Pure Substance

- A substance that has a fixed chemical composition throughout is called a *pure substance*.
- Water, nitrogen, helium, and carbon dioxide, for example, are all 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.
- Air, for example, is a mixture of several gases, but it is often considered to be a pure substance because it has a uniform chemical composition.
- However, a mixture of oil and water is not a pure substance. Since oil is not soluble in water, it will collect on top of the water, forming two chemically dissimilar regions.

Dr. Román Miguel Moreno, Ph.D., CEM, REP

Pure Substance

- A <u>mixture of two or more phases of a pure substance is still a pure substance</u> as long as the chemical composition of all phases is the same.

- A mixture of ice and liquid water, for example, is a pure substance because both phases have the same chemical composition.

- A mixture of liquid air and gaseous air, however, is not a pure substance since the composition of liquid air is different from the composition of gaseous air, and thus the mixture is no longer chemically homogeneous.

- This is due to different components in air condensing at different temperatures at a specified pressure.
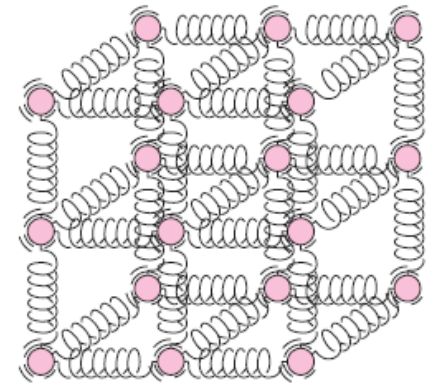
Pure Substance

Phases of a Pure Substance

- A ***phase*** is identified as having a distinct molecular arrangement that is homogeneous throughout and separated from the others by easily identifiable boundary surfaces.

- Even though there are three principal phases—solid, liquid, and gas—a substance may have several phases within a principal phase, each with a different molecular structure.

- Carbon, for example, may exist as graphite or diamond in the solid phase. Helium has two liquid phases; iron has three solid phases. Ice may exist at seven different phases at high pressures.
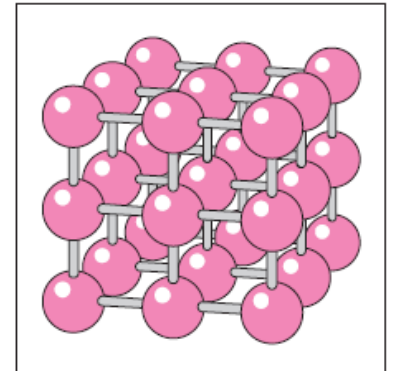
Pure Substance

Solid

- The molecules in a solid are arranged in a three-dimensional pattern (lattice) that is repeated throughout.

- Because of the small distances between molecules in a solid, the attractive forces of molecules on each other are large and keep the molecules at fixed positions.

- Note that the attractive forces between molecules turn to repulsive forces as the distance between the molecules approaches zero, thus preventing the molecules from piling up on top of each other.

The molecules in a solid are kept at their positions by the large springlike intermolecular forces.
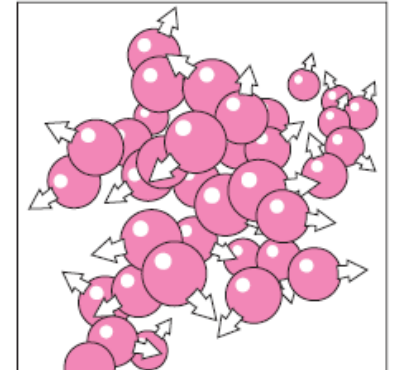
Pure Substance

- Even though the molecules in a solid cannot move relative to each other, they continually oscillate about their equilibrium positions. The velocity of the molecules during these oscillations depends on the temperature.
- At sufficiently high temperatures, the velocity (and thus the momentum) of the molecules may reach a point where the intermolecular forces are partially overcome and groups of molecules break away.
- This is the beginning of the melting process.
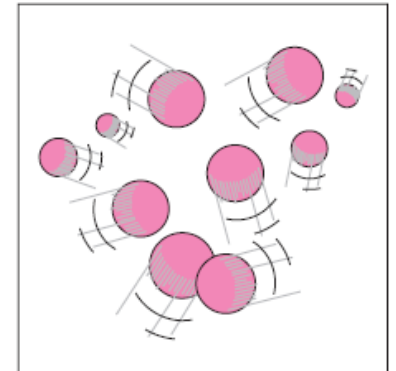
Pure Substance

Liquid

- The molecular spacing in the liquid phase is not much different from that of the solid phase, except the molecules are no longer at fixed positions relative to each other and they can rotate and translate freely.

- In a liquid, the intermolecular forces are weaker relative to solids, but still relatively strong compared with gases.

- The distances between molecules generally experience a slight increase as a solid turns liquid, with water being a notable exception.
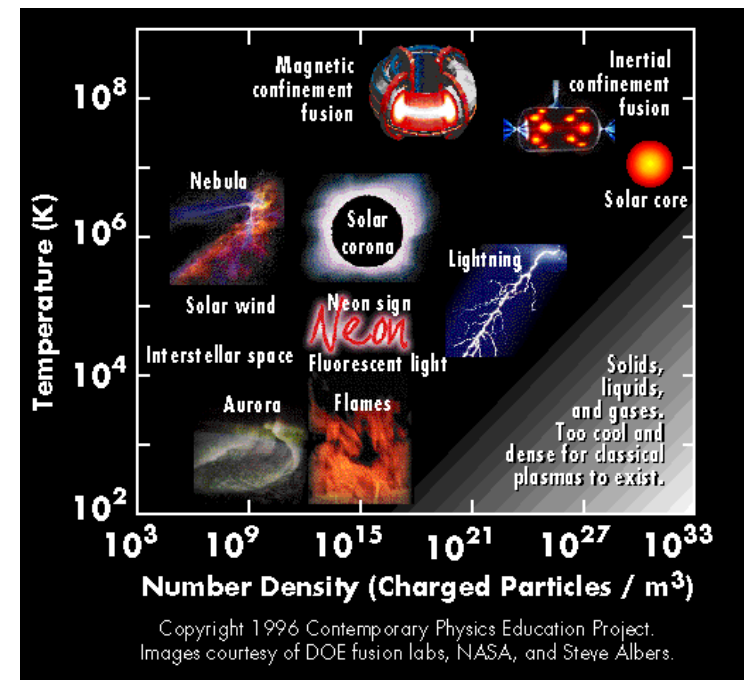
Pure Substance

Gas

- In the gas phase, the molecules are far apart from each other, and a molecular order is nonexistent.

- Gas molecules move about at random, continually colliding with each other and the walls of the container they are in.

- Particularly at low densities, the intermolecular forces are very small, and collisions are the only mode of interaction between the molecules, which 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.

Pure Substance

Plasma

- Plasma, according to natural science, is one of the four fundamental states of matter (the others being solid, liquid, and gas).

- When air or gas is ionized, plasma forms with similar conductive properties to that of metals.

- Plasma is the most abundant form of matter in the Universe, because most stars are in a plasma state.
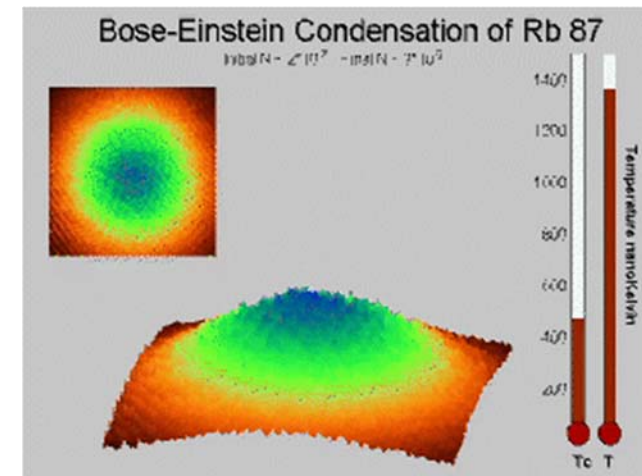
Pure Substance

Bose Einstein Condensation (BEC)

- A Bose–Einstein condensate (BEC) is a state of matter of a dilute gas of bosons cooled to temperatures very close to absolute zero (that is, very near 0 K or −273.15 °C).

- Under such conditions, a large fraction of the bosons occupy the lowest quantum state, at which point quantum effects become apparent on a macroscopic scale.

- These effects are called macroscopic quantum phenomena.

- Although later experiments have revealed complex interactions, this state of matter was first predicted, generally, in 1924–25 by Satyendra Nath Bose and Albert Einstein.

Bose-Einstein Condensation of Rb 87

Pure Substance

- Phase-Change Processes of Pure Substances (Water)

STATE 1

$P = 1$ atm
$T = 20°C$
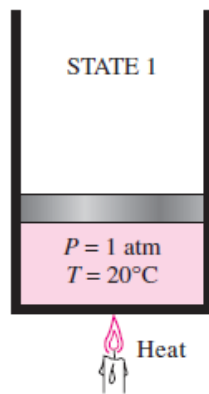
Heat

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

STATE 2

$P = 1$ atm
$T = 100°C$
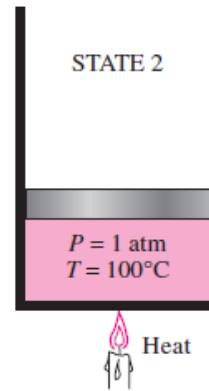
Heat

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

STATE 3

Saturated vapor

$P = 1$ atm
$T = 100°C$

Saturated liquid
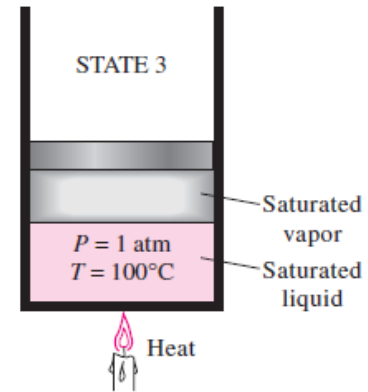
Heat

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

Pure Substance

STATE 4

$P = 1$ atm
$T = 100°C$
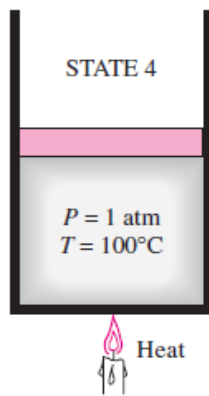
Heat

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

STATE 5

$P = 1$ atm
$T = 300°C$
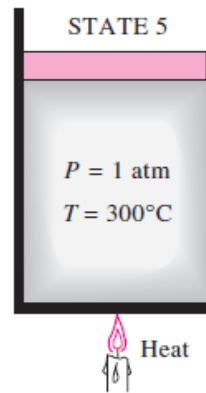
Heat

As more heat is transferred, the temperature of the vapor starts to rise (*superheated vapor*).
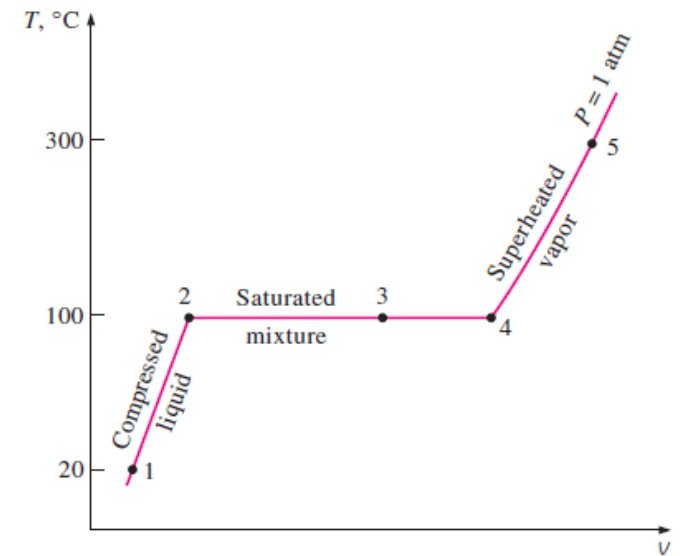
T-v diagram for the heating process of water at constant pressure.

Pure Substance

Saturation Temperature and Saturation Pressure

- At a given pressure, the temperature at which a pure substance changes phase is called the saturation temperature T_{sat}.

- Likewise, at a given temperature, the pressure at which a pure substance changes phase is called the saturation pressure P_{sat}.
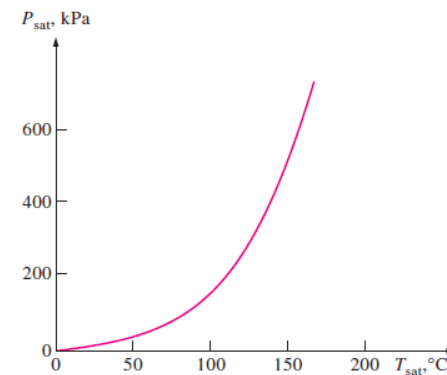
Saturation (boiling) pressure of water at various temperatures

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

Pure Substance

The *T-v* Diagram
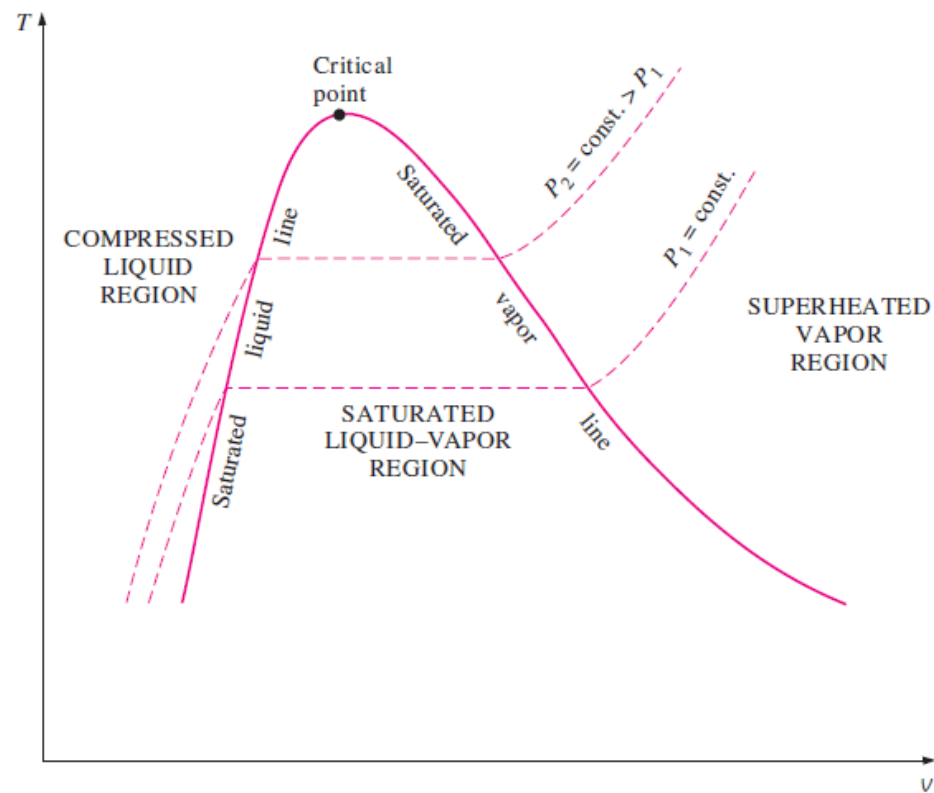
Pure Substance

The *P-v* Diagram
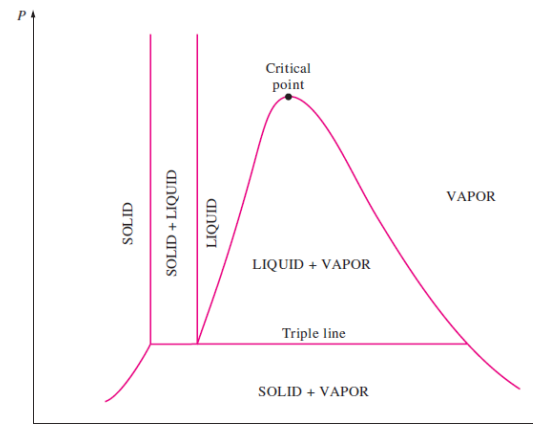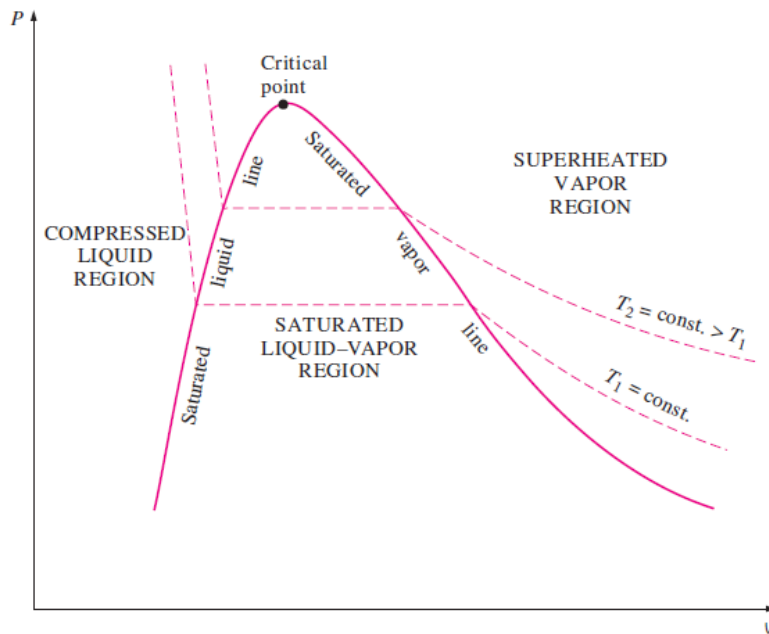
P-v diagram of a substance that contracts on freezing.
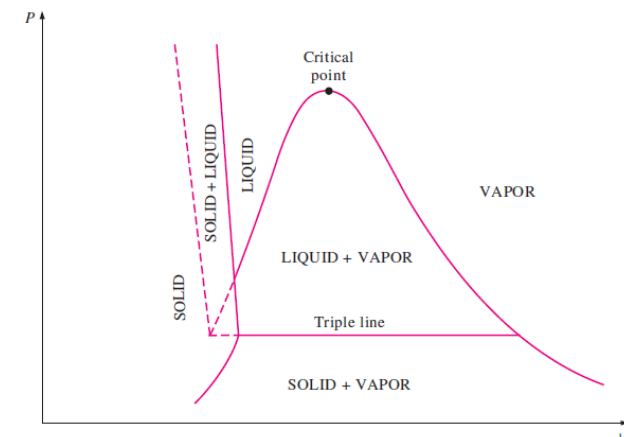
P-v diagram of a substance that expands on freezing (such as water).

Pure Substance

The *P-T* Diagram
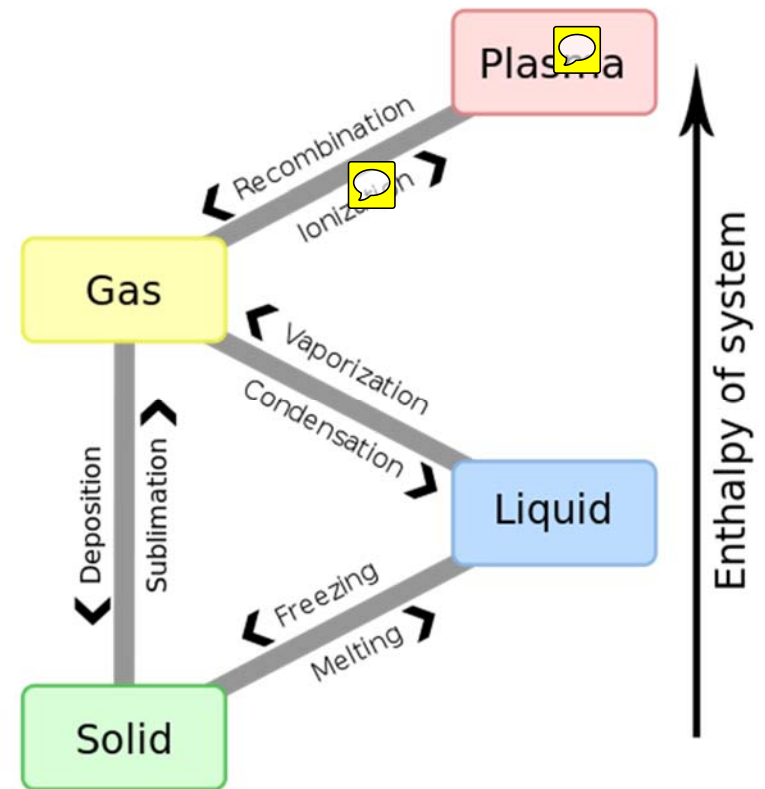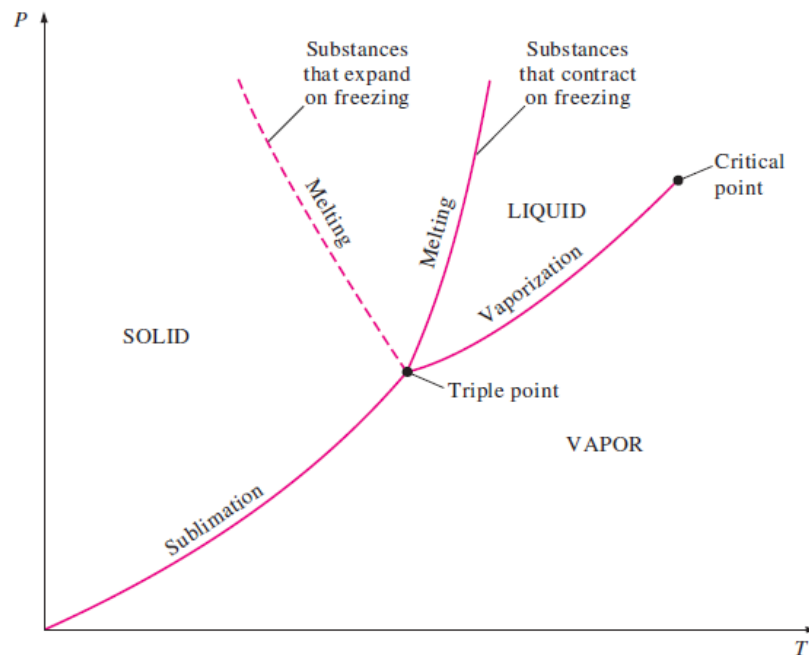
Pure Substance

The *P-v-T* Surface
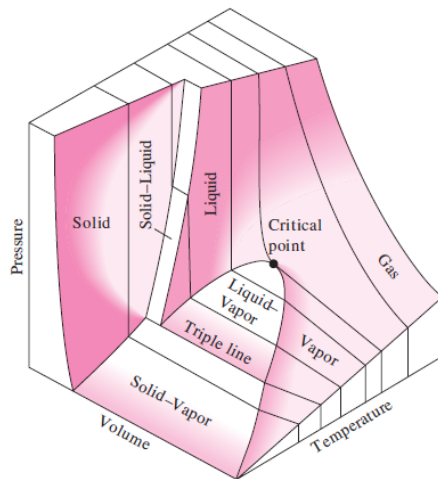
P-v-T surface of a substance that *contracts* on freezing.
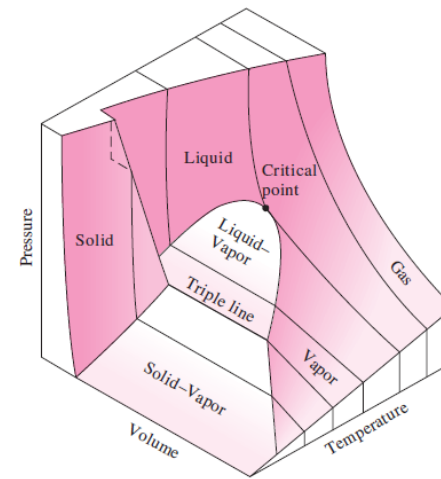
P-v-T surface of a substance that *expands* on freezing (like water).

Pure Substance

Enthalpy

- In the analysis of certain types of processes, particularly in power generation and refrigeration, we frequently encounter the combination of properties $u + Pv$.

- For the sake of simplicity and convenience, this combination is defined as a new property, ***enthalpy***, and given the symbol h:

    Enthalpy $\qquad\qquad H = U + PV \quad$ (kJ)

    Specific Enthalpy $\quad h = u + Pv \quad$ (kJ/kg)
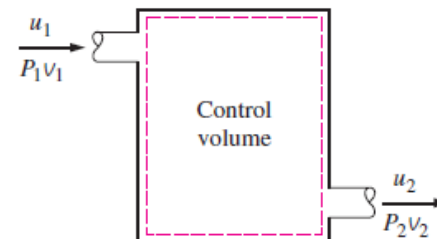
Pure Substance

<u>Saturated Liquid and Saturated Vapor States</u>
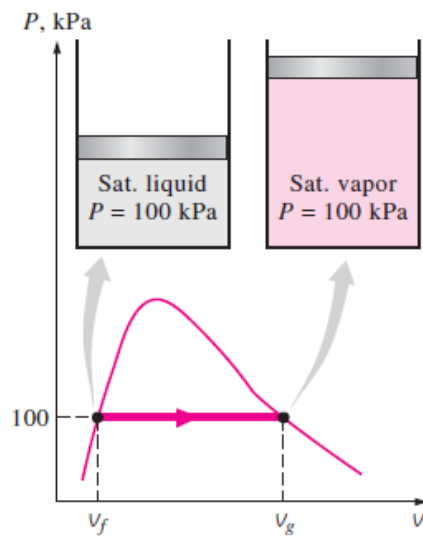
v_f = specific volume of saturated liquid

v_g = specific volume of saturated vapor

v_{fg} = difference between v_g and v_f (that is, $v_{fg} = v_g - v_f$)

Pure Substance

Vapor Mixture
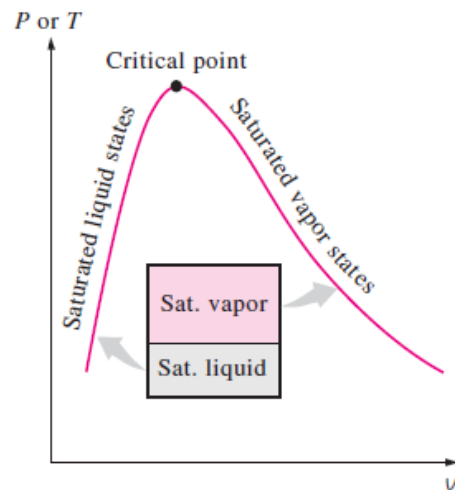
Quality (x)

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

$$x = \frac{\overline{AB}}{\overline{AC}}$$
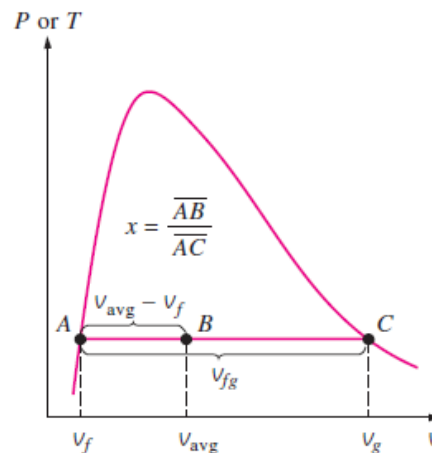
Quality is related to the horizontal distances on P-v and T-v diagrams.

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

$$v_{avg} = v_f + x v_{fg} \qquad (m^3/kg)$$

$$u_{avg} = u_f + x u_{fg} \qquad (kJ/kg)$$

$$h_{avg} = h_f + x h_{fg} \qquad (kJ/kg)$$

Pure Substance

Superheated Vapor
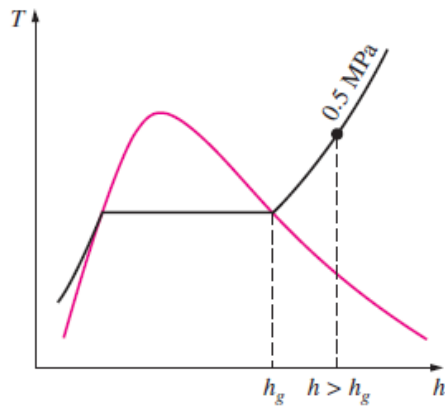
Compressed Liquid

Pure Substance

Water Tables

(Saturated Water-Temperature Table)

TABLE A–4

Saturated water—Temperature table

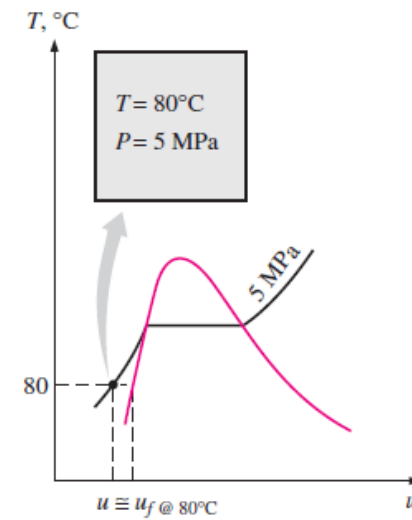| Temp., T °C	Sat. press., P_{sat} kPa	Specific volume, m³/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg·K		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249
10	1.2281	0.001000	106.32	42.020	2346.6	2388.7	42.022	2477.2	2519.2	0.1511	8.7488	8.8999
15	1.7057	0.001001	77.885	62.980	2332.5	2395.5	62.982	2465.4	2528.3	0.2245	8.5559	8.7803
20	2.3392	0.001002	57.762	83.913	2318.4	2402.3	83.915	2453.5	2537.4	0.2965	8.3696	8.6661
25	3.1698	0.001003	43.340	104.83	2304.3	2409.1	104.83	2441.7	2546.5	0.3672	8.1895	8.5567
30	4.2469	0.001004	32.879	125.73	2290.2	2415.9	125.74	2429.8	2555.6	0.4368	8.0152	8.4520
35	5.6291	0.001006	25.205	146.63	2276.0	2422.7	146.64	2417.9	2564.6	0.5051	7.8466	8.3517
40	7.3851	0.001008	19.515	167.53	2261.9	2429.4	167.53	2406.0	2573.5	0.5724	7.6832	8.2556
45	9.5953	0.001010	15.251	188.43	2247.7	2436.1	188.44	2394.0	2582.4	0.6386	7.5247	8.1633
50	12.352	0.001012	12.026	209.33	2233.4	2442.7	209.34	2382.0	2591.3	0.7038	7.3710	8.0748
55	15.763	0.001015	9.5639	230.24	2219.1	2449.3	230.26	2369.8	2600.1	0.7680	7.2218	7.9898
60	19.947	0.001017	7.6670	251.16	2204.7	2455.9	251.18	2357.7	2608.8	0.8313	7.0769	7.9082
65	25.043	0.001020	6.1935	272.09	2190.3	2462.4	272.12	2345.4	2617.5	0.8937	6.9360	7.8296
70	31.202	0.001023	5.0396	293.04	2175.8	2468.9	293.07	2333.0	2626.1	0.9551	6.7989	7.7540
75	38.597	0.001026	4.1291	313.99	2161.3	2475.3	314.03	2320.6	2634.6	1.0158	6.6655	7.6812
80	47.416	0.001029	3.4053	334.97	2146.6	2481.6	335.02	2308.0	2643.0	1.0756	6.5355	7.6111
85	57.868	0.001032	2.8261	355.96	2131.9	2487.8	356.02	2295.3	2651.4	1.1346	6.4089	7.5435
90	70.183	0.001036	2.3593	376.97	2117.0	2494.0	377.04	2282.5	2659.6	1.1929	6.2853	7.4782
95	84.609	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
105	120.90	0.001047	1.4186	440.15	2071.8	2511.9	440.28	2243.1	2683.4	1.3634	5.9319	7.2952
110	143.38	0.001052	1.2094	461.27	2056.4	2517.7	461.42	2229.7	2691.1	1.4188	5.8193	7.2382
115	169.18	0.001056	1.0360	482.42	2040.9	2523.3	482.59	2216.0	2698.6	1.4737	5.7092	7.1829
120	198.67	0.001060	0.89133	503.60	2025.3	2528.9	503.81	2202.1	2706.0	1.5279	5.6013	7.1292
125	232.23	0.001065	0.77012	524.83	2009.5	2534.3	525.07	2188.1	2713.1	1.5816	5.4956	7.0771
130	270.28	0.001070	0.66808	546.10	1993.4	2539.5	546.38	2173.7	2720.1	1.6346	5.3919	7.0265
135	313.22	0.001075	0.58179	567.41	1977.3	2544.7	567.75	2159.1	2726.9	1.6872	5.2901	6.9773
140	361.53	0.001080	0.50850	588.77	1960.9	2549.6	589.16	2144.3	2733.5	1.7392	5.1901	6.9294
145	415.68	0.001085	0.44600	610.19	1944.2	2554.4	610.64	2129.2	2739.8	1.7908	5.0919	6.8827

Pure Substance

Water Tables

(Saturated Water-
Pressure Table)

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
1.0	6.97	0.001000	129.19	29.302	2355.2	2384.5	29.303	2484.4	2513.7	0.1059	8.8690	8.9749
1.5	13.02	0.001001	87.964	54.686	2338.1	2392.8	54.688	2470.1	2524.7	0.1956	8.6314	8.8270
2.0	17.50	0.001001	66.990	73.431	2325.5	2398.9	73.433	2459.5	2532.9	0.2606	8.4621	8.7227
2.5	21.08	0.001002	54.242	88.422	2315.4	2403.8	88.424	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
101.325	99.97	0.001043	1.6734	418.95	2087.0	2506.0	419.06	2256.5	2675.6	1.3069	6.0476	7.3545
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
150	111.35	0.001053	1.1594	466.97	2052.3	2519.2	467.13	2226.0	2693.1	1.4337	5.7894	7.2231
175	116.04	0.001057	1.0037	486.82	2037.7	2524.5	487.01	2213.1	2700.2	1.4850	5.6865	7.1716
200	120.21	0.001061	0.88578	504.50	2024.6	2529.1	504.71	2201.6	2706.3	1.5302	5.5968	7.1270
225	123.97	0.001064	0.79329	520.47	2012.7	2533.2	520.71	2191.0	2711.7	1.5706	5.5171	7.0877
250	127.41	0.001067	0.71873	535.08	2001.8	2536.8	535.35	2181.2	2716.5	1.6072	5.4453	7.0525
275	130.58	0.001070	0.65732	548.57	1991.6	2540.1	548.86	2172.0	2720.9	1.6408	5.3800	7.0207
300	133.52	0.001073	0.60582	561.11	1982.1	2543.2	561.43	2163.5	2724.9	1.6717	5.3200	6.9917
325	136.27	0.001076	0.56199	572.84	1973.1	2545.9	573.19	2155.4	2728.6	1.7005	5.2645	6.9650
350	138.86	0.001079	0.52422	583.89	1964.6	2548.5	584.26	2147.7	2732.0	1.7274	5.2128	6.9402
375	141.30	0.001081	0.49133	594.32	1956.6	2550.9	594.73	2140.4	2735.1	1.7526	5.1645	6.9171

Pure Substance

Water Tables
(Superheated Water)

TABLE A–6

Superheated water

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	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg·K
	P = 0.01 MPa (45.81°C)*				P = 0.05 MPa (81.32°C)				P = 0.10 MPa (99.61°C)			
Sat.†	14.670	2437.2	2583.9	8.1488	3.2403	2483.2	2645.2	7.5931	1.6941	2505.6	2675.0	7.3589
50	14.867	2443.3	2592.0	8.1741								
100	17.196	2515.5	2687.5	8.4489	3.4187	2511.5	2682.4	7.6953	1.6959	2506.2	2675.8	7.3611
150	19.513	2587.9	2783.0	8.6893	3.8897	2585.7	2780.2	7.9413	1.9367	2582.9	2776.6	7.6148
200	21.826	2661.4	2879.6	8.9049	4.3562	2660.0	2877.8	8.1592	2.1724	2658.2	2875.5	7.8356
250	24.136	2736.1	2977.5	9.1015	4.8206	2735.1	2976.2	8.3568	2.4062	2733.9	2974.5	8.0346
300	26.446	2812.3	3076.7	9.2827	5.2841	2811.6	3075.8	8.5387	2.6389	2810.7	3074.5	8.2172
400	31.063	2969.3	3280.0	9.6094	6.2094	2968.9	3279.3	8.8659	3.1027	2968.3	3278.6	8.5452
500	35.680	3132.9	3489.7	9.8998	7.1338	3132.6	3489.3	9.1566	3.5655	3132.2	3488.7	8.8362
600	40.296	3303.3	3706.3	10.1631	8.0577	3303.1	3706.0	9.4201	4.0279	3302.8	3705.6	9.0999
700	44.911	3480.8	3929.9	10.4056	8.9813	3480.6	3929.7	9.6626	4.4900	3480.4	3929.4	9.3424
800	49.527	3665.4	4160.6	10.6312	9.9047	3665.2	4160.4	9.8883	4.9519	3665.0	4160.2	9.5682
900	54.143	3856.9	4398.3	10.8429	10.8280	3856.8	4398.2	10.1000	5.4137	3856.7	4398.0	9.7800
1000	58.758	4055.3	4642.8	11.0429	11.7513	4055.2	4642.7	10.3000	5.8755	4055.0	4642.6	9.9800
1100	63.373	4260.0	4893.8	11.2326	12.6745	4259.9	4893.7	10.4897	6.3372	4259.8	4893.6	10.1698
1200	67.989	4470.9	5150.8	11.4132	13.5977	4470.8	5150.7	10.6704	6.7988	4470.7	5150.6	10.3504
1300	72.604	4687.4	5413.4	11.5857	14.5209	4687.3	5413.3	10.8429	7.2605	4687.2	5413.3	10.5229
	P = 0.20 MPa (120.21°C)				P = 0.30 MPa (133.52°C)				P = 0.40 MPa (143.61°C)			
Sat.	0.88578	2529.1	2706.3	7.1270	0.60582	2543.2	2724.9	6.9917	0.46242	2553.1	2738.1	6.8955
150	0.95986	2577.1	2769.1	7.2810	0.63402	2571.0	2761.2	7.0792	0.47088	2564.4	2752.8	6.9306
200	1.08049	2654.6	2870.7	7.5081	0.71643	2651.0	2865.9	7.3132	0.53434	2647.2	2860.9	7.1723
250	1.19890	2731.4	2971.2	7.7100	0.79645	2728.9	2967.9	7.5180	0.59520	2726.4	2964.5	7.3804
300	1.31623	2808.8	3072.1	7.8941	0.87535	2807.0	3069.6	7.7037	0.65489	2805.1	3067.1	7.5677
400	1.54934	2967.2	3277.0	8.2236	1.03155	2966.0	3275.5	8.0347	0.77265	2964.9	3273.9	7.9003
500	1.78142	3131.4	3487.7	8.5153	1.18672	3130.6	3486.6	8.3271	0.88936	3129.8	3485.5	8.1933
600	2.01302	3302.2	3704.8	8.7793	1.34139	3301.6	3704.0	8.5915	1.00558	3301.0	3703.3	8.4580
700	2.24434	3479.9	3928.8	9.0221	1.49580	3479.5	3928.2	8.8345	1.12152	3479.0	3927.6	8.7012
800	2.47550	3664.7	4159.8	9.2479	1.65004	3664.3	4159.3	9.0605	1.23730	3663.9	4158.9	8.9274
900	2.70656	3856.3	4397.7	9.4598	1.80417	3856.0	4397.3	9.2725	1.35298	3855.7	4396.9	9.1394
1000	2.93755	4054.8	4642.3	9.6599	1.95824	4054.5	4642.0	9.4726	1.46859	4054.3	4641.7	9.3396
1100	3.16848	4259.6	4893.3	9.8497	2.11226	4259.4	4893.1	9.6624	1.58414	4259.2	4892.9	9.5295
1200	3.39938	4470.5	5150.4	10.0304	2.26624	4470.3	5150.2	9.8431	1.69966	4470.2	5150.0	9.7102

Pure Substance

Water Tables

(Compressed Liquid Water)

TABLE A–7

Compressed liquid water

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	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg·K
	P = 5 MPa (263.94°C)				*P* = 10 MPa (311.00°C)				*P* = 15 MPa (342.16°C)			
Sat.	0.0012862	1148.1	1154.5	2.9207	0.0014522	1393.3	1407.9	3.3603	0.0016572	1585.5	1610.3	3.6848
0	0.0009977	0.04	5.03	0.0001	0.0009952	0.12	10.07	0.0003	0.0009928	0.18	15.07	0.0004
20	0.0009996	83.61	88.61	0.2954	0.0009973	83.31	93.28	0.2943	0.0009951	83.01	97.93	0.2932
40	0.0010057	166.92	171.95	0.5705	0.0010035	166.33	176.37	0.5685	0.0010013	165.75	180.77	0.5666
60	0.0010149	250.29	255.36	0.8287	0.0010127	249.43	259.55	0.8260	0.0010105	248.58	263.74	0.8234
80	0.0010267	333.82	338.96	1.0723	0.0010244	332.69	342.94	1.0691	0.0010221	331.59	346.92	1.0659
100	0.0010410	417.65	422.85	1.3034	0.0010385	416.23	426.62	1.2996	0.0010361	414.85	430.39	1.2958
120	0.0010576	501.91	507.19	1.5236	0.0010549	500.18	510.73	1.5191	0.0010522	498.50	514.28	1.5148
140	0.0010769	586.80	592.18	1.7344	0.0010738	584.72	595.45	1.7293	0.0010708	582.69	598.75	1.7243
160	0.0010988	672.55	678.04	1.9374	0.0010954	670.06	681.01	1.9316	0.0010920	667.63	684.01	1.9259
180	0.0011240	759.47	765.09	2.1338	0.0011200	756.48	767.68	2.1271	0.0011160	753.58	770.32	2.1206
200	0.0011531	847.92	853.68	2.3251	0.0011482	844.32	855.80	2.3174	0.0011435	840.84	858.00	2.3100
220	0.0011868	938.39	944.32	2.5127	0.0011809	934.01	945.82	2.5037	0.0011752	929.81	947.43	2.4951
240	0.0012268	1031.6	1037.7	2.6983	0.0012192	1026.2	1038.3	2.6876	0.0012121	1021.0	1039.2	2.6774
260	0.0012755	1128.5	1134.9	2.8841	0.0012653	1121.6	1134.3	2.8710	0.0012560	1115.1	1134.0	2.8586
280					0.0013226	1221.8	1235.0	3.0565	0.0013096	1213.4	1233.0	3.0410
300					0.0013980	1329.4	1343.3	3.2488	0.0013783	1317.6	1338.3	3.2279
320									0.0014733	1431.9	1454.0	3.4263
340									0.0016311	1567.9	1592.4	3.6555
	P = 20 MPa (365.75°C)				*P* = 30 MPa				*P* = 50 MPa			
Sat.	0.0020378	1785.8	1826.6	4.0146								
0	0.0009904	0.23	20.03	0.0005	0.0009857	0.29	29.86	0.0003	0.0009767	0.29	49.13	−0.0010
20	0.0009929	82.71	102.57	0.2921	0.0009886	82.11	111.77	0.2897	0.0009805	80.93	129.95	0.2845
40	0.0009992	165.17	185.16	0.5646	0.0009951	164.05	193.90	0.5607	0.0009872	161.90	211.25	0.5528
60	0.0010084	247.75	267.92	0.8208	0.0010042	246.14	276.26	0.8156	0.0009962	243.08	292.88	0.8055
80	0.0010199	330.50	350.90	1.0627	0.0010155	328.40	358.86	1.0564	0.0010072	324.42	374.78	1.0442
100	0.0010337	413.50	434.17	1.2920	0.0010290	410.87	441.74	1.2847	0.0010201	405.94	456.94	1.2705
120	0.0010496	496.85	517.84	1.5105	0.0010445	493.66	525.00	1.5020	0.0010349	487.69	539.43	1.4859
140	0.0010679	580.71	602.07	1.7194	0.0010623	576.90	608.76	1.7098	0.0010517	569.77	622.36	1.6916
160	0.0010886	665.28	687.05	1.9203	0.0010823	660.74	693.21	1.9094	0.0010704	652.33	705.85	1.8889
180	0.0011122	750.78	773.02	2.1143	0.0011049	745.40	778.55	2.1020	0.0010914	735.49	790.06	2.0790
200	0.0011390	837.49	860.27	2.3027	0.0011304	831.11	865.02	2.2888	0.0011149	819.45	875.19	2.2628

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Examples (textbook)

EXAMPLE 3–1 **Pressure of Saturated Liquid in a Tank**

A rigid tank contains 50 kg of saturated liquid water at 90°C. Determine the pressure in the tank and the volume of the tank.
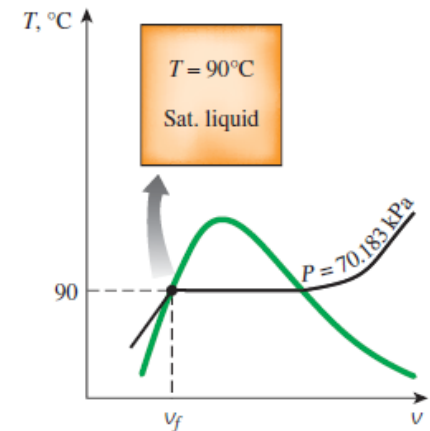
$P = P_{\text{sat@}90°C} \Rightarrow$ Table A4 $\qquad \Rightarrow \boldsymbol{P = 70.183 \text{ kPa}}$

$v = v_{f@90°C} \Rightarrow$ Table A4 $\qquad \Rightarrow v = 0.001036 \text{ m}^3/\text{kg}$

$V = mv$

$\quad = (50 \text{ kg})(0.001036 \text{ m}^3/\text{kg}) \qquad \Rightarrow \boldsymbol{V = 0.0518 \text{ m}^3}$
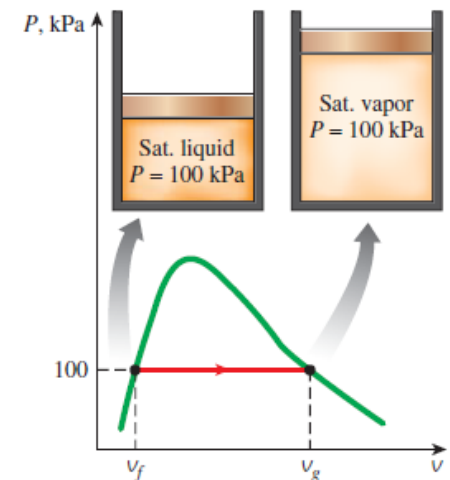
Examples (textbook)

EXAMPLE 3–3 **Volume and Energy Change during Evaporation**

A mass of 200 g of saturated liquid water is completely vaporized at a constant pressure of 100 kPa. Determine (a) the volume change and (b) the amount of energy transferred to the water.

a) $\Delta V = m v_{fg@100\text{kPa}} = m(v_g - v_f)$ (Table A5)

$= (0.2 \text{ kg})(1.6941 - 0.001043) \text{m}^3/\text{kg} = \mathbf{0.3386 \ m^3}$

b) $\Delta H = m h_{fg@100\text{kPa}}$ (Table A5)

$= (0.2 \text{ kg})(2257 \text{ kJ/kg}) = \mathbf{451.5 \ kJ}$

P, kPa

Sat. vapor
P = 100 kPa

Sat. liquid
P = 100 kPa

100

v_f

v_g

v

Examples (textbook)

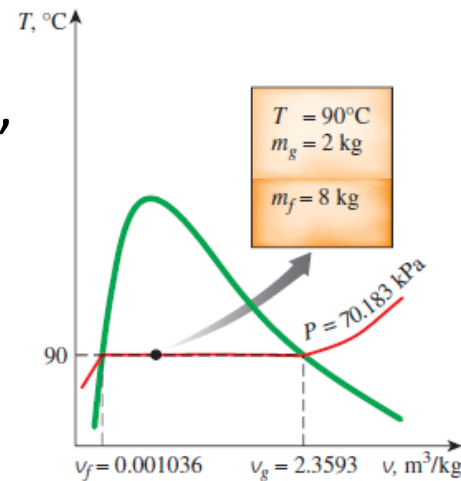EXAMPLE 3–4 **Pressure and Volume of a Saturated Mixture**

A rigid tank contains 10 kg of water at 90°C. If 8 kg of the water is in the liquid form and the rest is in the vapor form, determine (a) the pressure in the tank and (b) the volume of the tank.

a) $P = P_{\text{sat@90°}C} \Rightarrow$ Table A4 $\qquad \Rightarrow \boldsymbol{P = 70.183}$ **kPa**

b) $V = mv = m(v_f + xv_{fg})$

$$x = \frac{m_g}{m} = \frac{m_g}{m_f + m_g} = \frac{2 \text{ kg}}{8 \text{ kg} + 2 \text{ kg}} = \frac{2 \text{ kg}}{10 \text{ kg}} = 0.2$$

$$V = (10 \text{ kg})[0.001036 \text{ m}^3/\text{kg} + (0.2)(2.3593 - 0.001036)\text{m}^3/\text{kg}] = \boldsymbol{4.73 \text{ m}^3}$$

Examples (textbook)

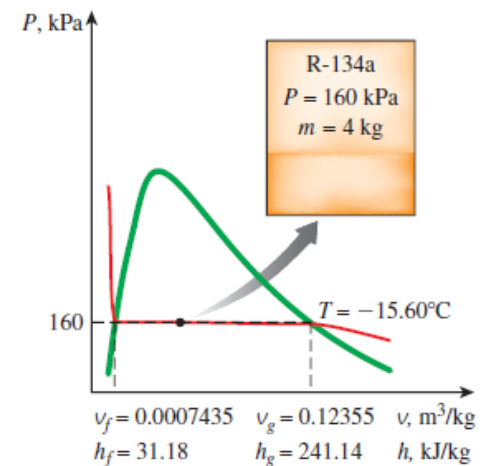EXAMPLE 3–5 **Properties of Saturated Liquid–Vapor Mixture**

An 80-L vessel contains 4 kg of refrigerant-134a at a pressure of 160 kPa. Determine (a) the temperature, (b) the quality, (c) the enthalpy of the refrigerant, and (d) the volume occupied by the vapor phase.

a)
$$v = \frac{V}{m} = \frac{0.080 \text{ m}^3}{4 \text{ kg}} = 0.02 \text{ m}^3/\text{kg}$$

@ 160 kPa (Table A12) $\begin{cases} v_f = 0.0007435 \text{ m}^3/\text{kg} \\ v_g = 0.12355 \text{ m}^3/\text{kg} \end{cases}$

$\Rightarrow$ Saturated mixture region $v_f < v < v_g$

$$T = T_{\text{sat@160kPa}} = -\mathbf{15.60°C}$$

P, kPa

R-134a
P = 160 kPa
m = 4 kg

160 — — — — — — — — — — — T = −15.60°C

$v_f = 0.0007435$ $v_g = 0.12355$ v, m³/kg
$h_f = 31.18$ $h_g = 241.14$ h, kJ/kg

Examples (textbook)

b) $x = ?$

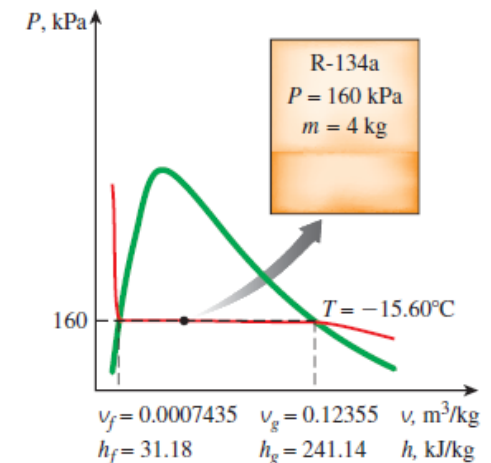$$v = v_f + xv_{fg} \quad \Rightarrow x = \frac{v - v_f}{v_{fg}} = \frac{v - v_f}{v_g - v_f}$$

$$x = \frac{0.02 \text{ m}^3/\text{kg} - 0.0007435 \text{ m}^3/\text{kg}}{0.12355 \text{ m}^3/\text{kg} - 0.0007435 \text{ m}^3/\text{kg}} = \boldsymbol{0.157}$$

c) $h = ?$ $\quad h = h_f + xh_{fg}$ $\quad h_f, h_{fg} @ 160$ kPa (Table A12)

$$h = 31.18 \text{ kJ/kg} + (0.157)(209.96 \text{ kJ/kg}) = \boldsymbol{64.1 \text{ kJ/kg}}$$

d) $V_g = ?$ $\quad V_g = m_g v_g = xmv_g$

$$V_g = (0.157)(4 \text{ kg})(0.12355 \text{ m}^3/\text{kg}) = \boldsymbol{0.0776 \text{ m}^3}$$

P, kPa

R-134a
$P = 160$ kPa
$m = 4$ kg

160

$T = -15.60°C$

$v_f = 0.0007435$ $\quad v_g = 0.12355$ $\quad v$, m³/kg
$h_f = 31.18$ $\quad\quad h_g = 241.14$ $\quad h$, kJ/kg

Examples (textbook)

EXAMPLE 3–7 **Temperature of Superheated Vapor**

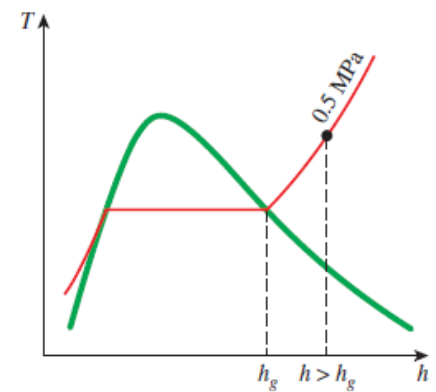Determine the temperature of water at a state of P = 0.5 MPa and h = 2890 kJ/kg.

@ $P = 0.5$ MPa (Table A5), $h_g = 2748.1$ kJ/kg

$$\Rightarrow h > h_g \Rightarrow \text{Table A6}, @ P = 0.5 \text{ MPa}$$

T (°C)	h (kJ/kg)
200	2855.8
$T = ?$	2890.0
250	2961.0

$$T = \frac{250 - 200}{2961.0 - 2855.8}(2890 - 2855.8) + 200$$

$$T = \mathbf{216.25°C}$$

Examples (textbook)

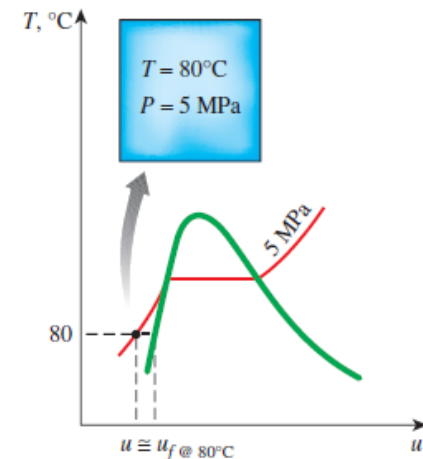## EXAMPLE 3–8 Approximating Compressed Liquid as Saturated Liquid

Determine the internal energy of compressed liquid water at 80°C and 5 MPa, using (a) data from the compressed liquid table and (b) saturated liquid data. What is the error involved in the second case?

a) @ $T = 80°C$ (Table A − 4), $P_{sat} = 47.416$ kPa
    $\Rightarrow$ Compressed Liquid Water

From Table A7, @ $\begin{Bmatrix} P = 5 \text{ MPa} \\ T = 80°C \end{Bmatrix}$ $u = \mathbf{333.82 \text{ kJ/kg}}$

b) From Table A4, @ $T = 80°C$, $u \cong u_{f@80°C} = \mathbf{334.97 \ kJ/kg}$

% error $= \dfrac{334.97 - 333.82}{333.82} \times 100 = \mathbf{0.34} \%$

$T, °C$

$T = 80°C$
$P = 5$ MPa

5 MPa

80

$u \cong u_{f@\ 80°C}$

u

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Examples (textbook)

EXAMPLE 3–9 **The Use of Steam Tables to Determine Properties**

Determine the missing properties and the phase descriptions in the following table for water:

	T (°C)	P (kPa)	u (kJ/kg)	x	Phase description
a)		200		0.6	
b)	125		1600		
c)		1000	2950		
d)	75	500		0.0	
f)		850			

Examples (textbook)

a) $P = 200 \text{ kPa}, x = 0.6, T = ?, u = ?, \text{Phase} = ?$

Since we have quality (x), then **Phase = saturated liquid-vapor mixture**

$\Rightarrow T = T_{\text{sat@200kPa}} = \mathbf{120.21°C}$ (Table A5)

From Table A5, @ $P = 200 \text{ kPa}, \begin{cases} u_f = 504.5 \text{ kJ/kg} \\ u_{fg} = 2024.6 \text{ kJ/kg} \end{cases}$

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

$= 504.5 \text{ kJ/kg} + (0.6)(2024.6 \text{ kJ/kg})$

$= \mathbf{1719.26 \text{ kJ/kg}}$

Examples (textbook)

b) $T = 125°C, u = 1600 \text{ kJ/kg}, P = ?, x = ?, \text{Phase} = ?$

From Table A4, @ $T = 125°C \begin{cases} u_f = 524.83 \text{ kJ/kg} \\ u_g = 2534.3 \text{ kJ/kg} \end{cases}$

$\Rightarrow u_f < u < u_g$ $\Rightarrow$ **Phase = saturated liquid–vapor mixture**

$P = P_{\text{sat@125°C}} = \mathbf{232.23\ kPa}$ (Table A4)

$x = \dfrac{u - u_f}{u_{fg}} = \dfrac{1600 - 524.83}{2009.5}$

$\boldsymbol{x = 0.535}$

Examples (textbook)

c) $P = 1000 \text{ kPa}, u = 2950 \text{ kJ/kg}, T = ?, x = ?, \text{Phase} = ?$

From Table A5, @ $P = 1 \text{ MPa}$ $\begin{cases} u_f = 761.39 \text{ kJ/kg} \\ u_g = 2582.8 \text{ kJ/kg} \end{cases}$

$\Rightarrow u_f < u_g < u$ $\Rightarrow$ **Phase = superheated vapor** $\Rightarrow$ **Not quality (x)**

T (°C)	u (kJ/kg)
350	2875.7
$T = ?$	2950.0
400	2957.9

Table A6

$$T = \frac{400 - 350}{2957.9 - 2875.7}(2950 - 2875.7) + 350$$

$$\boldsymbol{T = 395.19°C}$$

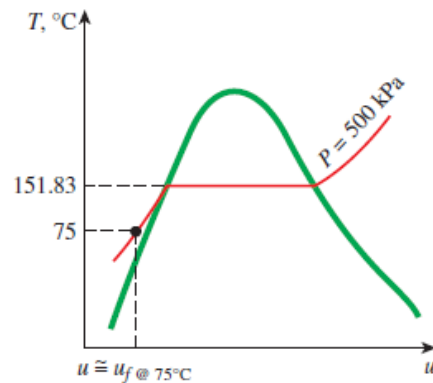Dr. Román Miguel Moreno, Ph.D., CEM, REP

Examples (textbook)

d) $T = $ <mark style="background-color:#00ff00">75°C</mark>$, P = 500 \text{ kPa}, u = ?, x = ?, \text{Phase} = ?$

From Table A5, @ $P = 500 \text{ kPa}, T_{sat} = 151.83°C$

$\Rightarrow T < T_{\text{sat}}$ $\Rightarrow$ **Phase = compressed liquid $\Rightarrow$ Not quality (x)**

$u \cong u_{f@T=}$<mark style="background-color:#ff0000">50</mark>$°_C = \mathbf{313.99 \ kJ/kg}$

Examples (textbook)

e) $P = 850 \text{ kPa}, x = 0.0, T = ?, u = ?, \text{Phase} = ?$

Since we have quality $x = 0.0$, then **Phase = saturated liquid**

$\Rightarrow T = T_{\text{sat@850kPa}} = \mathbf{172.94°C}$ (Table A5)

From Table A5, @ $P = 850 \text{ kPa}, u = u_f = \mathbf{731.0 \ kJ/kg}$