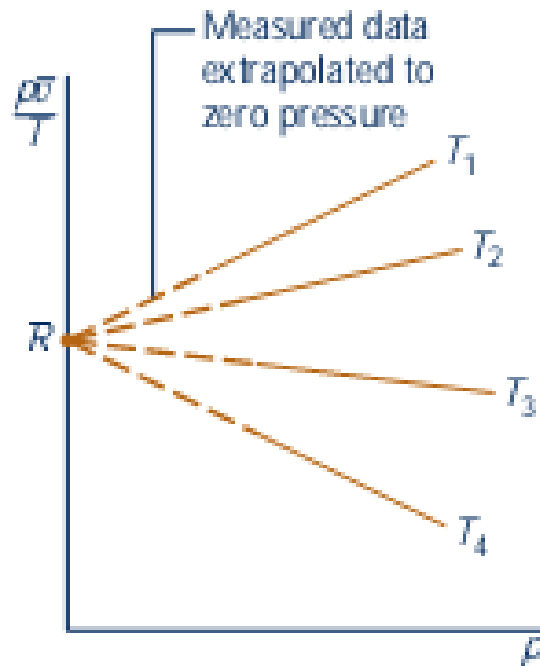
$$h_2 - h_1 = c(T_2 - T_1) +$$

$$v(p_2 - p_1)$$

(incompressible, constant  $c$ )

Negligible

# Ideal Gas Model



**Fig. 3.10** Sketch of  $p\bar{v}/T$  versus pressure for a gas at several specified values of temperature.

## Ideal Gas Equation of State (EOS)

$$pV = mRT$$

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

$$pv = RT$$

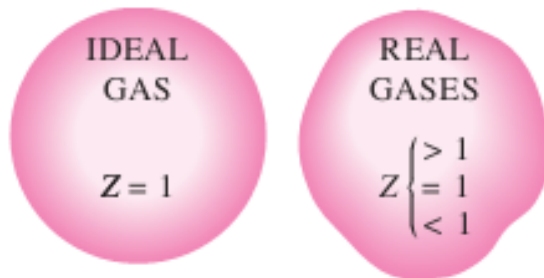
$$u = u(T)$$

$$h = h(T) = u(T) + RT$$

$$\lim_{p \rightarrow 0} \frac{p\bar{v}}{T} = \bar{R}$$

# Compressibility Factor

- A measure of deviation from Ideal Gas behavior

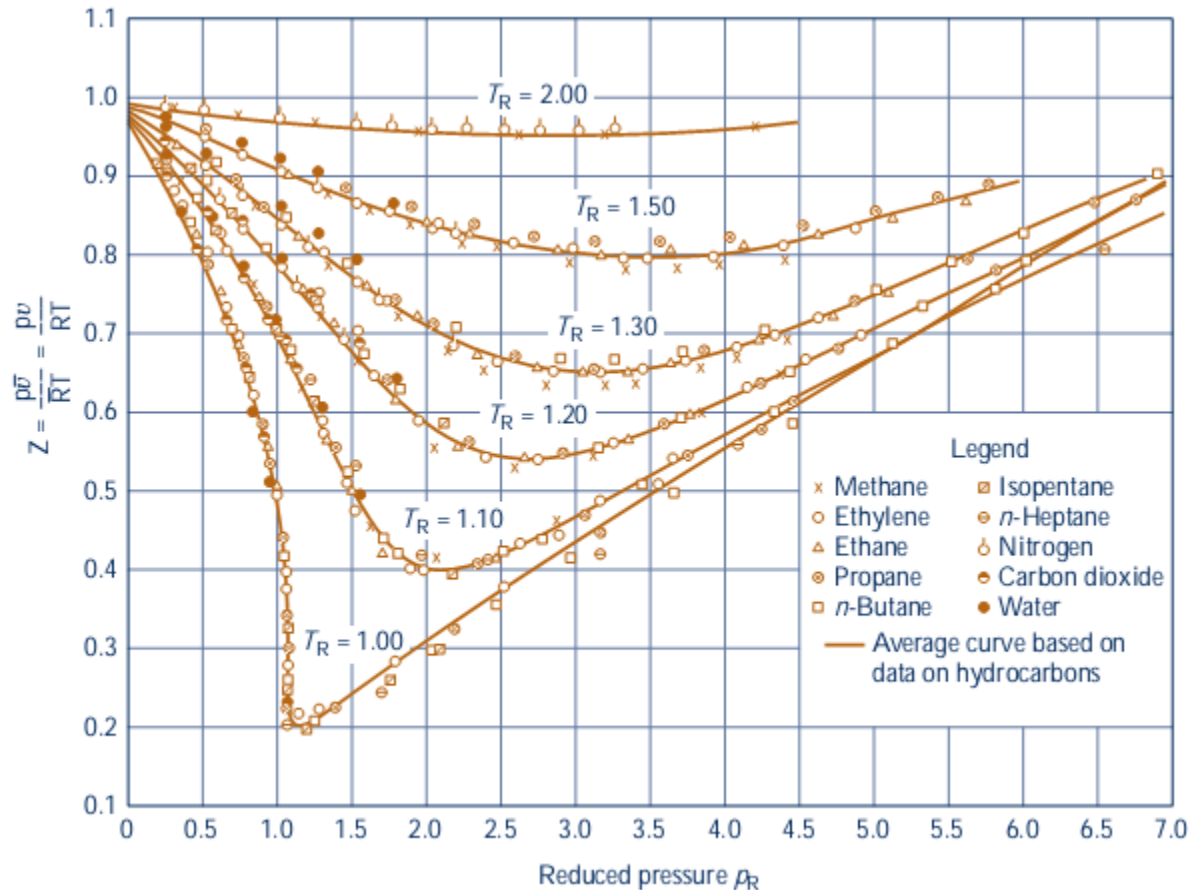


1. At very low pressures ( $P_R \ll 1$ ), gases behave as an ideal gas regardless of temperature (Fig. 3–52),
2. At high temperatures ( $T_R > 2$ ), ideal-gas behavior can be assumed with good accuracy regardless of pressure (except when  $P_R \gg 1$ ).
3. The deviation of a gas from ideal-gas behavior is greatest in the vicinity of the critical point (Fig. 3–53).

**FIGURE 3–50**

The compressibility factor is unity for ideal gases.

# General Compressibility data, Z-chart



$$p_R = p/p_c$$

$$T_R = T/T_c$$

In this lecture, only single component is considered.  
Multi-component Z-value will not be covered

# Other Equation of State

Van der Waals Equation of State

$$\left(P + \frac{a}{v^2}\right)(v - b) = RT$$

Beattie-Bridgeman Equation of State

$$P = \frac{R_u T}{\bar{v}^2} \left(1 - \frac{c}{\bar{v} T^3}\right) (\bar{v} + B) - \frac{A}{\bar{v}^2}$$

Benedict-Webb-Rubin Equation of State

$$P = \frac{R_u T}{\bar{v}} + \left(B_0 R_u T - A_0 - \frac{C_0}{T^2}\right) \frac{1}{\bar{v}^2} + \frac{b R_u T - a}{\bar{v}^3} + \frac{a\alpha}{\bar{v}^6} + \frac{c}{\bar{v}^3 T^2} \left(1 + \frac{\gamma}{\bar{v}^2}\right) e^{-\gamma/\bar{v}^2}$$

And still many more....

# $\Delta U, \Delta H, C_p, C_v$ Relations

$$u(T_2) - u(T_1) = \int_{T_1}^{T_2} c_v(T) dT \quad (\text{ideal gas})$$

$$h(T_2) - h(T_1) = \int_{T_1}^{T_2} c_p(T) dT \quad (\text{ideal gas})$$

For ideal gas:

$$h = h(T) = u(T) + RT$$

$$c_p(T) = c_v(T) + R \quad (\text{ideal gas})$$

# Using Specific Heat Function

$$\frac{\bar{c}_p}{R} = \alpha + \beta T + \gamma T^2 + \delta T^3 + \epsilon T^4$$

*T* is in K, equations valid from 300 to 1000 K

Gas	$\alpha$	$\beta \times 10^3$	$\gamma \times 10^6$	$\delta \times 10^9$	$\epsilon \times 10^{12}$
CO	3.710	-1.619	3.692	-2.032	0.240
CO <sub>2</sub>	2.401	8.735	-6.607	2.002	0
H <sub>2</sub>	3.057	2.677	-5.810	5.521	-1.812
H <sub>2</sub> O	4.070	-1.108	4.152	-2.964	0.807
O <sub>2</sub>	3.626	-1.878	7.055	-6.764	2.156
N <sub>2</sub>	3.675	-1.208	2.324	-0.632	-0.226
Air	3.653	-1.337	3.294	-1.913	0.2763
SO <sub>2</sub>	3.267	5.324	0.684	-5.281	2.559
CH <sub>4</sub>	3.826	-3.979	24.558	-22.733	6.963
C <sub>2</sub> H <sub>2</sub>	1.410	19.057	-24.501	16.391	-4.135
C <sub>2</sub> H <sub>4</sub>	1.426	11.383	7.989	-16.254	6.749

In some cases, constant Cp or Cv may be assumed

# Energy Balance using Ideal Gas Tables

- Table for Ideal Gas can be found in Table A.22 and A.23

TABLE A-22

Ideal Gas Properties of Air

T(K), h and u(kJ/kg), s° (kJ/kg · K)											
T	h	u	s°	when $\Delta s = 0$		T	h	u	s°	when $\Delta s = 0$	
				p <sub>r</sub>	v <sub>r</sub>					p <sub>r</sub>	v <sub>r</sub>
200	199.97	142.56	1.29559	0.3363	1707.	450	451.80	322.62	2.11161	5.775	223.6
210	209.97	149.69	1.34444	0.3987	1512.	460	462.02	329.97	2.13407	6.245	211.4
220	219.97	156.82	1.39105	0.4690	1346.	470	472.24	337.32	2.15604	6.742	200.1
230	230.02	164.00	1.43557	0.5477	1205.	480	482.49	344.70	2.17760	7.268	189.5
240	240.02	171.13	1.47824	0.6355	1084.	490	492.74	352.08	2.19876	7.824	179.7

Note that this table is different from Table A.2-A-18, since this table is only applicable for **Ideal Gas**



# Exercise

- A rigid tank contains 50 kg of saturated liquid water at  $90^{\circ}\text{C}$ . Determine the pressure in the tank and the volume of the tank.
- A piston–cylinder device contains 2 ft<sup>3</sup> of saturated water vapor at 50-psia pressure. Determine the temperature and the mass of the vapor inside the cylinder
- A mass of 200 g of saturated liquid water is completely vaporized at a constant pressure of 100 kPa. Determine;
  - a. the volume change
  - b. the amount of energy transferred to the water

# Exercise

- determine the specific enthalpy of Refrigerant-22 when its temperature is  $12^{\circ}\text{C}$  and its specific internal energy is  $144.58 \text{ kJ/kg}$ .

# Homework #4 due on Tuesday, March 13<sup>th</sup>

- Create a summary of Key Learning Points from Chapter 1-3, in one page of Plain Duplex A4, It can contain:
  - Equations
  - Important Conversion Factors
  - Theory, Concepts, Definition
  - Sketches/Diagram
  - Problem example with solution
  - Other important Key Learning Points
- Must be **Hand written**, using non-black pen (Blue/Red/etc)
- Fit as many information as possible, small writing is encouraged (as long as you can read it), utilize every space available
- This summary will be a part of your notes for Mid-Exam (you'll be allowed to bring 2 pages of this summary)