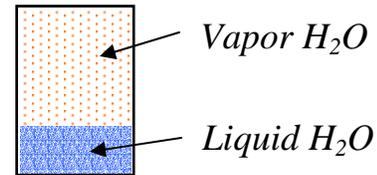# Lecture notes Week 10, part (a). Properties of a Pure Substance

Pure substance: homogeneous, uniform chemical composition.

A pure substance may exist in more than one phase.

- VAPOR
- LIQUID
- SOLID

Vapor H₂O → $Vapor\ H_2O$

Liquid H₂O → $Liquid\ H_2O$

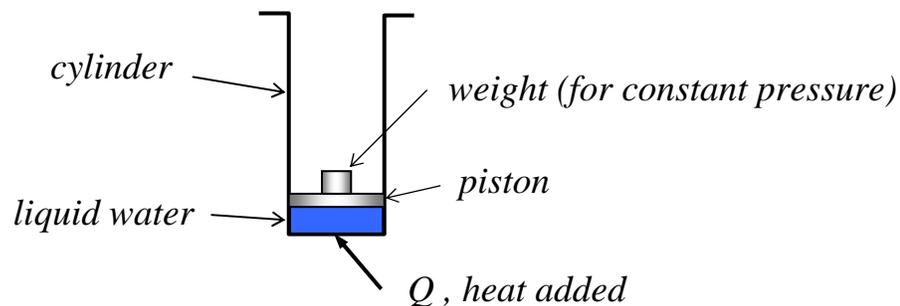A substance may coexist in any two or three phases

<u>Properties</u>: pressure (p), specific volume (v), and temperature (T)

<u>Phase equilibrium</u>: Consider a thought experiment of a phase change from a liquid phase to a vapor phase at constant pressure.
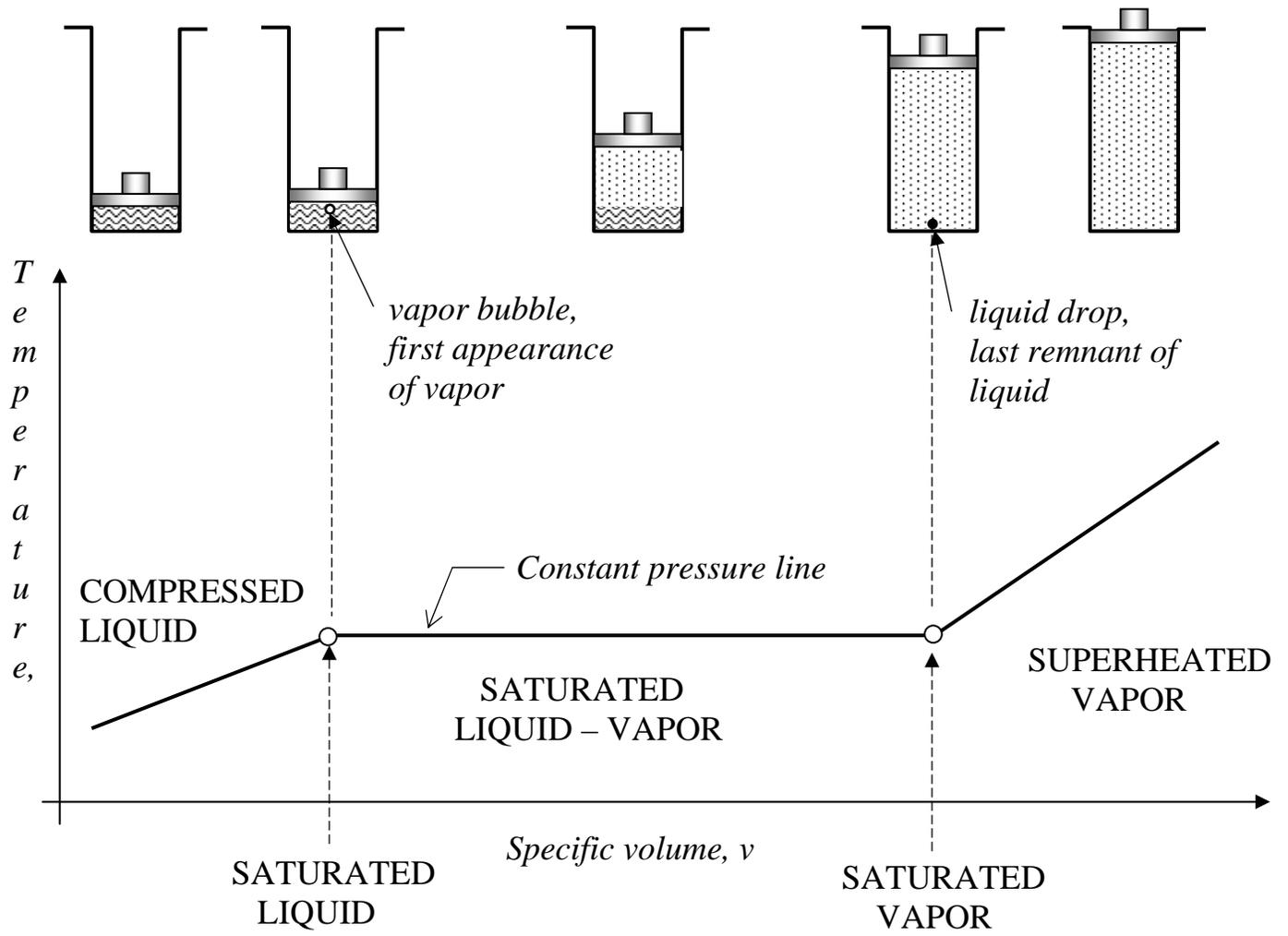
Consider the following experiment:

- take a cylinder with some liquid water
- cover it with a frictionless piston
- place a weight on top of the piston
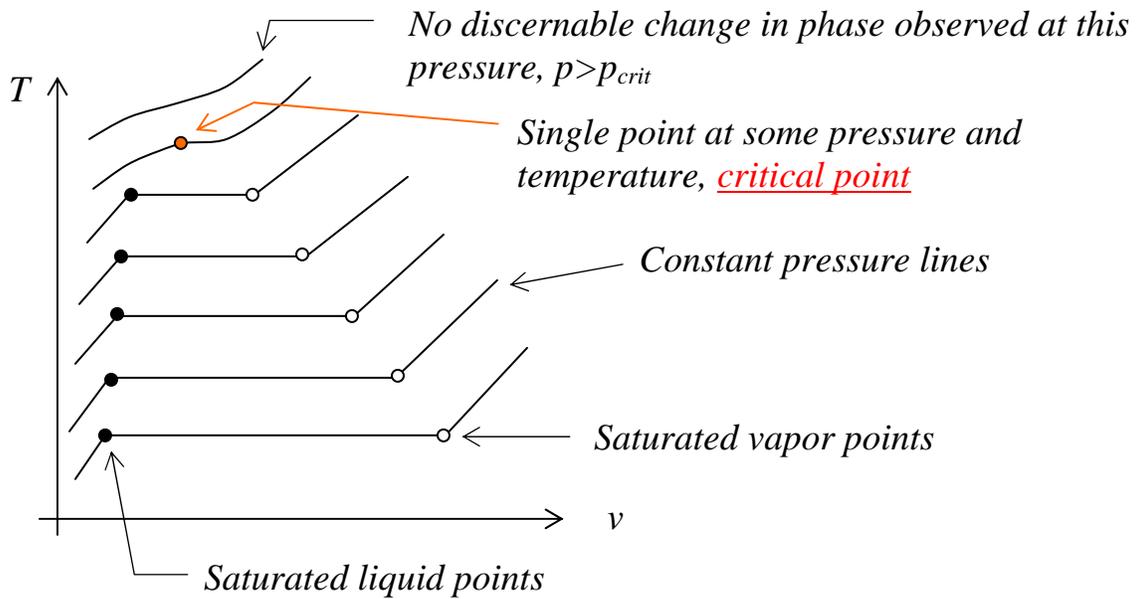- heat the water in the piston

This will be a constant pressure process. The weight on top of the piston determines the pressure exerted on the contents in the cylinder below the piston.

cylinder

weight (for constant pressure)

piston

liquid water

Q , heat added

Observe the temperature and phase of the water as more and more heat is added.

vapor bubble, first appearance of vapor

liquid drop, last remnant of liquid

T
e
m
p
e
r
a
t
u
r
$e,$

Constant pressure line

COMPRESSED
LIQUID

SATURATED
LIQUID – VAPOR

SUPERHEATED
VAPOR

SATURATED
LIQUID

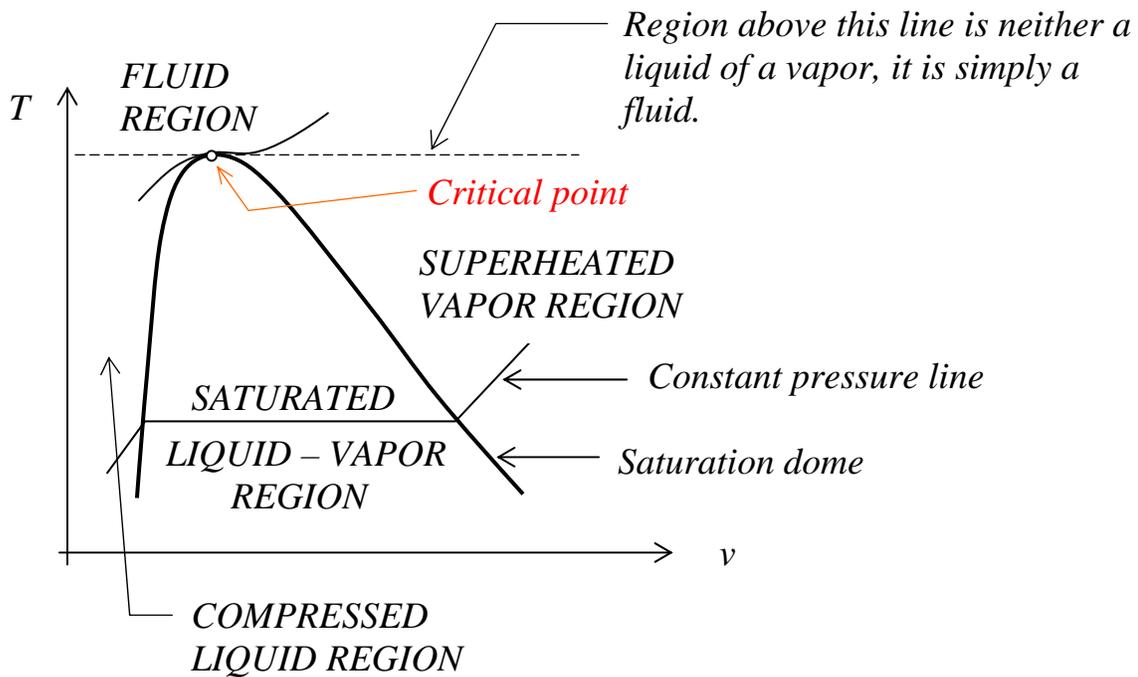*Specific volume, v*

SATURATED
VAPOR

Conduct the above experiment at many different pressures and plot similar constant pressrue lines, noting when first vapor appears (saturated liquid point) and the last drop of liquid disappears (saturated vapor poit).

No discernable change in phase observed at this pressure, p>p_crit

Single point at some pressure and temperature, critical point

Constant pressure lines

Saturated vapor points

Saturated liquid points

Connect all the observed saturated liquid and saturated vapor points. The line connecting all of these points forms a saturated dome.

CRITICAL POINT

SATURATED VAPOR LINE

SATURATED LIQUID LINE
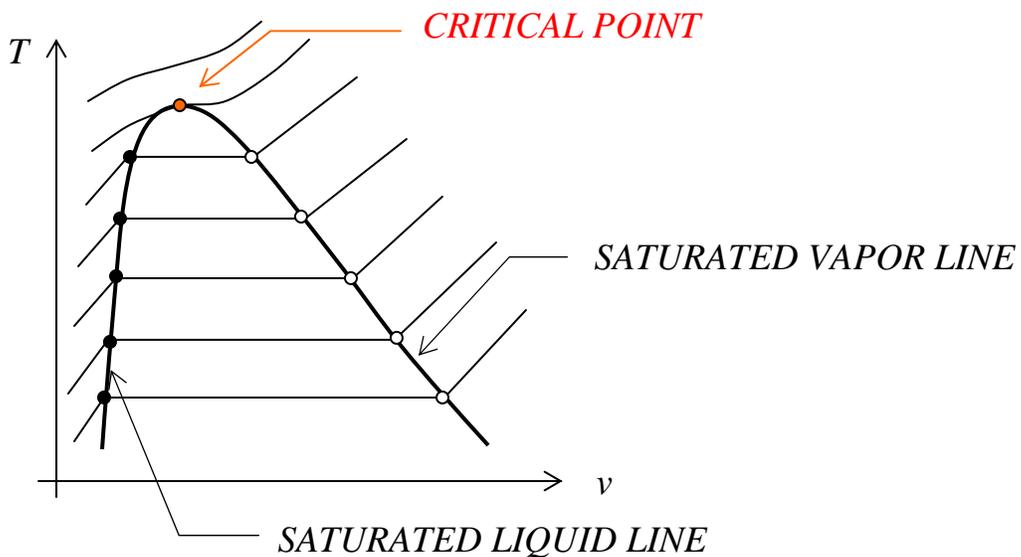
Regions in and around the saturation dome.

T

FLUID REGION

Region above this line is neither a liquid of a vapor, it is simply a fluid.

Critical point

SUPERHEATED VAPOR REGION

SATURATED

LIQUID – VAPOR REGION

Constant pressure line

Saturation dome

v

COMPRESSED LIQUID REGION

Note that in the saturated liquid–vapor region, the temperature and pressure are not independent as they are in the regions outside the dome.

If the temperature and pressure are not independent, and two independent variables are needed to specify a state, what might be the other independent variable?

We shall define a new variable, called the *QUALITY* , and give it the symbol χ.

$$Quality = \chi = \frac{m_{vapor}}{m_{vapor} + m_{liquid}} = \frac{m_{vapor}}{m_{total}}$$

NOTE:
- Quality is defined only in the saturated liquid-vapor region.
- Its value lies between 0 and 1, $0 \le \chi \le 1$
- $\chi = 0$ for saturated liquid
- $\chi = 1$ for saturated vapor
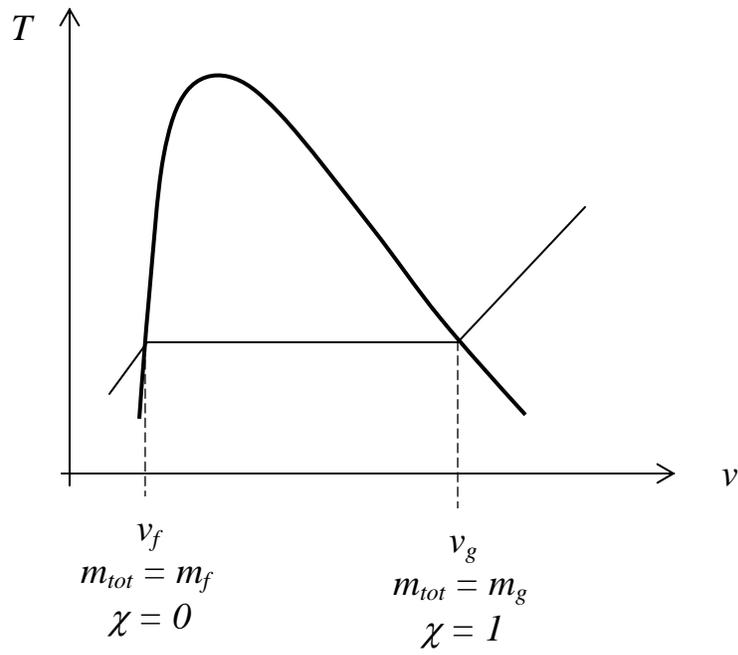
The following notation is used:

$$v_{sat.liq} = v_f$$
$$v_{satvapor} = v_g$$

Recall:

$$v = \frac{V}{m} \quad \text{or} \quad V = mv, \quad \text{where } v \text{ is the specific volume and } m \text{ is the mass.}$$

Also

$$m = m_{liq} + m_{vap} = m_f + m_g$$

From

$$V = V_f + V_g$$

we have

$$mv = m_{liq}v_f + m_{vap}v_g$$
$$mv = (m - m_{vap})v_f + m_{vap}v_g$$
$$v = (1 - \frac{m_{vap}}{m})v_f + \frac{m_{vap}}{m}$$
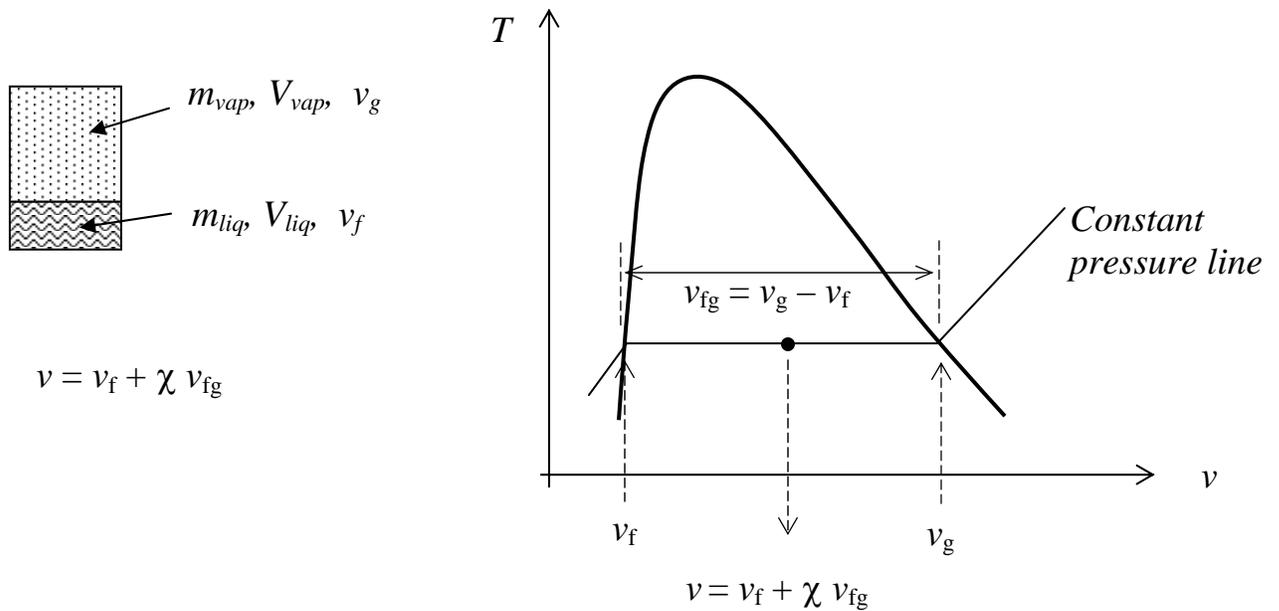$$v = (1 - \chi) v_f + \chi v_g = v_f + \chi (v_g - f_v)$$

let

$$v_{fg} = v_g - v_f$$

hence

$$\boxed{v = v_f + \chi \, v_{fg}}$$

Note that a saturated liquid-vapor specific volume, v, represents a combination of saturated vapor, v_g , and saturated liquid, v_f, in proportion to their masses, as given by the quality, χ.

m_{vap}, V_{vap}, v_g

m_{liq}, V_{liq}, v_f

$v = v_f + \chi\, v_{fg}$

$v_{fg} = v_g - v_f$

Constant pressure line

v_f

v_g

$v = v_f + \chi\, v_{fg}$

Note that the same pvT data can also be represented on a p-v diagram as shown below. Note that the constant temperature line has a negative slope.

$v_{fg} = v_g - v_f$

Constant temperature line

v_f

v_g

$v = v_f + \chi\, v_{fg}$
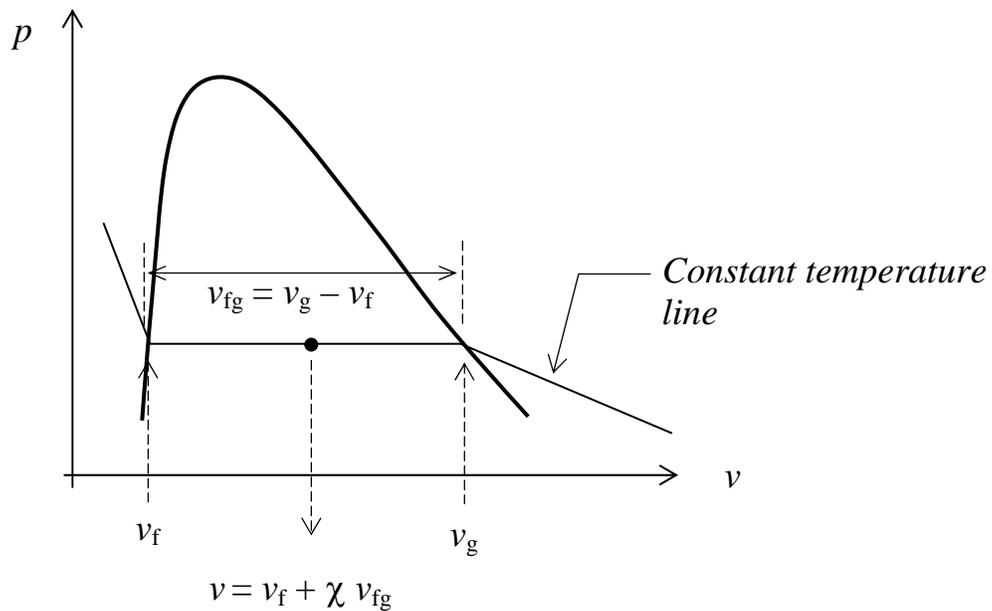
We see that in the saturation dome, temperature and pressure are not independent. We can thus plot one against the other, in particular:

More generally

P_sat

no distinction between liquid and vapor phases.

(S) (L)

← critical point

solid to liquid to vapor

(V)

← tripple point, coexistance of solid, liquid, vapor

solid to vapor

T_sat
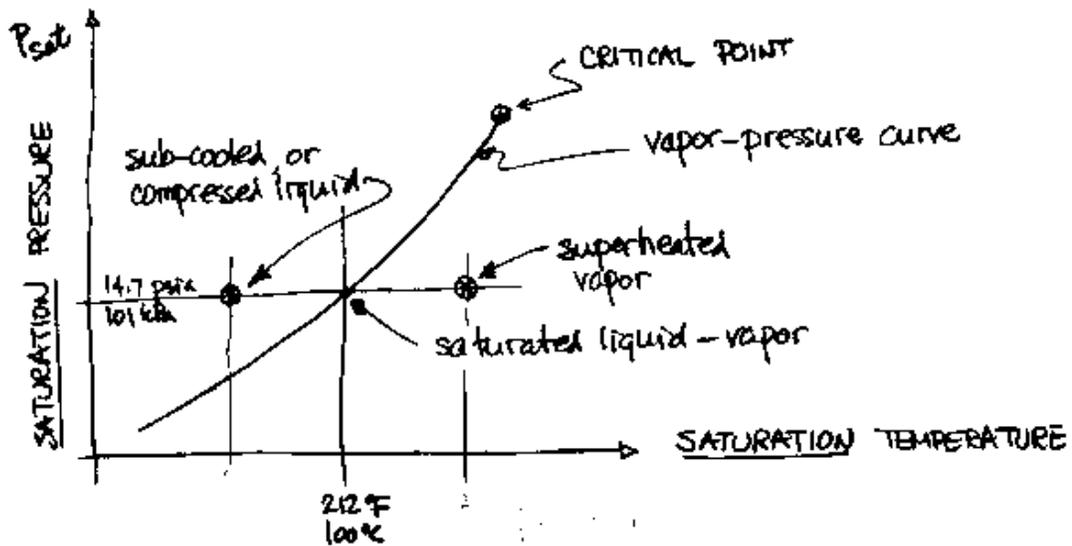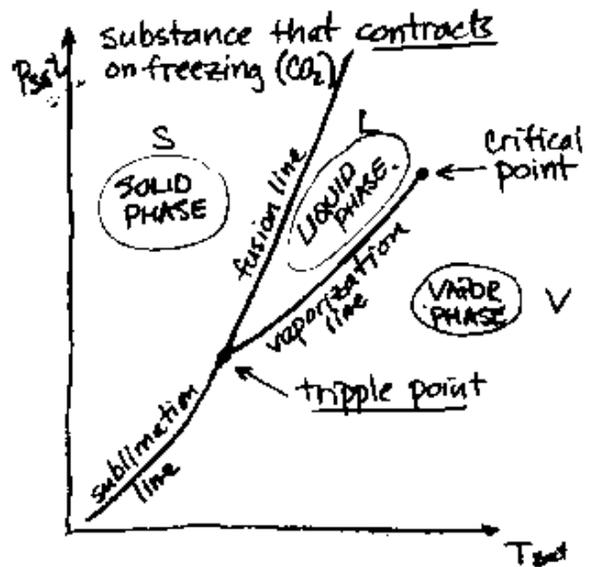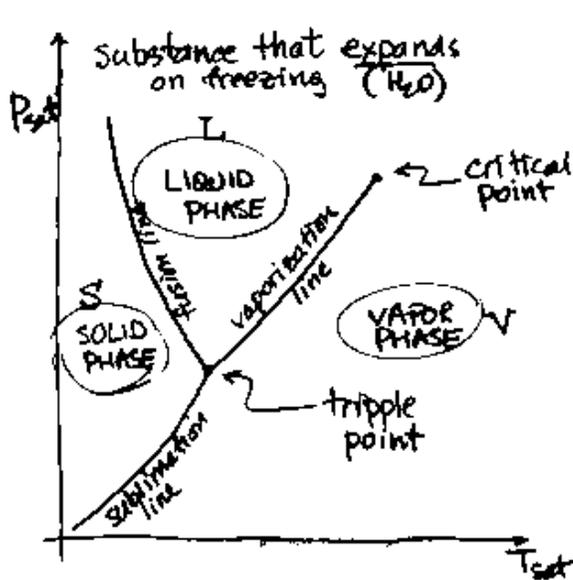
Tables of Thermodynamic Properties

Saturation Tables – These tables include the saturation temperature and pressure, and the specific volume, internal energy, enthalpy and entropy for both the liquid and vapor phases. Data is organized in columns. 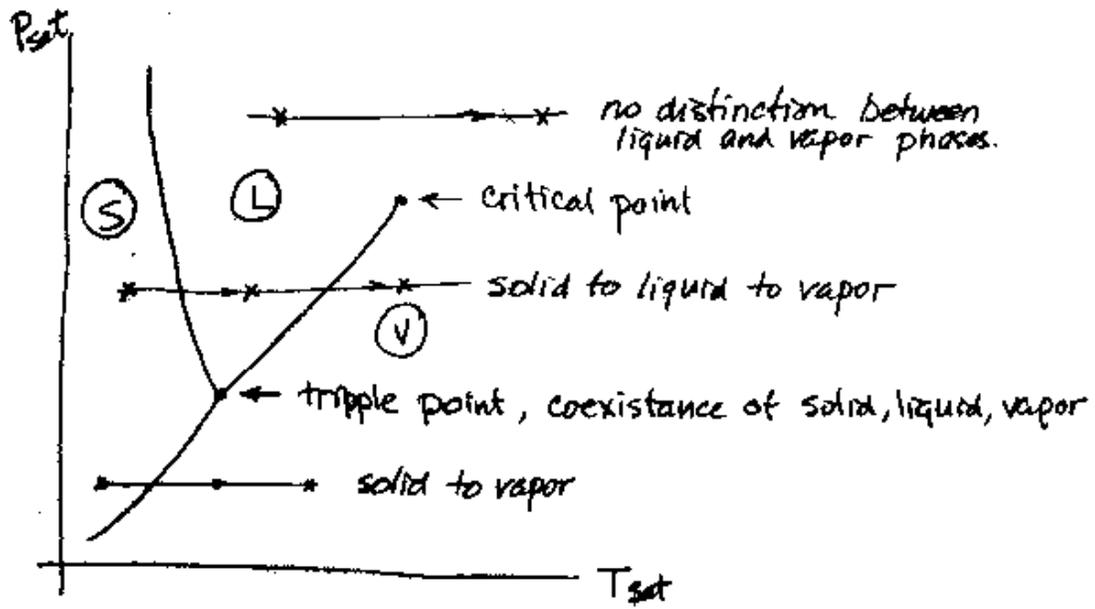The first column is keyed to either the temperature or pressure as the independent variable. An example of a table with temperature in the first column (the Temperature Table) is shown below.

TABLE A-2 Properties of Saturated Water (Liquid–Vapor): Temperature Table

| Temp. °C	Press. bars	Specific Volume m³/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

The temperature in the above table is generally listed in some convenient equal intervals. The intervals are close enough to allow linear interpolation between the listings. For each temperature there is a corresponding pressure and values for the liquid and vapor phases of other dependent variables.
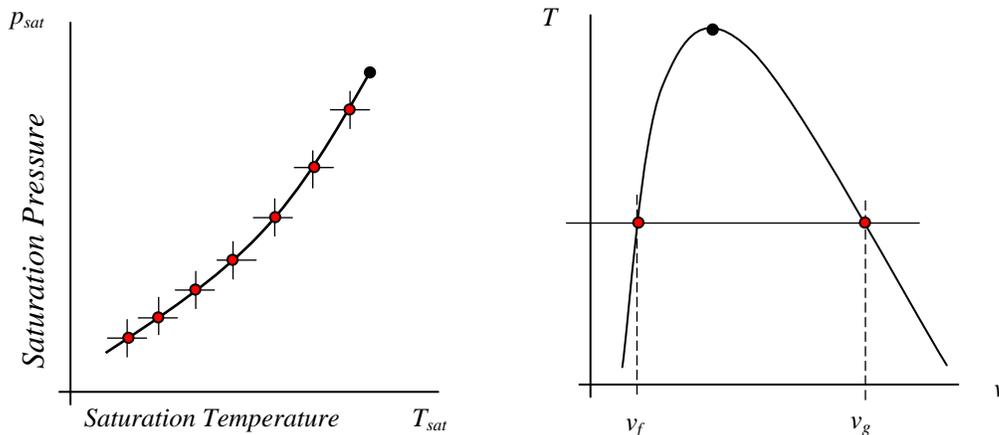
An example of a Pressure Table, with pressure as the independent variable, is shown below. Note that here the pressure is also spaced in some convenient small intervals to allow linear interpolation for intermediate data.

TABLE A-3 Properties of Saturated Water (Liquid–Vapor): Pressure Table

Press. bars	Temp. °C	Specific Volume m³/kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg · K		Press. bars
		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
0.80	93.50	1.0380	2.087	391.58	2498.8	391.66	2274.1	2665.8	1.2329	7.4346	0.80
0.90	96.71	1.0410	1.869	405.06	2502.6	405.15	2265.7	2670.9	1.2695	7.3949	0.90
1.00	99.63	1.0432	1.694	417.36	2506.1	417.46	2258.0	2675.5	1.3026	7.3594	1.00
1.50	111.4	1.0528	1.159	466.94	2519.7	467.11	2226.5	2693.6	1.4336	7.2233	1.50
2.00	120.2	1.0605	0.8857	504.49	2529.5	504.70	2201.9	2706.7	1.5301	7.1271	2.00
2.50	127.4	1.0672	0.7187	535.10	2537.2	535.37	2181.5	2716.9	1.6072	7.0527	2.50
3.00	133.6	1.0732	0.6058	561.15	2543.6	561.47	2163.8	2725.3	1.6718	6.9919	3.00
3.50	138.9	1.0786	0.5243	583.95	2546.9	584.33	2148.1	2732.4	1.7275	6.9405	3.50
4.00	143.6	1.0836	0.4625	604.31	2553.6	604.74	2133.8	2738.6	1.7766	6.8959	4.00
4.50	147.9	1.0882	0.4140	622.25	2557.6	623.25	2120.7	2743.9	1.8207	6.8565	4.50
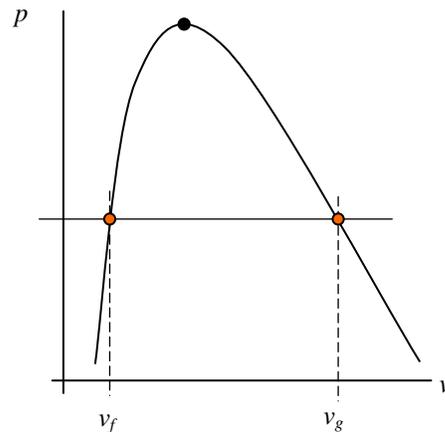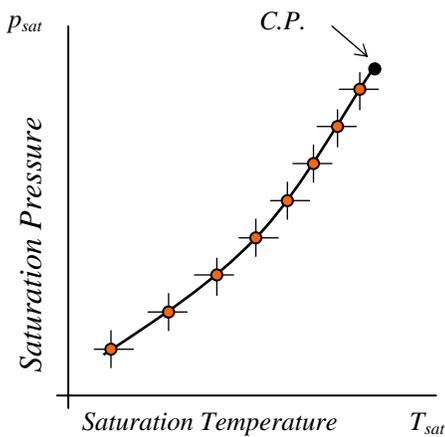
Superheated Tables – In the superheated vapor state there are two independent variables, generally the temperature and pressure. It is common practice to organize the data in blocks of selected pressures and list the remaining data as a function of temperature at that pressure. An example of a superheated table is shown below.

TABLE A-4 Properties of Superheated Water Vapor

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	$p = 0.06$ bar $= 0.006$ MPa ($T_{sat} = 36.16$°C)				$p = 0.35$ bar $= 0.035$ MPa ($T_{sat} = 72.69$°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
	$p = 0.70$ bar $= 0.07$ MPa ($T_{sat} = 89.95$°C)				$p = 1.0$ bar $= 0.10$ MPa ($T_{sat} = 99.63$°C)			
Sat.	2.365	2494.5	2660.0	7.4797	1.694	2506.1	2675.5	7.3594
100	2.434	2509.7	2680.0	7.5341	1.696	2506.7	2676.2	7.3614
120	2.571	2539.7	2719.6	7.6375	1.793	2537.3	2716.6	7.4668
160	2.841	2599.4	2798.2	7.8279	1.984	2597.8	2796.2	7.6597
200	3.108	2659.1	2876.7	8.0012	2.172	2658.1	2875.3	7.8343
240	3.374	2719.3	2955.5	8.1611	2.359	2718.5	2954.5	7.9949
280	3.640	2780.2	3035.0	8.3162	2.546	2779.6	3034.2	8.1445
320	3.905	2842.0	3115.3	8.4504	2.732	2841.5	3114.6	8.2849
360	4.170	2904.6	3196.5	8.5828	2.917	2904.2	3195.9	8.4175
400	4.434	2968.2	3278.6	8.7086	3.103	2967.9	3278.2	8.5435
440	4.698	3032.9	3361.8	8.8286	3.288	3032.6	3361.4	8.6636
500	5.095	3131.8	3488.5	8.9991	3.565	3131.6	3488.1	8.8342

Linear interpolation is used to obtain intermediate data.

The data in the tables is nothing more that a digitized representation of actual continuous physical behavior.

Tabular data is represented schematically on *T-v* and *p-v* diagrams below. Each dot represents a data point in the table.

Saturated vapor line

T

SUPERHEATED
REGION

Pressure block

Temperatures at the given
pressure block

T_{sat}

v

p

SUPERHEATED
VAPOR REGION

Pressure block

Temperatures at the given
pressure block

T_{sat}

v