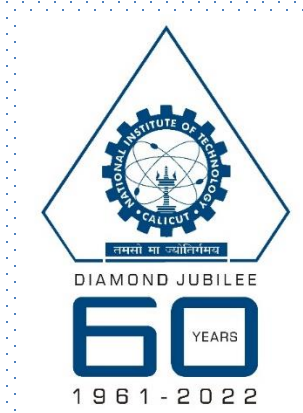# Properties of Pure Substance

Dr. Vinod Kumar Sharma
Department of Mechanical Engineering
**NIT Calicut**

Pure Substance

A pure substance-has a homogeneous and fixed chemical composition throughout. It may exist in more than one phase, but the chemical composition is the same in all phase.

Homogeneous Substance

A substance that has uniform thermodynamic properties throughout is said to be homogeneous.

Examples:

1. Water (H_2O) (solid, liquid, and vapor phases)
2. Mixture of liquid water (H_2O) and

   water vapor (H_2O)
3. Carbon dioxide, CO_2
4. Nitrogen, N_2
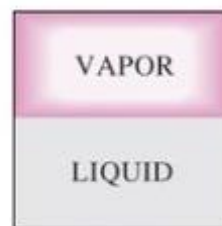5. Mixtures of gases, such as air, as long as there is no change of phase.

N_2

AIR
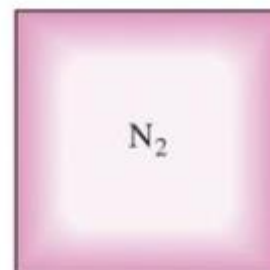
Nitrogen and gaseous air are pure substances.
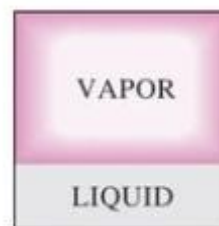
Examples of non-pure substances:
Mixture of water and oil
Mixture of liquid air(78% N_2 and 21% oxygen) and gaseous air

VAPOR

LIQUID

(a) H_2O

VAPOR

LIQUID

(b) AIR

A mixture of liquid and gaseous water is a pure substance, but a mixture of liquid and gaseous air is not.

Phases of pure substance

- **Solid**: The <u>large attractive forces of molecules</u> on each other keep the molecules at fixed position. Ice is the solid phase of water

- **Liquid:** The molecules are no longer at fixed position relative to each other and they can rotate and translate freely. The intermolecular forces are weaker relative to solids, but still relatively strong compared with gases.

- **Gas** : The molecules are far apart from each other, and a molecular order is nonexistent. Gas molecules move about randomly, continually colliding with each other and the walls of the container they are in. Molecules in the gas phase are at a considerably higher energy level than they are in the liquid or solid phases. Therefore, the gas must release a large amount of its energy before it can condense or freeze
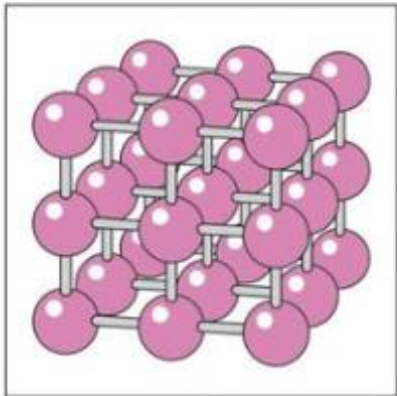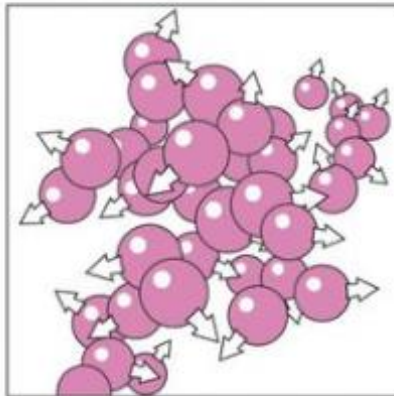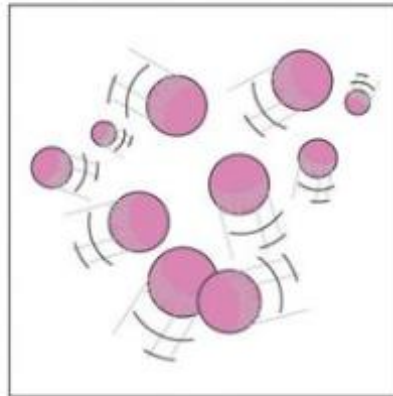
The arrangement of atoms in different phases: (*a*) molecules are at relatively fixed positions in a solid, (*b*) groups of molecules move about each other in the liquid phase, and (*c*) molecules move about at random in the gas phase.

(*a*)   (*b*)   (*c*)

Phase Change

• Molecular motion determined by temperature
• Higher temperatures result in higher microscopic internal energy (translational,
ro...
•E
•P
ar
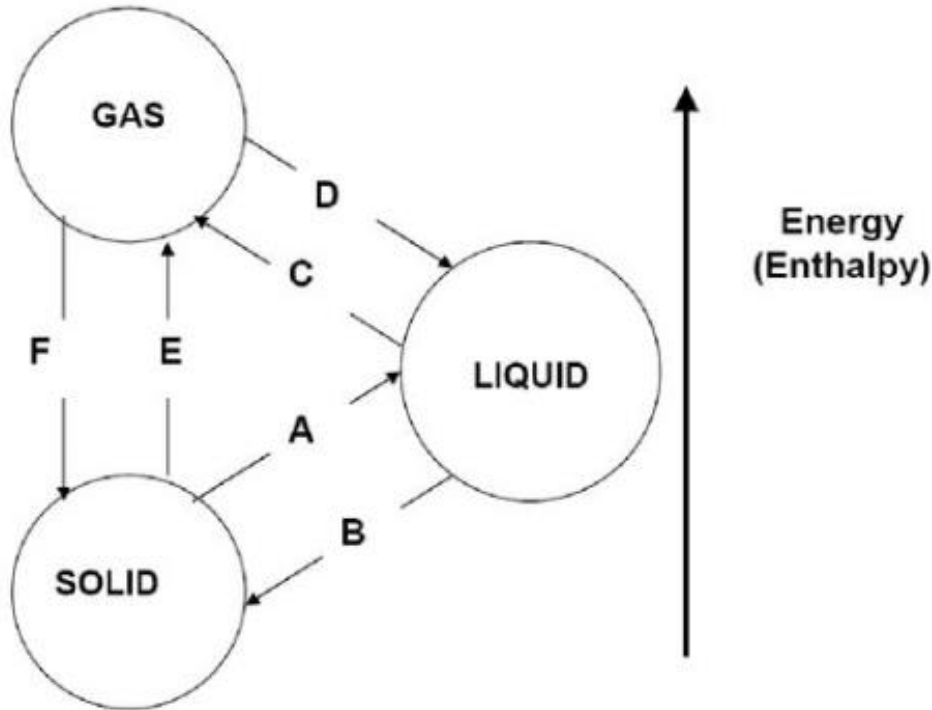
A: Melting

B: Freezing

C: <u>Vaporization</u>

D: <u>Condensation</u>

E: Sublimation

F: Deposition

•C
•V
•F
•M
•S
• *Deposition*: gas changing to solid without becoming liquid.

Phase Change Process in Pure Substance

STATE 1

$P = 1$ atm
$T = 20°C$

Heat

At 1 atm and 20°C, water exists in the liquid phase (*compressed liquid*).

STATE 2

$P = 1$ atm
$T = 100°C$

Heat

At 1 atm pressure and 100°C, water exists as a liquid that is ready to vaporize (*saturated liquid*).

Phase Change Process in Pure Substance

STATE 3

Saturated
vapor

$P = 1$ atm
$T = 100°C$

Saturated
liquid
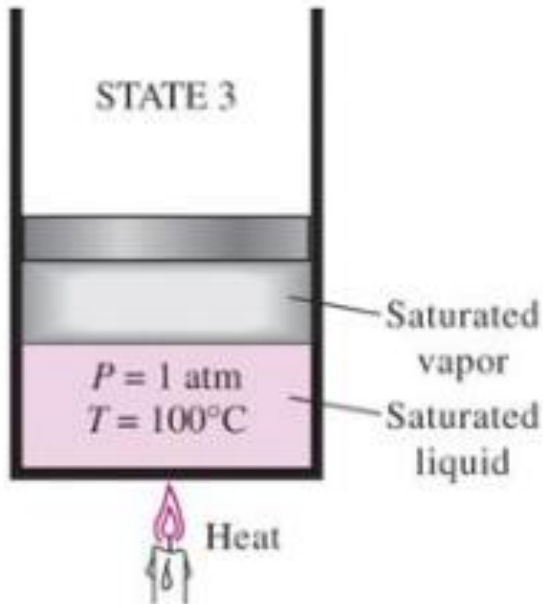
Heat

As more heat is transferred,
part of the saturated liquid
vaporizes (**saturated liquid–
vapor mixture**).

STATE 4

$P = 1$ atm
$T = 100°C$
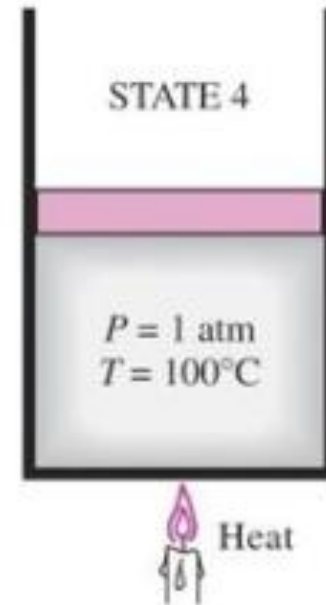
Heat

At 1 atm pressure, the
temperature remains constant
at 100°C until the last drop of
liquid is vaporized (**saturated
vapor**).

Phase Change Process in Pure Substance

STATE 5

$P = 1$ atm

$T = 300°C$
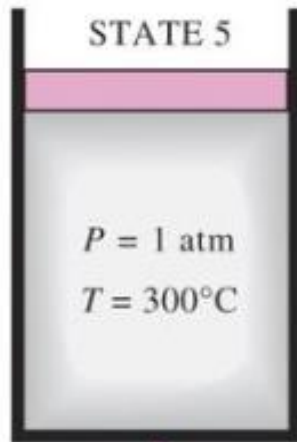
Heat

As more heat is transferred, the temperature of the vapor starts to rise (**superheated vapor**).

$T, °C$

300

$P = 1$ atm

5

Superheated vapor

2   Saturated   3

100

mixture   4

Compressed liquid

20   1

v
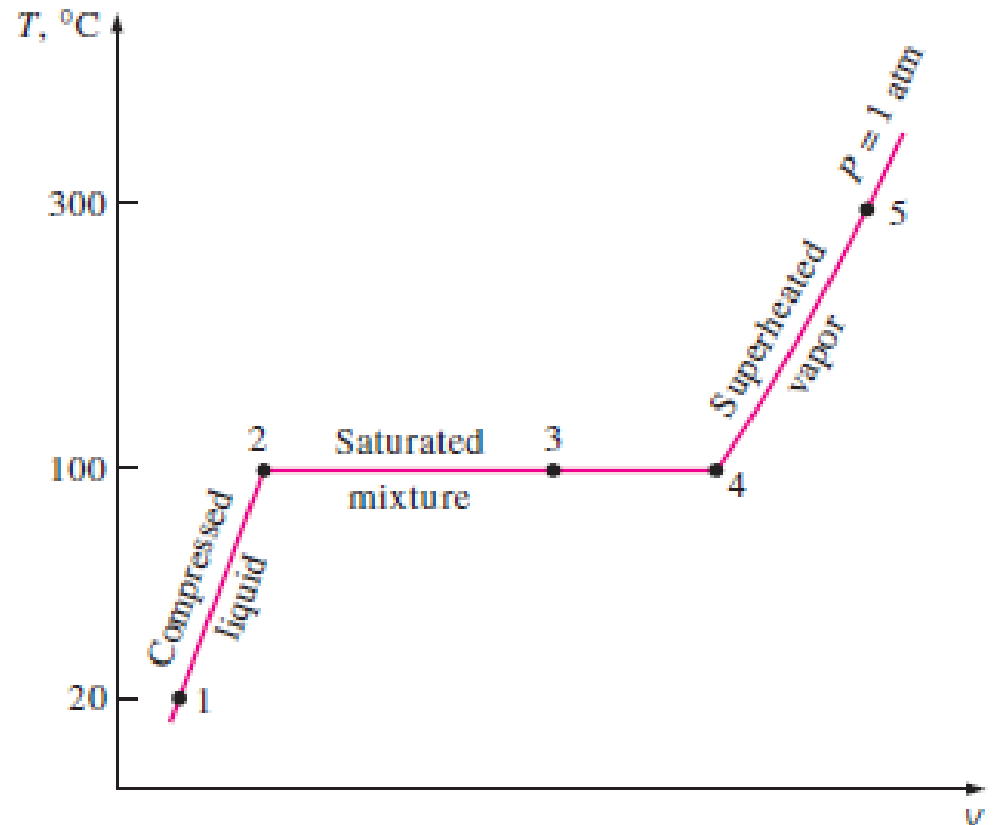
Saturation Temperature and Saturation Pressure

- Water boils at 100°C at 1 atm pressure.
- *The temperature at which water starts boiling depends on the pressure; therefore, if the pressure is fixed, so is the boiling temperature.*
- **Saturation temperature Tsat**: The temperature at which a pure substance changes phase at a given pressure.
- **Saturation pressure Psat**: The pressure at which a pure substance changes phase at a given temperature.
- At a pressure of 101.325 kPa, T_{sat} is 99.97°C.
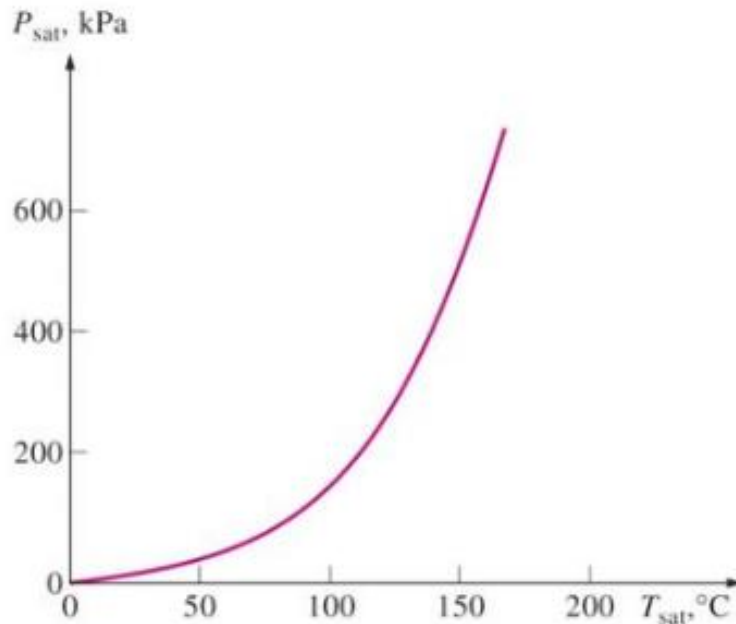
The liquid–vapor saturation curve of a pure substance (numerical values are for water).

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

Property Diagram

Property Diagram

P–v diagram of a pure substance showing the compressed liquid region, saturated liquid–vapor region, superheated vapor region, critical point, saturated liquid line, and saturated vapor line. A piston–cylinder device with $P = 1$ MPa and $T = 150°C$ is heated.

COMPRESSED LIQUID REGION

Critical point

SUPERHEATED VAPOR REGION

SATURATED LIQUID–VAPOR REGION

Saturated liquid line

Saturated vapor line

$T_2 = \text{const.} > T_1$

$T_1 = \text{const.}$

$P = 1$ MPa
$T = 150°C$

Heat

Steam Tables

- The properties of water are arranged in the steam tables as functions of pressure and temperature.

- Separate tables are provided to give the properties of water in the saturation states and in the liquid and vapour phases.

- The *internal energy of saturated water at the triple point (t = 0.0 1°C) is arbitrarily chosen to be zero.*

- Since *h = u + pv, the enthalpy of saturated water at 0.0 1 °C is slightly positive* because of the small value of *(pv) term.*

- *The entropy of saturated water is also chosen to be zero at the triple point.*

Temp., $T\,°C$	Sat. Press., P_{sat} kPa	Specific volume, m³/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg·K		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	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

TABLE A-5
Saturated water-Pressure table

Press. P kPa	Sat. Temp., T_{sat} °C	Specific volume, m³/kg			Internal energy, kJ/kg		Enthalpy, kJ/kg			Entropy, kJ/kg·K		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.6117	0.01	0.001000	206.00	0.00	2374.9	2374.9	0.00	2500.9	2500.9	0.0000	9.1556	9.1556
1.0	6.97	0.001000	129.19	29.30	2355.2	2384.5	29.30	2484.4	2513.7	0.1059	8.8690	8.9749
1.5	13.02	0.001001	87.964	54.69	2338.1	2392.8	54.69	2470.1	2524.7	0.1956	8.6314	8.8270
2.0	17.50	0.001001	66.990	73.43	2325.5	2398.9	73.43	2459.5	2532.9	0.2606	8.4621	8.7227
2.5	21.08	0.001002	54.242	88.42	2315.4	2403.8	88.42	2451.0	2539.4	0.3118	8.3302	8.6421
3.0	24.08	0.001003	45.654	100.98	2306.9	2407.9	100.98	2443.9	2544.8	0.3543	8.2222	8.5765
4.0	28.96	0.001004	34.791	121.39	2293.1	2414.5	121.39	2432.3	2553.7	0.4224	8.0510	8.4734
5.0	32.87	0.001005	28.185	137.75	2282.1	2419.8	137.75	2423.0	2560.7	0.4762	7.9176	8.3938
7.5	40.29	0.001008	19.233	168.74	2261.1	2429.8	168.75	2405.3	2574.0	0.5763	7.6738	8.2501
10	45.81	0.001010	14.670	191.79	2245.4	2437.2	191.81	2392.1	2583.9	0.6492	7.4996	8.1488
15	53.97	0.001014	10.020	225.93	2222.1	2448.0	225.94	2372.3	2598.3	0.7549	7.2522	8.0071
20	60.06	0.001017	7.6481	251.40	2204.6	2456.0	251.42	2357.5	2608.9	0.8320	7.0752	7.9073
25	64.96	0.001020	6.2034	271.93	2190.4	2462.4	271.96	2345.5	2617.5	0.8932	6.9370	7.8302
30	69.09	0.001022	5.2287	289.24	2178.5	2467.7	289.27	2335.3	2624.6	0.9441	6.8234	7.7675
40	75.86	0.001026	3.9933	317.58	2158.8	2476.3	317.62	2318.4	2636.1	1.0261	6.6430	7.6691
50	81.32	0.001030	3.2403	340.49	2142.7	2483.2	340.54	2304.7	2645.2	1.0912	6.5019	7.5931
75	91.76	0.001037	2.2172	384.36	2111.8	2496.1	384.44	2278.0	2662.4	1.2132	6.2426	7.4558
100	99.61	0.001043	1.6941	417.40	2088.2	2505.6	417.51	2257.5	2675.0	1.3028	6.0562	7.3589
125	105.97	0.001048	1.3750	444.23	2068.8	2513.0	444.36	2240.6	2684.9	1.3741	5.9100	7.2841
·	·	·	·	·	·	·	·	·	·	·	·	·
·	·	·	·	·	·	·	·	·	·	·	·	·
20,000	365.75	0.002038	0.005862	1785.84	509.0	2294.8	1826.59	585.5	2412.1	4.0146	0.9164	4.9310
21,000	369.83	0.002207	0.004994	1841.62	391.9	2233.5	1887.97	450.4	2338.4	4.1071	0.7005	4.8076
22,000	373.71	0.002703	0.003644	1951.65	140.8	2092.4	2011.12	161.5	2172.6	4.2942	0.2496	4.5439
22,064	373.95	0.003106	0.003106	2015.8	0	2015.8	2084.3	0	2084.3	4.4070	0	4.4070

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

Corresponding
saturation
pressure

Specific
volume of
saturated
liquid

Specific
volume of
saturated
vapor

Variation of the standard atmospheric pressure and the boiling (saturation) temperature of water with altitude

Elevation, m	Atmospheric pressure, kPa	Boiling tempera- ture, °C
0	101.33	100.0
1,000	89.55	96.5
2,000	79.50	93.3
5,000	54.05	83.3
10,000	26.50	66.3
20,000	5.53	34.7

Quality and Saturated Liquid-Vapor Mixture

Now, let's review the constant pressure heat addition process for water shown in Figure 4-11. Since state 3 is a mixture of saturated liquid and saturated vapor, how do we locate it on the T-v diagram? To establish the location of state 3 a new parameter called the quality x is defined as

$$x = \frac{mass_{saturated\ vapor}}{mass_{total}} = \frac{m_g}{m_f + m_g}$$

The quality is zero for the saturated liquid and one for the saturated vapor ($0 \leq x \leq 1$). The average specific volume at any state 3 is given in terms of the quality as follows. Consider a mixture of saturated liquid and saturated vapor. The liquid has a mass m_f and occupies a volume V_f. The vapor has a mass m_g and occupies a volume V_g.
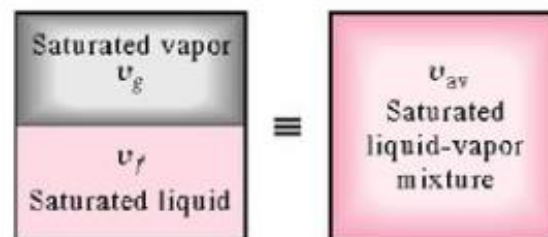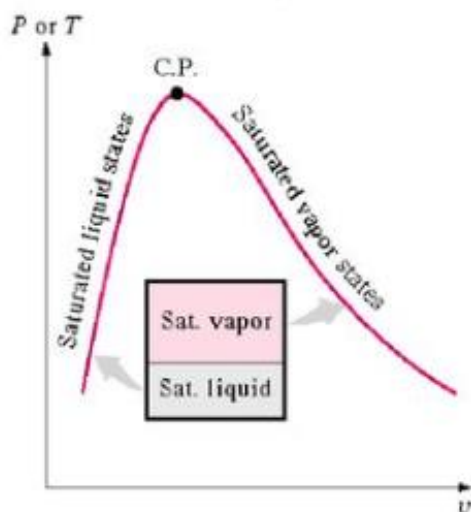
We note

$$V = V_f + V_g$$

$$m = m_f + m_g$$

$$V = mv, \quad V_f = m_f v_f, \quad V_g = m_g v_g$$

$$mv = m_f v_f + m_g v_g$$

$$v = \frac{m_f v_f}{m} + \frac{m_g v_g}{m}$$

Recall the definition of quality x

$$x = \frac{m_g}{m} = \frac{m_g}{m_f + m_g}$$

Then

$$\frac{m_f}{m} = \frac{m - m_g}{m} = 1 - x$$

Note, quantity $1 - x$ is often given the name moisture. The specific volume of the saturated mixture becomes

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

Superheated Water Table

A substance is said to be **superheated** if the given temperature is greater than the saturation temperature for the given pressure.
State 5 in Figure 4-11 is a superheated state.

In the superheated water Table A-6, T and P are the independent properties. The value of temperature to the right of the pressure is the saturation temperature for the pressure.

The first entry in the table is the saturated vapor state at the pressure.

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

Higher tempreatures ($T > T_{sat}$ 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)

TABLE A-6 Superheated water

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg·K
			P = 0.01 MPa (45.81°C)	
Sat.	14.670	2437.2	2583.9	8.1488
50	14.867	2443.3	2592.0	8.1741
100	17.196	2515.5	2687.5	8.4489
150	19.513	2587.9	2783.0	8.6893
200	21.826	2661.4	2879.6	8.9049
250	24.136	2736.1	2977.5	9.1015
300	26.446	2812.3	3076.7	9.2827
400	31.063	2969.3	3280.0	9.6094
500	35.680	3132.9	3489.7	9.8998
600	40.296	3303.3	3706.3	10.1631
700	44.911	3480.8	3929.9	10.4056
800	49.527	3665.4	4160.6	10.6312
900	54.143	3856.9	4398.3	10.8429
1000	58.758	4055.3	4642.8	11.0429
1100	63.373	4260.0	4893.8	11.2326
1200	67.989	4470.9	5150.8	11.4132
1300	72.604	4687.4	5413.4	11.5857

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

Note: If $T \gg T_{critical}$ or $P \ll P_{critical}$, then the vapor is called "gas" and can be approximated as an "ideal gas"

Linear interpolation

Assumes any two data points connected by straight line
(set slopes equal to find missing value)

A	B
100	5
130	X
200	10

$$\frac{130-100}{200-100} = \frac{x-5}{10-5}$$

Useful Ideal Gas Relation: The Combined Gas Law

By writing the ideal gas equation twice for a fixed mass and simplifying, the properties of an ideal gas at two different states are related by

$$m_1 = m_2$$

$$PV = mRT$$

$$m = \frac{PV}{RT}$$

or

$$\frac{P_1 V_1}{R T_1} = \frac{P_2 V_2}{R T_2}$$

But, the gas constant is_____(fill in the blank), so

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

Special cases:

» Isobaric process:
(constant pressure)

$$\frac{v_1}{v_2} = \frac{T_1}{T_2}$$

» Isothermal process:
(constant temperature)

$$\frac{v_1}{v_2} = \frac{P_2}{P_1}$$

» Isochoric process at constant mass:
(constant specific volume)

$$\frac{P_1}{P_2} = \frac{T_1}{T_2}$$

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