

#### Chapter 3

# Properties of Pure Substances



#### Pure Substance

- A substance that has a fixed (homogeneous and invariable) chemical composition throughout is called a *pure substance*.
- It may exist in more than one phase, but the chemical composition is the same in all phases.
- Examples:
  - Water (solid, liquid, and vapor phases)
  - Mixture of liquid water and water vapor
  - Carbon Dioxide
  - Nitrogen
  - Homogeneous mixture of gases, such as air, as long as there is no change of phases.



# Multiple phases mixture of a Pure Substance

Water

Air

vapor

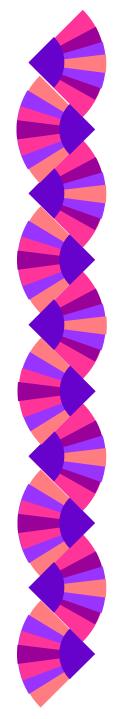
liquid

Pure  $H_2O$ 

vapor

liquid

Not pure, different condensation temperatures for different components



#### Important Questions ....

- How many properties are needed to define the state of a system?
- The number of independent intensive properties needed to characterize the state of a system is *n+1* where *n* is the number of relevant quasi equilibrium work modes.
- This is empirical, and is based on the experimental observation.



#### Important Questions ....

• How do we obtain those properties?

**Equation of State** 

**Property Tables** 



### Simple System

- A <u>simple system</u> is defined as one for which only <u>one</u> quasiequilibrium work mode applies.
- Simple elastic systems
- Simple magnetic systems
- Simple electrostatic systems, etc.
- Simple compressible systems  $W = \int PdV$ ,

$$\frac{W}{m} = w = \int P d\left(\frac{V}{m}\right) = \int P dv$$



#### For a simple compressible system,

• We may write P = P(v,T)

or v = v(P,T)

or perhaps T = T(P,v)

- Equations used to relate properties are called "Equations of State"
- A simple state equation is the one applied to ideal gases:

PV = mRT

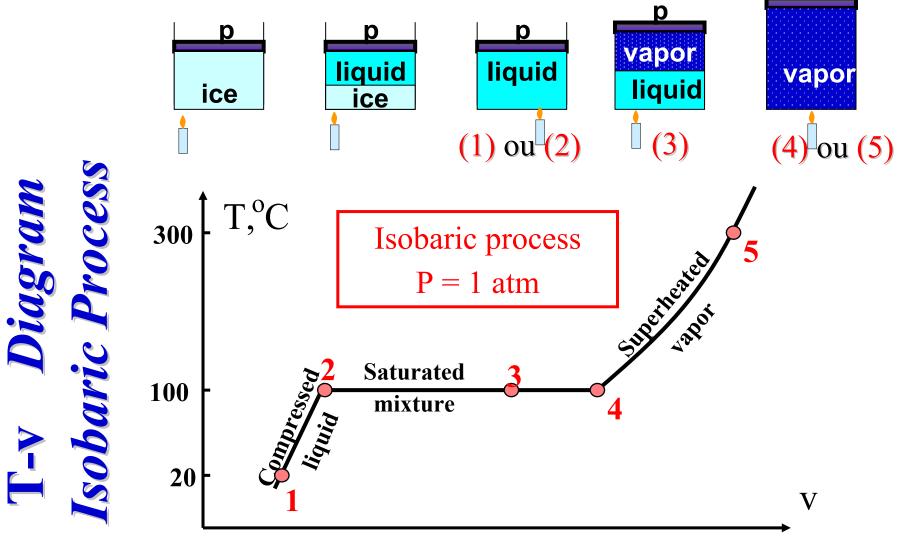


- The properties of fluids near liquid to vapor transition CAN NOT be represented by Ideal Gas Law!
- Today we are going to study these substances.
- There is no simple relationship to define a state equation.
- The properties are usually in the form of tables.



#### Phases of a Pure Substance

- Solid phase -- molecules are arranged in a 3D pattern (lattice).
- Liquid phase -- chunks of molecules float about each other, but maintain an orderly structure and relative positions within each chunk.
- Gas phase -- random motion, high energy level.



- Tsat -- Temperature at which a phase change takes place at a given pressure.
- Psat -- Pressure at which a phase change takes place at a given temperature.



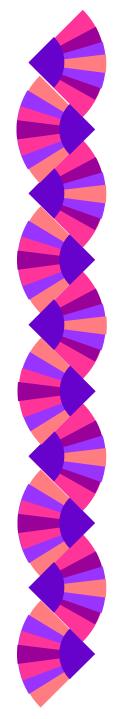
#### Saturation Temperature

 $T_{sat} = f(P_{sat})$ 

```
p = 1atm = 101.3 \text{ kPa}, 	 T = 100^{\circ}\text{C}

p = 500 \text{ kPa}, 	 T = 151.9^{\circ}\text{C}
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- \*T and P are dependent during phase change
- \*Allow us to control boiling temperature by controlling the pressure (i.e., pressure cooker).

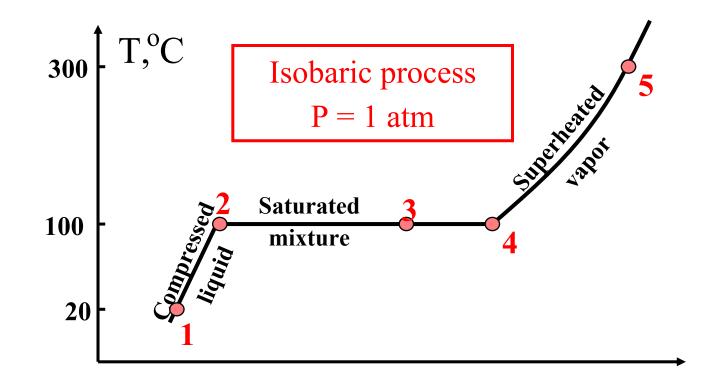


#### Latent Heat

 Latent heat is the amount of energy absorbed or released during phase change

- Latent heat of fusion -- melting/freezing
   =333.7 kJ/kg for 1 atm H<sub>2</sub>O
- Latent heat of vaporization --boiling/condensation
   =2257.1 kJ/kg for 1 atm H<sub>2</sub>O

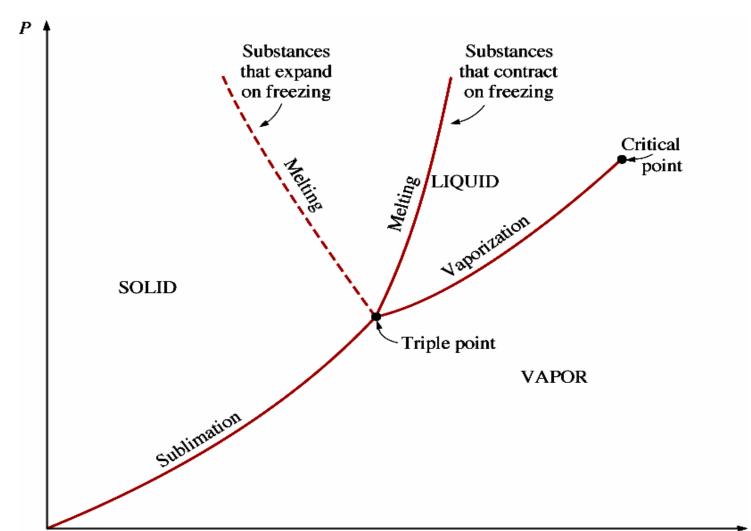
# Equilibrium Phase



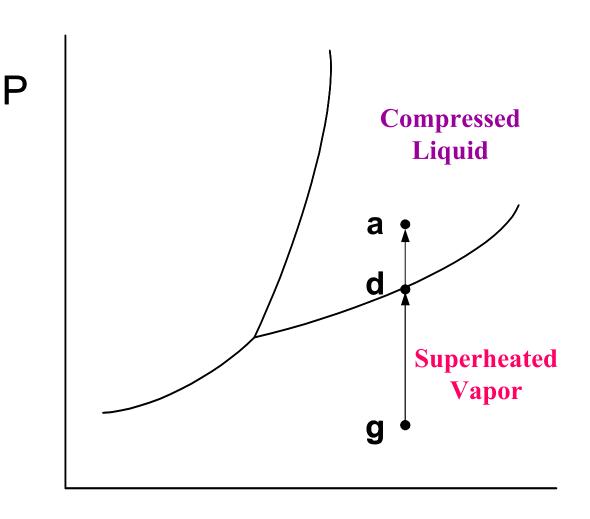
- Compressed liquid -- not about to evaporate
- Saturated liquid -- about to evaporate
- Saturated liquid-vapor mixture --two phase
- Saturated Vapor -- about to condense
- Superheated Vapor -- not about to condense

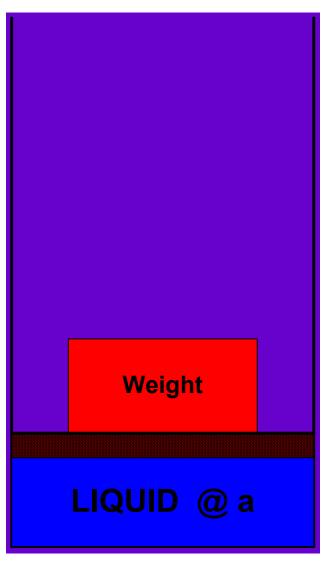


### P-T Diagram (Phase Diagram) of Pure Substances

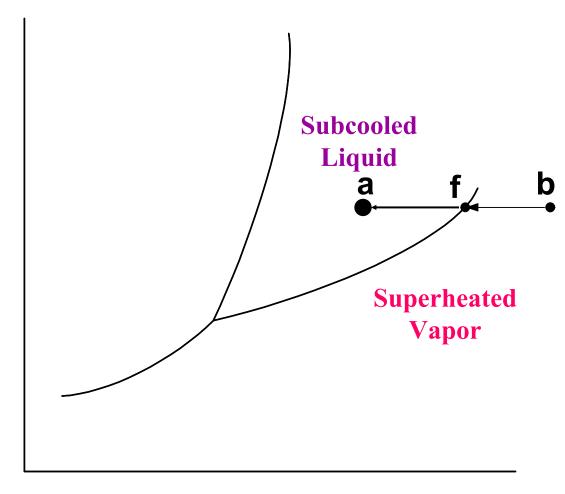


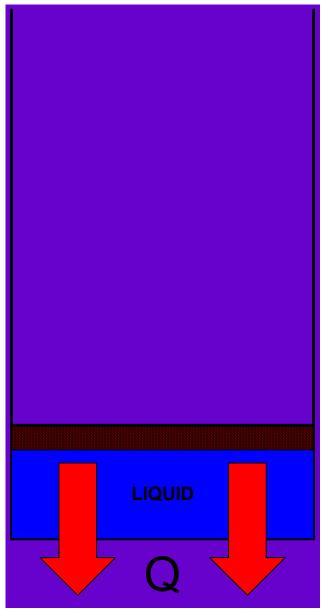
#### **Isothermal Process**





#### **Isobaric Process**



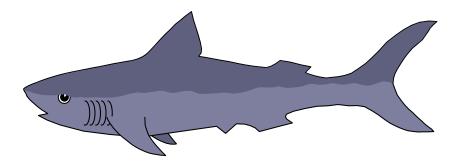


T



#### Water Expands on Freezing!

- Ice floats on top of the water body (lakes, rivers, oceans, soft drinks, etc.).
- If ice sinks to the bottom (contracts on freezing), the icing of lakes and oceans would start from bottom to top.
- This will seriously disrupt marine life.





#### Vapor (Steam) Dome

- The dome-shaped region encompassing the two-phase, vapor-liquid equilibrium region.
- It is bordered by the <u>saturated liquid line</u> and the <u>saturated vapor line</u>, both of which end at the triple line and at at the critical point.
- The region below the vapor dome is also called: saturated liquid-vapor region, wet region, two-phase region, or saturation region.



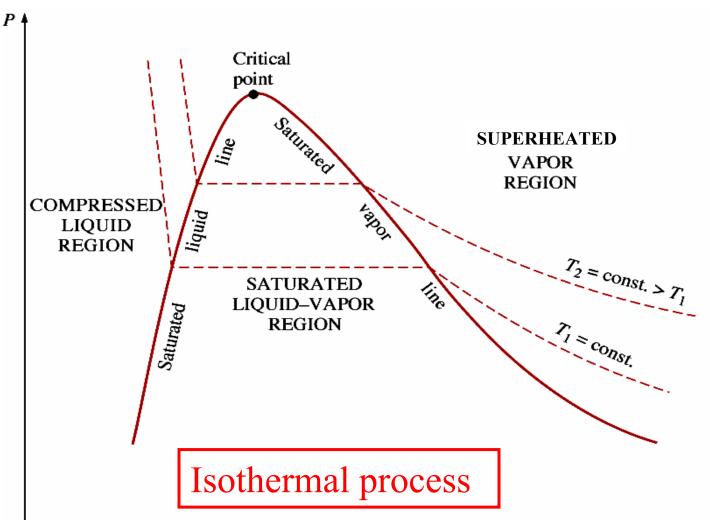
#### Critical & Supercritical

- The state beyond which there is no distinct vaporization process is called the *critical point*.
- At supercritical pressures, a substance gradually and uniformly expands from the liquid to vapor phase.
- \*Above the critical point, the <u>phase</u> <u>transition</u> from liquid to vapor is no longer discrete.
- Substances in this region are sometimes known as "fluids" rather than as vapors or liquids.

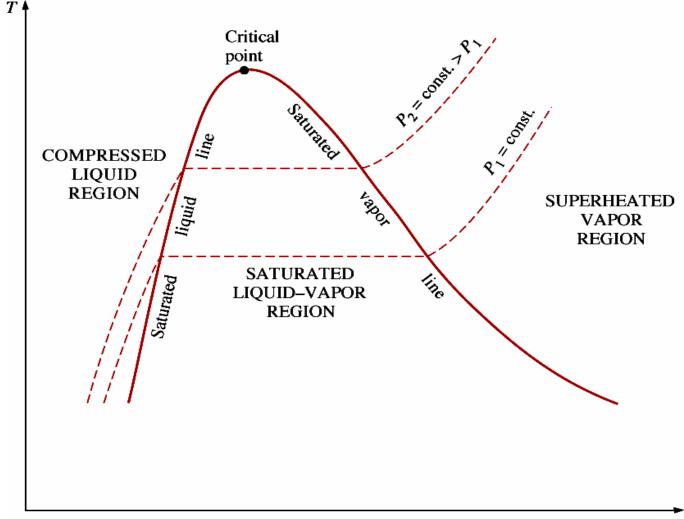
#### P-v Diagram

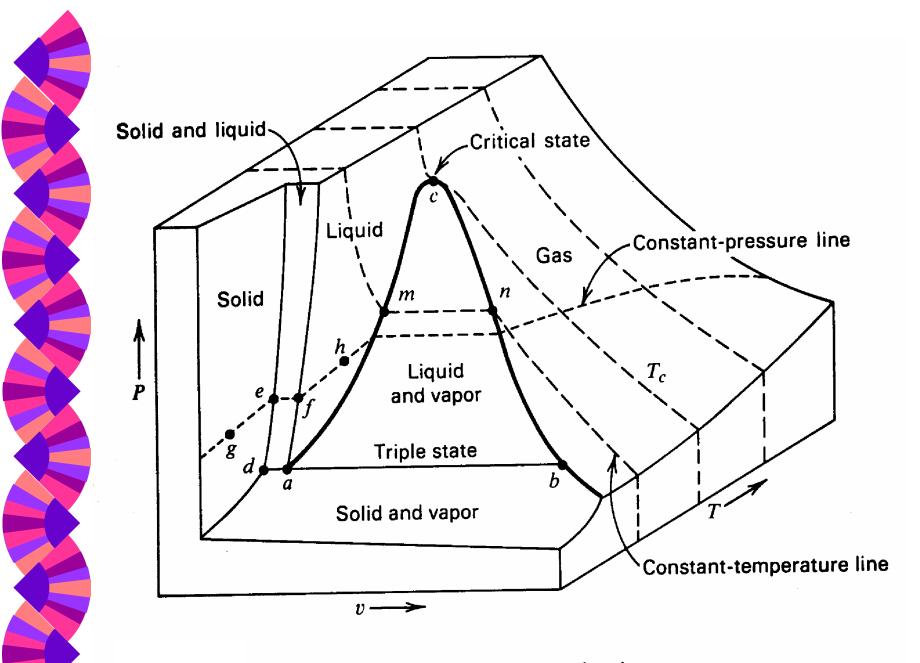
Subcooled or Critical point compressed Superheated liquid region region --Saturated liquid line substance is Two-phase or saturation 100% vapor region -- gas and liquid coexist

### P-v Diagram of a Pure Substance



### T-v Diagram of a Pure Substance





The PvT surface for a substance which contracts on freezing.



## THERMODYNAMIC TABLES

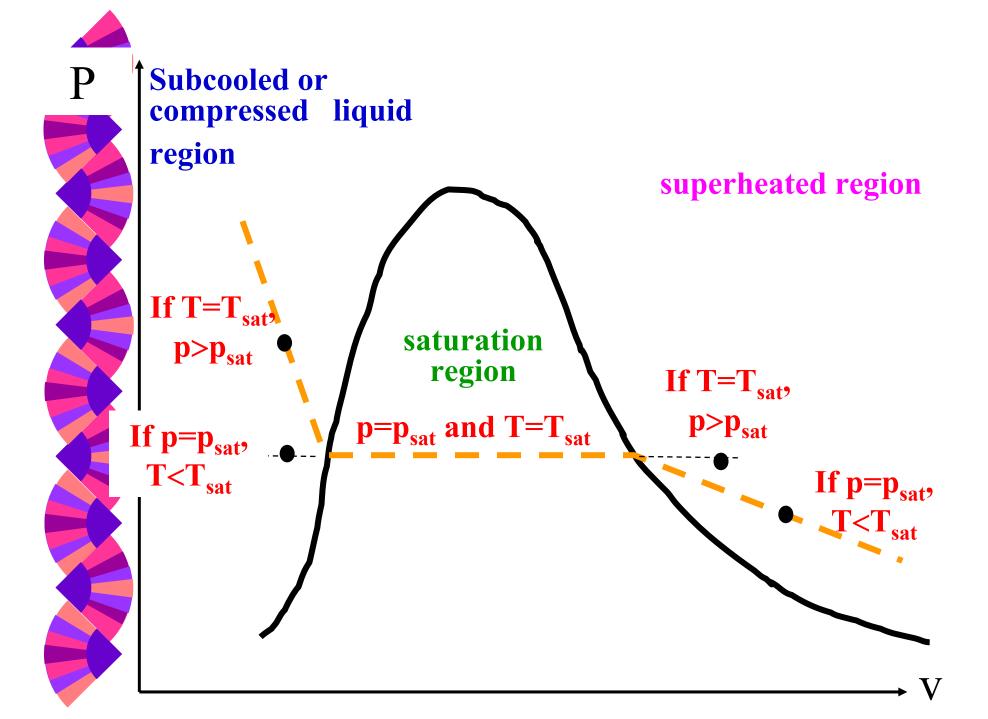


# STEAM ISNOTAN GAS!



#### Steam Tables

- Table A-1.1
- Saturation water -- temperature table
- Table A-1.2
- Saturation water -- pressure table
- **Table A-1.3**
- Superheated vapor





# Two properties are not independent in the vapor dome (the two-phase region)

• The temperature and pressure are uniquely related. Knowing a T defines the P and *vice versa*.

• Use <u>quality</u> x to determine the <u>state</u> in two-phase region.

### Quality, $0 \le x \le 1$

• In a saturated liquid-vapor mixture, the mass fraction (not volume fraction) of the vapor phase is called the *quality* and is defined as

$$x = \frac{m_{vapor}}{m_{total}} = \frac{m_{vapor}}{m_{liquid} + m_{vapor}} = \frac{m_g}{m_f + m_g}$$

• The quality may have values between 0 (saturated liquid) and 1 (saturated vapor). It has no meaning in the compressed liquid or superheated vapor regions.



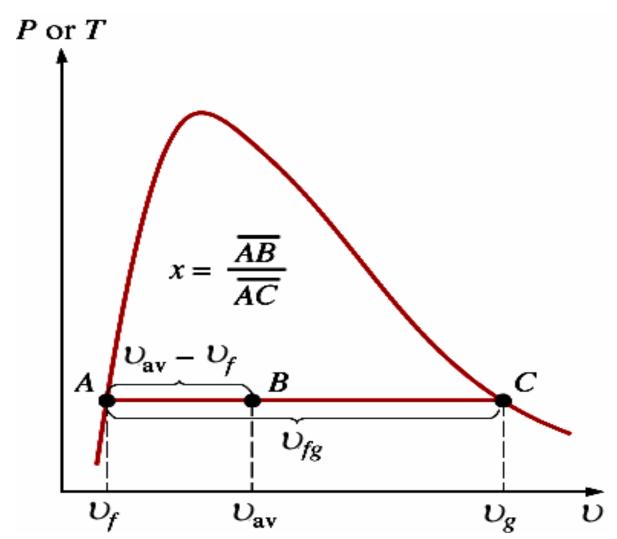
#### What is v in the two-phase region?

$$v = \begin{array}{ccc} \frac{V}{m_{tot}} & = & \frac{V_{liq} + V_{vap}}{m_{tot}} = \frac{v_l m_{liq} + v_v m_{vap}}{m_{tot}} \\ \end{array}$$

$$x = \frac{m_{\text{vap}}}{m_{\text{tot}}}; \frac{m_{\text{liq}}}{m_{\text{tot}}} = 1 - x$$

$$v = (1-x)v_1 + xv_v = v_1 + x(v_v - v_1)$$
  
=  $v_1 + xv_{v_1}$ 

### Quality is related to the horizontal differences of P-v and T-v Diagrams





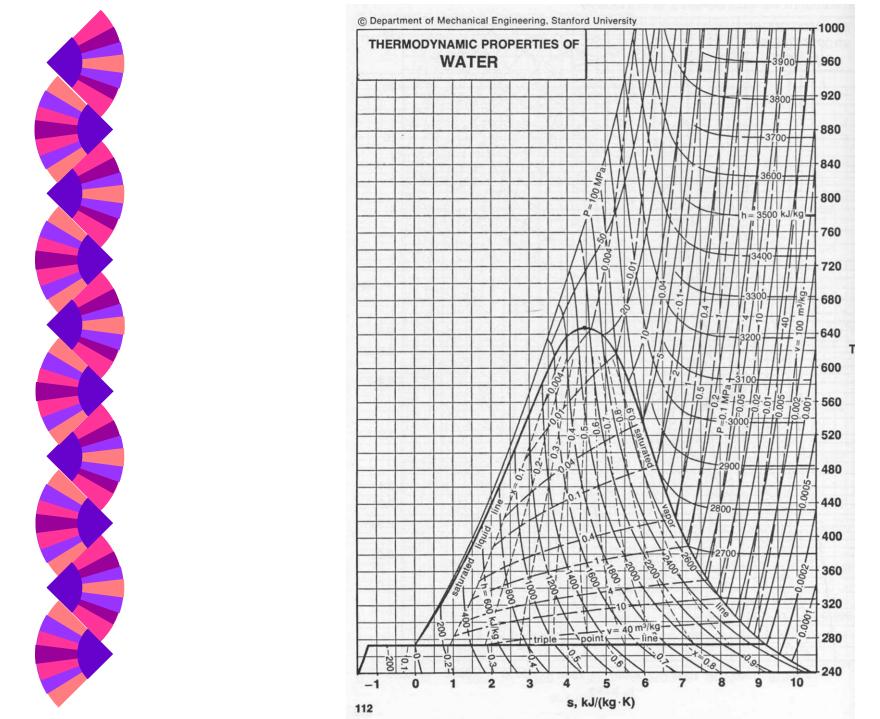
#### Saturated Mixture

• In the saturated mixture region, the average value of any intensive property 'y' is determined from:

$$v = v_1 + x(v_v - v_l) = v_1 + xv_{lv}$$
  
 $u = u_1 + x(u_v - u_l) = u_1 + xu_{lv}$   
 $h = h_1 + x(h_v - h_1) = h_1 + xh_{lv}$   
 $s = s_1 + x(s_v - s_1) = s_1 + xs_{lv}$ 

1: saturated liquid

v: saturated vapor





#### Saturated Water (temperature)

Tabela A-1 Continuação												
Temp.		Volume específico, m³/kg		Energia interna, kJ/kg			Entalpia, kJ/kg			Entropia, kJ/kg.K		
		líquido	vapor sat.	líquido sat.	Evap.	vapor sat.	líquido sat. h <sub>I</sub>	Evap.	vapor sat.	líquido sat.	Evap.	sat.
		sat.										
100	0,101 35	0,001 044		418,94 440,02	2087,6 2072,3	2506,5 2512,4	419,04 440,15	2257,0 2243,7	2676,1 2683,8	1,3069 1,3630	6,0480 5,9328	7,3549 7,2958
110	0,120 82 0,143 27	0,001 048 0,001 052	1,4194	461,14 482,30	2057,0	2518,1 2523,7	461,30 482,48	2230,2	2691,5 2699,0	1,4185 1,4734	5,8202 5,7100	7,2387 7,1833
115 120	0,169 06 0,198 53	0,001 056 0,001 060	1,0366 0,8919	503,50	2025,8	2529,3 2534,6	503,71 524,99	2202,6 2188,5	2706,3 2713,5	1,5276 1,5813	5,6020 5,4962	
125 130	0,2321	0,001 065 0,001 070	0,7706 0,6685	524,74 546,02 567,35	1993,9 1977,7	2539,9 2545,0	546,31 567,69	2174,2 2159,6	2720,5 2727,3	1,6344 1,6870	5,3925 5,2907	6,9777
135 140	0,3130	0,001 075 0,001 080	0,5089	588,74	1961,3 1944,7	2550,0 2554,9	589,13 610,63	2144,7 2129,6	2733,9 2740,3	1,7391 1,7907		6,9299 6,8833
145 150	0,4154 0,4758	0,001 085 0,001 091	0,3928	610,18	1927,9	2559,5 2564,1	632,20 653,84	2114,3 2098,6	2746,5 2752,4	1,8418 1,8925	4,9960	6,8379 6,7935
155 160	0,5431 0,6178	0,001 096 0,001 102	0,3071	653,24 674,87	1910,8	2568,4	675,55	2082,6	2758,1 2763,5	1,9427	4,8075 4,7153	6,7502
165 170	0,7005 0,7917	0,001 108 0,001 114	0,2428	696,56 718,33	1876,0 1858,1	2572,5 2576,5	697,34 719,21	2049,5	2768,7 2773,6	2,0419	4,6244 4,5347	6,6663
175 180	0,8920	0,001 121 0,001 127	,	740,17 762,09	1840,0 1821,6	2580,2 2583,7	741,17 763,22	2032,4	2778,2	2,1396 2,1879	4,4461	6,6857
185 190	1,1227	0,001 134 0,001 141	,	784,10 806,19	1802,9 1783,8	2587,0 2590,0	785,37 807,62	1997,1	2782,4 2786,4	2,2359	4,2720 4,1863	6,5079
195	1,3978 1,5538	0,001 149 0,001 157	,	828,37 850,65	1764,4 1744,7	2592,8 2595,3	829,98 852,45	1960,0 1940,7	2790,0 2793,2	2,2835	4,1014	6,4323
205	1,7230	0,001 164	,	873,04 895,53	1724,5 1703,9	2597,5 2599,5	875,04 897,76	1921,0	2796,0 2798,5	2,3780 2,4248	4,0172 3,9337	



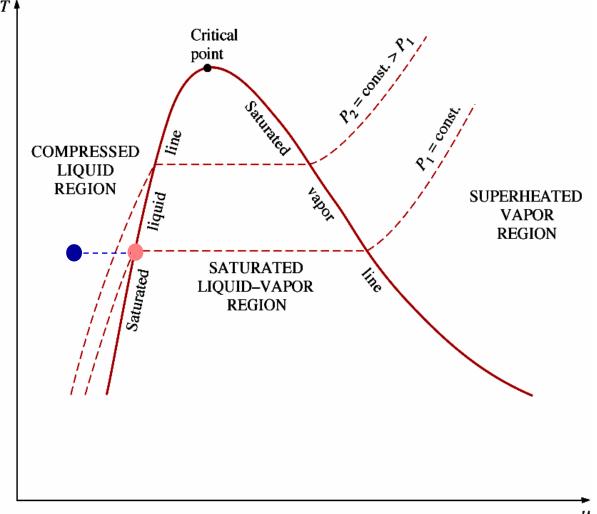
### Superheated Vapor Tabela A-1.3 Vapor Superaquecido

1000	P	= 0,010 N	MPa (45,8	11)	P	= 0,050 N	P = 0,10 MPa (99,63)					
T	V	и	h	s	V	и	h	s	V	и	h	S
Sat.	14,674	2437,9	2584,7	8,1502	3,240	2483,9	2645,9	7,5939	1,6940	2506,1	2675,5	7,3594
50	14,869	2443,9	2592,6	8,1749		2012.0	2017					P TOLK
100	17,196	2515,5	2687,5	8,4479	3,418	2511,6	2682,5	7,6947	1,6958	2506,7	2676,2	7,3614
150	19,512	2587,9	2783,0	8,6882	3,889	2585,6	2780,1	7,9401	1,9364	2582,8	2776,4	7,6134
200	21,825	2661,3	2879,5	8,9038	4,356	2659,9	2877,7	8,1580	2,172	2658,1	2875,3	7,8343
250	24,136	2736,0	2977,3	9,1002	4,820	2735,0	2976,0	8,3556	2,406	2733,7	2974,3	8,0333
300	26,445	2812,1	3076,5	9,2813	5,284	2811,3	3075,5	8,5373	2,639	2810.4	3074,3	8,2158
400	31,063	2968,9	3279,6	9,6077	6,209	2968,5	3278,9	8,8642	3,103	2967,9	3278,2	8,5435
500	35,679	3132,3	3489,1	9,8978	7,134	3132,0	3488,7	9,1546	3,565	3131.6	3488,1	8,8342
600	40,295	3302,5	3705,4	10,1608	8,057	3302,2	3705,1	9,4178	4,028	3301,9	3704.7	9,0976
700	44,911	3479,6	3928,7	10,4028	8,981	3479,4	3928,5	9,6599	4,490	3479,2	3928,2	9,3398
800	49,526	3663,8	4159,0	10,6281	9,904	3663,6	4158,9	9,8852	4,952	3663,5	4158,6	9,5652
900	54,141	3855,0	4396,4	10,8396	10,828	3854,9	4396.3	10,0967	5.414	3854.8	4396,1	9,7767
1000	58,757	4053,0	4640,6	11,0393	11,751	4052,9	4640,5	10,2964	5,875	4052,8	4640,3	9,9764
1100	63,372	4257,5	4891,2	11,2287	12,674	4257,4	4891,1	10,4859	6,337	4257,3	4891.0	10,1659
1200	67,987	4467,9	5147,8	11,4091	13,597	4467,8	5147,7	10,6662	6.799	4467,7	5147,6	10,3463
1300	72,602	4683,7	5409,7	11,5811	14,521	4683,6	5409,6	10,8382	7,260	4683,5	5409,5	10,5183
500	P = 0,20 MPa (120,23)				P	= 0,30 MF	a (133,5	5)	P = 0.40  MPa  (143.63)			
Sat.	0,8857	2529,5	2706,7	7,1272	0,6058	2543,6	2725,3	6,9919	0,4625	2553,6	2738,6	6.8959
150	0,9596	2576,9	2768,8	7,2795	0,6339	2570,8	2761,0	7,0778	0,4708	2564,5	2752,8	6,9299
200	1,0803	2654,4	2870,5	7,5066	0,7163	2650,7	2865,6	7,3115	0,5342	2646,8	2860,5	7,1706
250	1,1988	2731,2	2971,0	7,7086	0,7964	2728,7	2967,6	7,5166	0,5951	2726,1	2964,2	7,3789
300	1,3162	2808,6	3071,8	7,8926	0,8753	2806,7	3069,3	7,7022	0,6548	2804,8	3066,8	7,5662
400	1,5493	2966,7	3276,6	8,2218	1,0315	2965,6	3275,0	8,0330	0,7726	2964,4	3273,4	7,8985
500	1,7814	3130,8	3487,1	8,5133	1,1867	3130.0	3486,0	8,3251	0,8893	3129,2	3484,9	8,1913
600	2,013	3301,4	3704,0	8,7770	1,3414	3300,8	3703,2	8,5892	1,0055	3300,2	3702,4	8,4558
700	2,244	3478,8	3927,6	9,0194	1,4957	3478,4	3927,1	8,8319	1,1215	3477,9	3926.5	8,6987
800	2,475	3663,1	4158,2	9,2449	1,6499	3662,9	4157,8	9,0576	1,2372	3662,4	4157,3	8,9244
900	2,706	3854,5	4395,8	9,4566	1,8041	3854,2	4395,4	9,2692	1,3529	3853,9	4395,1	9.1362



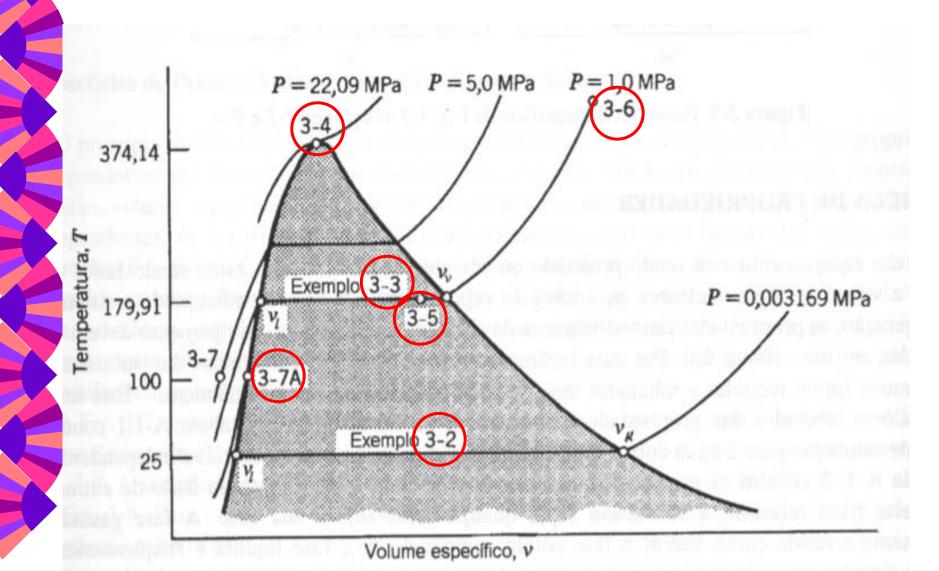
### Compressed Liquid

- There are no Tables for Compressed Liquid properties on the Text Book.
- How do I evaluate a Compressed Liquid property?
- Approximate the Compressed Liquid Property to the Saturated Liquid (x = 0) at the same temperature





# Examples 3-2 thru 3-7 Steam Tables A-1.1 and A-1.3



Ex. 3.1) Utilizando a Tabela A-1.1 ou A-1.2, determine se os estados da água são de líquido comprimido, líquido-vapor, vapor superaquecido ou se estão nas linhas de líquido saturado ou vapor saturado.

- a) P=1,0 MPa; T=207 °C  $\rightarrow$  a) Vapor superaquecido
- b) P=1,0 MPa; T=107,5 °C  $\rightarrow$  b) Líquido comprimido
- c) P=1,0 MPa; T=179,91 °C;  $x=0,0 \rightarrow c$ ) Líquido saturado
- d) P=1,0 MPa; T=179,91 °C;  $x=0,45 \rightarrow d$ ) Líquido-Vapor
- e) T=340 °C; P=21,0 MPa  $\rightarrow$  e) Líquido comprimido
- f) T=340 °C; P=2,1 MPa  $\rightarrow$  f) Vapor superaquecido
- g) T=340 °C; P=14,586 MPa;  $x=1,0 \rightarrow g$ ) Vapor saturado
- h) T=500 °C; P=25 MPa  $\rightarrow$  h) Vapor superaquecido Fluido
- i) P=50 MPa; T=25 °C  $\rightarrow$  i) Líquido comprimido Fluido





• Ex. 3.2) Encontre o volume específico dos estados "b", "d" e "h" do exercício anterior.

b) P=1,0 MPa; T=107,5 °C  $\rightarrow$  v $\approx$ v<sub>l</sub>=0,001050 (liq. comprimido, utilizar T=107,5°C)

d) P=1,0 MPa; T=179,91 °C; x=0,45  $\rightarrow$  v=0,08812 [v=(1-x)v<sub>l</sub>+x(v<sub>v</sub>)]

h) T=500 °C; P=25 MPa → v=0,011123 m³/kg (Tabela A-1.3 Vapor Superaquecido)

### Exercise 3-11

- A bucket containing 2 liters of water at 100°C is heated by an electric resistance.
- a) Identify the energy interactions if the system boundary is i) the water, ii) the electric coil
- b) If heat is supplied at 1 KW, then how much time is needed to boil off all the water to steam? (latent heat of vap at 1 atm is 2257 kJ/kg)
- c) If the water is at  $25^{\circ}$ C, how long will take to boil off all the water (Cp =  $4.18 \text{ J/kg}^{\circ}$ C)

Part a)

If the water is the system then Q > 0 and W = 0. There is a temperature difference between the electric coil and the water.

If the electric coil is the system then Q < 0 and W < 0. It converts 100% of the electric work to heat!

### Part b)

The mass of water is of 2 kg. It comes from 2liters times the specific volume of 0.001 m<sup>3</sup>/kg

To boil off all the water is necessary to supply all the vaporization energy:

$$Evap = 2257*2=4514 KJ$$

The power is the energy rate. The time necessary to supply 4514 KJ at 1KJ/sec is therefore:

$$Time = 4514/1 = 4514 \ seconds \ or \ 1.25 \ hour$$



The heat to boil off all the water initially at 25°C is the sum of: (1) the sensible heat to increase the temperature from 25°C to 100°C, (2) the vap. heat of part (b)

The sensible heat to increase from 25°C to 100°C is determined using the specific heat ( $C_P = 4.18$  kJ/kg°C check  $\Delta u/\Delta T$  from table A1)

$$Heat = 4.18*2*(100-25)=627 \text{ KJ}$$

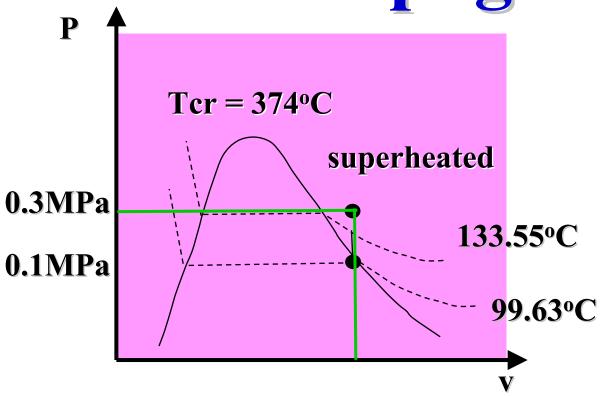
The time necessary to supply (4570+627)KJ at 1KJ/sec is:

Time = 5197/1 = 5197 seconds or 1.44 hour



### Exercise 3-17

A rigid tank contains saturated steam (x = 1) at 0.1 MPa. Heat is added to the steam to increase the pressure to 0.3 MPa. What is the final temperature?



- Process at constant volume,
- Search at the superheated steam table for a temperature corresponding to the 0.3 MPa and v = 1.690 m<sup>3</sup>/kg -> nearly 820°C.



- A bucket containing 2 liters of R-12 is left outside in the atmosphere (0.1 MPa)
- a) What is the R-12 temperature assuming it is in the saturated state.
- b) the surrounding transfer heat at the rate of 1KW to the liquid. How long will take for all R-12 vaporize?

Part a)

From table A-2, at the saturation pressure of 0.1 MPa one finds:

- Tsaturation =  $-30^{\circ}$ C
- $V_{liq} = 0.000672 \text{ m}^3/\text{kg}$
- $v_{vap} = 0.159375 \text{ m}^3/\text{kg}$
- $h_{lv} = 165 KJ/kg$  (vaporization heat)

Part b)

The mass of R-12 is  $m = Volume/v_L$ , m=0.002/0.000672 = 2.98 kg

The vaporization energy:

Evap = vap energy \* mass = 165\*2.98 = 492 KJ

Time = Heat/Power = 492 sec or 8.2 min



### TEAMPLAY

Complete the table below as a team. The substance is water. Make sure everybody understands how to do it!

P (MPa)	T(°C)	v(m³/kg)	x (if appl.)
	300		1.0
0.15		0.65	
0.50	300		



### TEAMPLAY

Complete the table below as a team. The substance is water. Use linear interpolation if needed.

P(MPa)	T(°C)	u (kJ/kg)	x (if appl.)
7.0			0.0
7.0			1.0
7.0			0.05
7.0	600		
7.0	100		
7.0	460		



### Exercícios — Capítulo 3 Propriedades das Substâncias Puras

**Exercícios Propostos:** 3.6 / 3.9 / 3.12 / 3.16 / 3.21 / 3.22 / 3.26 / 3.30 / 3.32 / 3.34

**Team Play: 3.1 / 3.2 / 3.4**