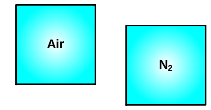
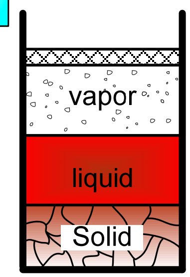
Properties of Pure Substance

By: Yidnekachew Messele

Pure substance

- A substance that has a fixed chemical composition throughout is called a ***pure substance***.
  - Water
  - Nitrogen
  - Air
  - Helium
  - Carbon dioxide

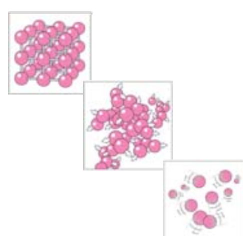




- Pure substance may exist in different phases, but the chemical compositions is the same.
  - water made up of two atoms of hydrogen and one atom oxygen. It will have the same composition when in ice, liquid and vapor forms.

Phase of pure substances

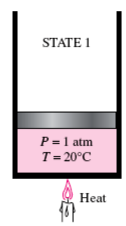
- Under different conditions a substance may appear in different phases. The three principal phases are solid, liquid and gas.
  - Considering water, it can be exist as
    - Pure solid phase (ice)
    - Pure liquid phase
    - Pure vapor phase (steam)



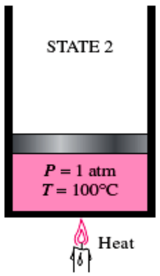
  - It can also exist as an equilibrium mixture of different phase

Phase-change processes of pure substances

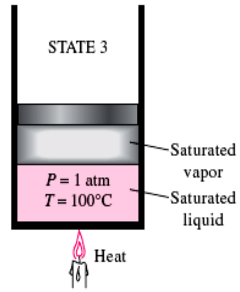
- Consider the piston-cylinder device containing liquid water 20^{o}C at and 1atm.



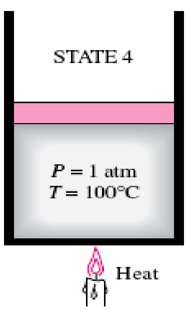
  - Under these conditions, water exists in the liquid phase, and it is called a ***compressed liquid***, or a ***sub cooled liquid.***
  - As the temperature rises, the liquid water expands slightly, and so its specific volume increases.



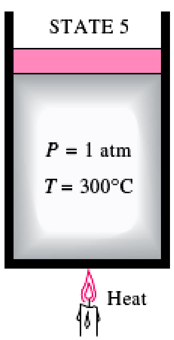
- At this point water still a liquid, but any heat addition will cause some of the liquid to vaporize.
- That is, a phase change process from liquid to vapor is about to take place.
- A liquid about to vaporize is called ***saturated liquid.***



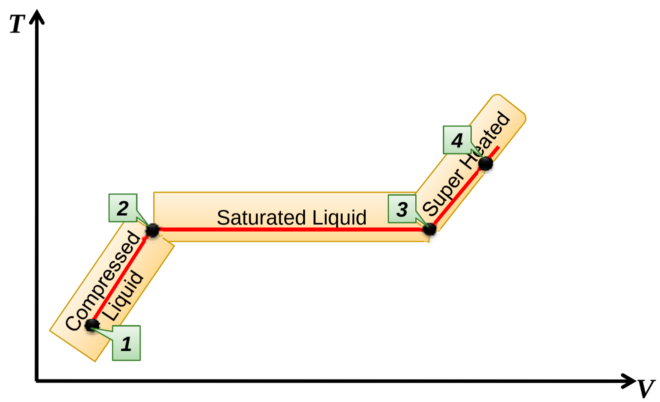
- Once boiling starts, the ***temperature stops rising*** until the liquid is completely vaporized (it is a constant phase - change process at p-constant).
- During this process the only thing is change in volume.
- At this stage liquid and vapor phase coexist in equilibrium and it is called ***saturated liquid-vapor mixture***.



- At this point, the entire cylinder is filled with vapor that is on the borderline of the liquid phase.
- Any heat loss from this vapor will cause some of the vapor to condense (phase change from vapor to liquid).
- The vapor that is about to condense is called a ***saturated vapor.***



- At this stage the phase-change process is completed is completed, we back to a single-phase region (vapor).
- Further transfer of heat will result in an increase in both the temperature and the specific volume.
- A vapor that is not about to condense (i.e. not a saturated vapor) is called a ***superheated vapor***.



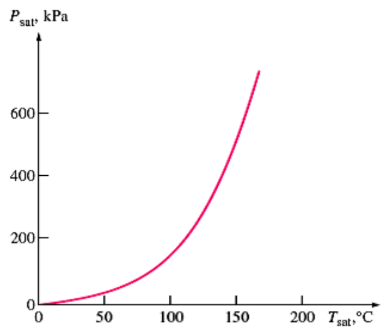
- At a given pressure, the temperature at which a pure substance changes phase is called the ***saturation temperature*** $T_{sat.}$
- At a given temperature, the pressure at which a pure substance changes phase is called the ***saturation pressure*** P_{sat}.
- At a pressure of 101.325 kPa, T_{sat} is 99.97°C.
- At a temperature of 99.97°C, P_{sat} is 101.325 kPa.

Saturation (boiling) pressure of water at various temperatures

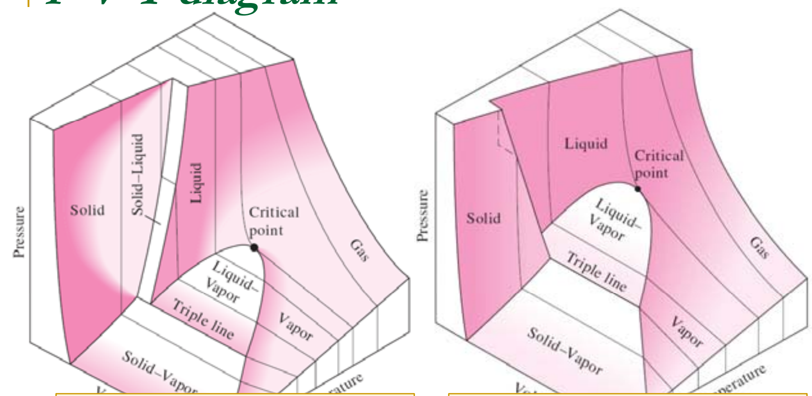
Temperature, T, °C	Saturation pressure, P_{sat}, kPa
−10	0.26
−5	0.40
0	0.61
5	0.87
10	1.23
15	1.71
20	2.34
25	3.17
30	4.25
40	7.39
50	12.35
100	101.4
150	476.2
200	1555
250	3976
300	8588

- The amount of energy absorbed or released during a phase-change process is called the ***latent heat.***
- The amount of energy absorbed during vaporization is called the ***latent heat of vaporization*** *a*nd it is equivalent to the energy released during condensation.
- The amount of energy absorbed during melting is called the ***latent heat of fusion*** and it is equivalent to the amount of energy released during freezing.

- During a phase-change process, pressure and temperature are obviously dependent properties $T_{sat} = f(P_{sat})$

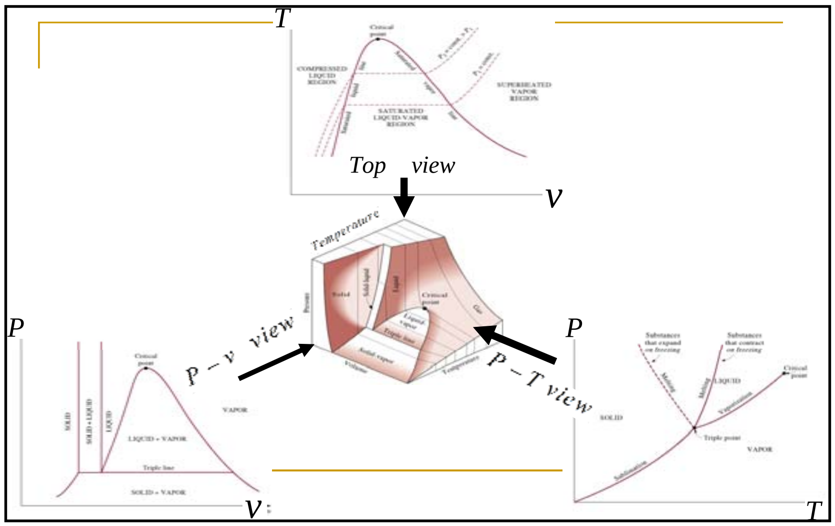


P-V-T diagram



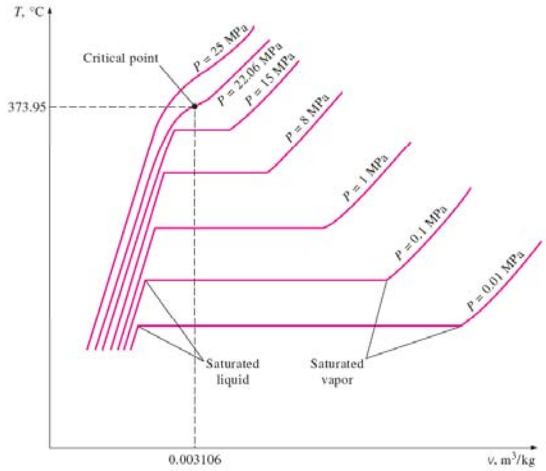
substance that *contracts on freezing.*

substance that *expands on freezing.*

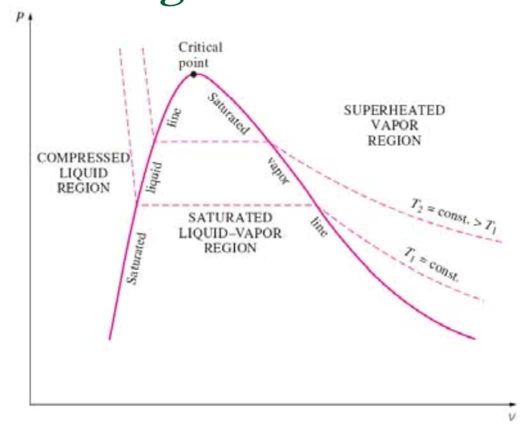


The T-V diagram

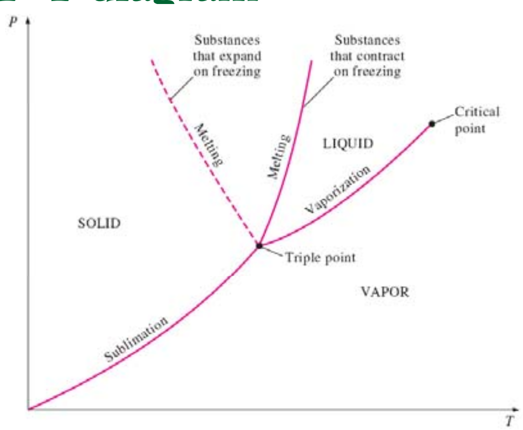
- Experimental result tells us, as the pressure is increased further, the saturation line of the process will continue to get shorter and it will become a point.
- This point is called the ***critical point*** of the substance and it may be defined as the point at which the saturated liquid saturated vapor states are identical.
- At pressures above the critical pressure, there is not a distinct phase-change process.
- We can never tell when the change has occurred.



The P-V diagram



The P-T diagram



Thermodynamic tables

- Thermodynamic properties of substance are usually given in tabular form to facilitate calculation.
- Among them ***saturated, superheated steam*** and ***compressed liquid*** are the most frequently used properties.

Saturated water-Temperature table

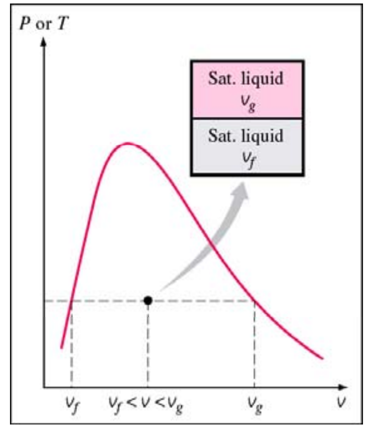
Temp., T °C	Sat. Press., P_{sat} kPa	Specific volume, m³/kg: Sat. liquid, v_f	Sat. vapor, v_g	Internal energy, kJ/kg: Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Enthalpy, kJ/kg: Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Entropy, kJ/kg·K: Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.01	0.6117	0.001000	206.00	0.00	2374.9	2374.9	0.00	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.02	2360.8	2381.8	21.02	2489.1	2510.1	0.0763	8.9487	9.0249
10	1.228	0.001000	106.32	42.02	2346.6	2388.7	42.02	2477.2	2519.2	0.1511	8.7488	8.8999
15	1.706	0.001001	77.885	62.98	2332.5	2395.5	62.98	2465.4	2528.3	0.2245	8.5559	8.7803
20	2.339	0.001002	57.762	83.91	2318.4	2402.3	83.91	2453.5	2537.4	0.2965	8.3696	8.6661
25	3.170	0.001003	43.340	104.83	2304.3	2409.1	104.83	2441.7	2546.5	0.3672	8.1895	8.5567
30	4.247	0.001004	32.879	125.73	2290.2	2415.9	125.74	2429.8	2555.6	0.4368	8.0152	8.4520
35	5.629	0.001006	25.205	146.63	2276.0	2422.7	146.64	2417.9	2564.6	0.5051	7.8466	8.3517
40	7.385	0.001008	19.515	167.53	2261.9	2429.4	167.53	2406.0	2573.5	0.5724	7.6832	8.2556
45	9.595	0.001010	15.251	188.43	2247.7	2436.1	188.44	2394.0	2582.4	0.6386	7.5247	8.1633
50	12.35	0.001012	12.026	209.33	2233.4	2442.7	209.34	2382.0	2591.3	0.7038	7.3710	8.0748
55	15.76	0.001015	9.5639	230.24	2219.1	2449.3	230.26	2369.8	2600.1	0.7680	7.2218	7.9898
60	19.95	0.001017	7.6670	251.16	2204.7	2455.9	251.18	2357.7	2608.8	0.8313	7.0769	7.9082
65	25.04	0.001020	6.1935	272.09	2190.3	2462.4	272.12	2345.4	2617.5	0.8937	6.9360	7.8296
70	31.20	0.001023	5.0396	293.04	2175.8	2468.9	293.07	2333.0	2626.1	0.9551	6.7989	7.7540
75	38.60	0.001026	4.1291	313.99	2161.3	2475.3	314.03	2320.6	2634.6	1.0158	6.6655	7.6812
80	47.42	0.001029	3.4053	334.97	2146.6	2481.6	335.02	2308.0	2643.0	1.0756	6.5355	7.6111
85	57.87	0.001032	2.8261	355.96	2131.9	2487.8	356.02	2295.3	2651.4	1.1346	6.4089	7.5435
90	70.18	0.001036	2.3593	376.97	2117.0	2494.0	377.04	2282.5	2659.6	1.1929	6.2853	7.4782
95	84.61	0.001040	1.9808	398.00	2102.0	2500.1	398.09	2269.6	2667.6	1.2504	6.1647	7.4151
100	101.42	0.001043	1.6720	419.06	2087.0	2506.0	419.17	2256.4	2675.6	1.3072	6.0470	7.3542
.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.
360	18666	0.001895	0.006950	1726.16	625.7	2351.9	1761.53	720.1	2481.6	3.9165	1.1373	5.0537
365	19822	0.002015	0.006009	1777.22	526.4	2303.6	1817.16	605.5	2422.7	4.0004	0.9489	4.9493
370	21044	0.002217	0.004953	1844.53	385.6	2230.1	1891.19	443.1	2334.3	4.1119	0.6890	4.8009
373.95	22064	0.003106	0.003106	2015.8	0	2015.8	2084.3	0	2084.3	4.4070	0	4.4070

Saturated liquid-vapor mixture

- During a vaporization process, a substance exists as part liquid and part vapor.
- To analyze this mixture properly, we need to know the proportions of the liquid and vapor phases in the mixture.
- ***Quality (x)*** as the ratio of the mass of vapor to the total mass of the mixture:

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

Its value is between 0 and 1



$$V = V_f + V_g$$

$$V = mv$$

$$m_{tot} v_{avr} = m_f v_f + m_g v_g$$

$$m_f = m_{tot} - m_g$$

$$m_{tot} v_{avr} = (m_{tot} - m_g) v_f + m_g v_g$$

$$v_{avr} = (1 - x) v_f + x v_g$$

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

$$v_{avg} = v_f + x v_{fg} \qquad x = \frac{v_{avg} - v_f}{v_{fg}}$$

$$u = u_f + x u_{fg}$$

$$h = h_f + x h_{fg}$$

$$s = s_f + x s_{fg}$$

Saturated Liquid and Saturated Vapor States

- The properties of saturated liquid and saturated vapor for water are listed in Thermodynamics tables.

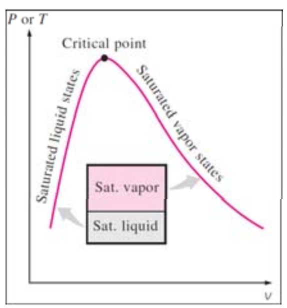
Temp. °C T	Sat. press. kPa P_{sat}	Specific volume m³/kg: Sat. liquid v_f	Sat. vapor v_g
85	57.868	0.001032	2.8261
90	70.183	0.001036	2.3593
95	84.609	0.001040	1.9808

Specific temperature

Specific volume of saturated liquid

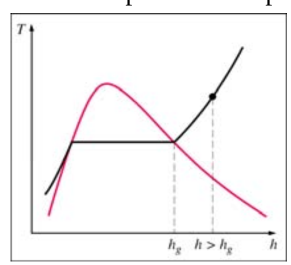
Corresponding saturation pressure

Specific volume of saturated vapor



Superheated steam table

- In the region to the right of the saturated vapor line and at temperatures above the critical point temperature, a substance exists as superheated vapor.

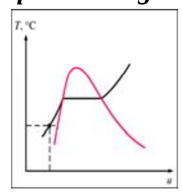


T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg·K
	P = 0.05 MPa (81.32°C)			
Sat.	3.2403	2483.2	2645.2	7.5931
100	3.4187	2511.5	2682.4	7.6953
150	3.8897	2585.7	2780.2	7.9413
200	4.3562	2660.0	2877.8	8.1592
250	4.8206	2735.1	2976.2	8.3568
300	5.2841	2811.6	3075.8	8.5387
400	6.2094	2968.9	3279.3	8.8659
500	7.1338	3132.6	3489.3	9.1566
600	8.0577	3303.1	3706.0	9.4201
700	8.9813	3480.6	3929.7	9.6626
800	9.9047	3665.2	4160.4	9.8883
900	10.828	3856.8	4398.2	10.1000
1000	11.751	4055.2	4642.7	10.3000
1100	12.675	4259.9	4893.7	10.4897
1200	13.598	4470.8	5150.7	10.6704
1300	14.521	4687.3	5413.3	10.8429

- 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)

Compressed liquid table

- Compressed liquid tables are not as commonly available this is because the compressed liquid properties depend on temperature much more strongly than they do on pressure.
- In the absence of compressed liquid data, a general approximation is ***to treat compressed liquid as saturated liquid at the given temperature.***



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)

How to Choose the Right Table

- Given the temperature or pressure and one other property from the group v, u, h, and s, the following procedure is used.
- For example if the pressure and specific volume are specified, three questions are asked: For the given pressure,

Is $v < v_f$?

Is $v_f < v < v_g$?

Is $v_g < v$?

  - If the answer to the first question is yes, the state is in the ***compressed liquid region.***
  - If the answer to the second question is yes, the state is in the ***saturation region.***
  - If the answer to the third question is yes, the state is in the ***superheated region***