

ENGINEERING THERMODYNAMICS

1. Properties of Working Fluids (pure substances)

a- Water

b- Ideal Gases (perfect gases)

2. First Law of Thermodynamics

a- Closed Systems and Non flow Processes

b- Open Systems (control volume) and Flow processes

3. Second Law of Thermodynamics

a- Entropy

b- Carnot Cycle and Heat Engines

c- Heat Pumps and Refrigerators

Basic Concepts

Unit = **SI units**

F (force) = $m \cdot a = \text{kg} \cdot \text{m}/\text{s}^2 = \text{N}$ (Newton)

P (pressure) = Force/Area = $F/A = \text{N}/\text{m}^2 = \text{Pascal} = \text{Pa}$ Pressure = Pa, kPa, Mpa

W (work) = Force*Distance = $F \cdot d = \text{N} \cdot \text{m} = \text{Joule} = \text{J}$ Work = J, kJ, MJ

$W = (F/A) \cdot d \cdot A$ $F/A = P$ $d \cdot A = \text{Volume} = V$ $W = P \cdot V$

a process between initial and final states $W = P \cdot (V_2 - V_1) = P \cdot \Delta V = W_{\text{boundary}}$

-during an expansion process volume of the working fluid and system increases

$\Delta V = + \text{value}$ $W_{\text{boundary}} = +$ work done by the system or working fluid

-during a compression process volume of the working fluid and system decreases

$\Delta V = - \text{value}$ $W_{\text{boundary}} = -$ work done on the system or working fluid

-constant volume process

$\Delta V = 0$ $W_{\text{boundary}} = 0$

Q = Heat = J, kJ, MJ

During a process, heat transfer from system to surroundings (heat rejection) Q = - value

During a process, heat transfer from surroundings to system (heat addition) Q = + value

1. Properties of Working Fluids

In all problems in thermodynamics we are concerned with energy transfers to or from a system. In practice the matter contained within the boundaries of the system can be liquid, vapor or gas, and is known as the **working fluid**. At any instant the **state** of the working fluid may be defined by certain characteristics called its **properties**.

The thermodynamic properties are pressure, temperature, specific volume, internal energy, enthalpy and entropy. It has been found that, for any pure working fluid, only two independent properties are necessary to define completely the state of the working fluid.

a- Ideal or Perfect Gases

State before and after processes : Gas State

State does not change during a process

(i). Monoatomic gases (Ar, He) $\gamma = 1.6$

(ii). Diatomic gases (air, O₂, N₂, H₂) $\gamma = 1.4$

(iii). Triatomic gases (CO₂, SO₂) $\gamma = 1.3$

They obey the equation of state or ideal gas equation

$$P \cdot V = n \cdot R_o \cdot T$$

P = pressure; V = volume; R_o = universal gas constant; T = temperature in Kelvin

n = mass/Mol Weight = m/MW

$P \cdot V = (m/MW) \cdot R_o \cdot T$ using R (gas constant) = R_o/MW and rearranging equation

$P \cdot V = m \cdot R \cdot T$ or v (specific volume) = V/m specific volume

$$P \cdot v = R \cdot T$$

P = pressure in kPa; V = volume in m³; R = gas constant; T = temperature in Kelvin

v = specific volume in m³/kg

Example

R for O₂ gas R = R_o/MW R = 8.314/32 = 0.260 kJ/kg.K

R for Air R = R_o/MW R = 8.314/29 = 0.287 kJ/kg.K

R for H₂ R = R_o/MW R = 8.314/2 = 4.157 kJ/kg.K

1. Monoatomic gases (Ar, He) $\gamma = 1.6$

2. Diatomic gases (air, O₂, N₂, H₂) $\gamma = 1.4$

3. Triatomic gases (CO₂, SO₂) $\gamma = 1.3$

$$\gamma = c_p/c_v \quad c_v = R/(\gamma - 1) \quad c_p - c_v = R$$

Joules Law

$$u = c_v * T \quad u = \text{internal energy in kJ/kg}$$

c_v = specific heat kJ/kg.K (constant volume)

$$\Delta u = u_2 - u_1 = c_v * (T_2 - T_1)$$

$$h = c_p * T \quad h = \text{enthalpy in kJ/kg}$$

c_p = specific heat kJ/kg.K (constant pressure)

$$\Delta h = h_2 - h_1 = c_p * (T_2 - T_1)$$

$$h = u + P * v$$

Properties: P, T, V, v, u, h ***use equations***

Water

State changes during a process

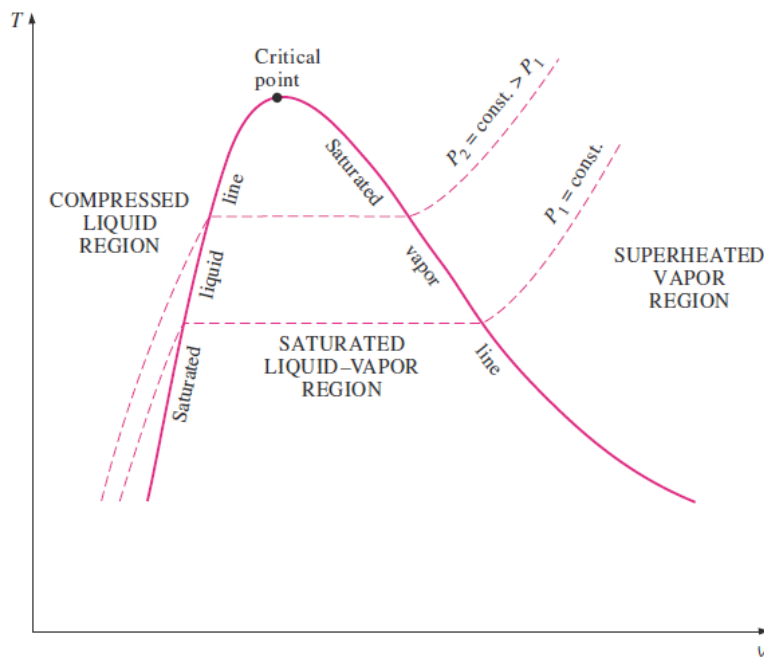


Figure 1. T-v diagram of water

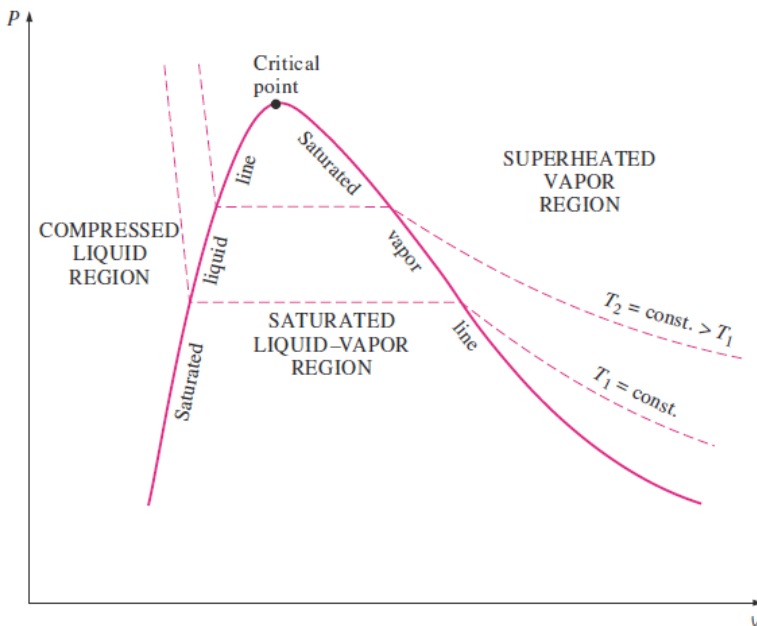


Figure 2. P-v diagram of water

Consider a p - v diagram for water. The solid phase is not important in engineering thermodynamics.

When a liquid is heated at any one constant pressure there is one fixed temperature at which bubbles of vapor form in the liquid; this phenomenon is known as boiling.

The higher the pressure of the liquid then the higher the temperature at which boiling occurs.

1. Liquid Water
2. Saturated Liquid Water (at boiling point)
3. Mixture (saturated liquid and saturated vapor)
4. Saturated Water Vapor

Table: saturated water table (pressure or temperature table)

5. Superheated Water Vapor Table: superheated water vapor table

Liquid or saturated liquid : subscript -f

Saturated vapor: subscript -g

Properties: P, T, v, u, h ***use tables***

Dryness fraction (x) in mixture region

x = fraction of vapor present in mixture = kg vapor/kg mixture

in mixture region

v : specific volume in m^3/kg

$v = v_f + x \cdot v_{fg}$ or sometimes v_f is negligible use $v = x \cdot v_g$

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

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

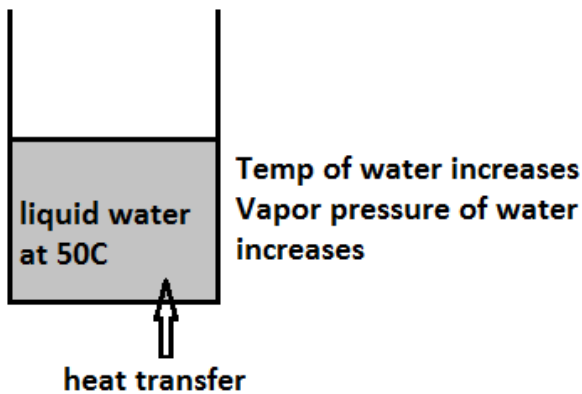
$h = u + P \cdot v$

Steam Tables

Saturated water—Pressure table

Press., P kPa	Sat. temp., T_{sat} °C	Specific volume, m^3/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
400	143.61	0.001084	0.46242	604.22	1948.9	2553.1	604.66	2133.4	2738.1	1.7765	5.1191	6.8955
450	147.90	0.001088	0.41392	622.65	1934.5	2557.1	623.14	2120.3	2743.4	1.8205	5.0356	6.8561
500	151.83	0.001093	0.37483	639.54	1921.2	2560.7	640.09	2108.0	2748.1	1.8604	4.9603	6.8207

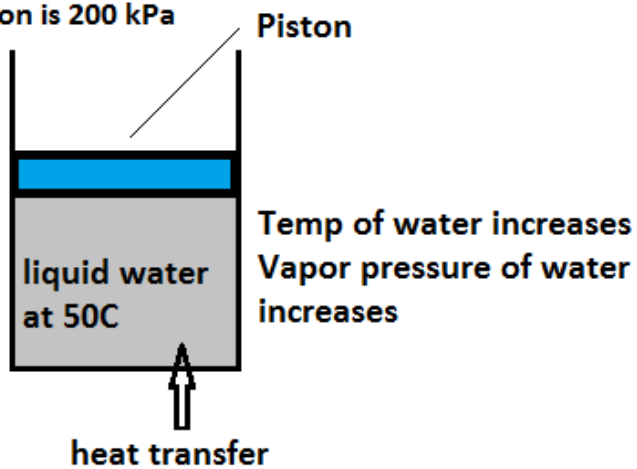
atm pressure 101.3 kPa



At 100°C vapor pressure of water is 101.3 kPa. Now, atmospheric pressure or external pressure = vapor pressure of water. Then water boils at 100°C (also saturation temperature, T_s) if the pressure above the liquid water is 101.3 kPa.

If pressure is constant then saturation temperature remains constant from saturated liquid to saturated vapor

Pressure exerted by the piston is 200 kPa

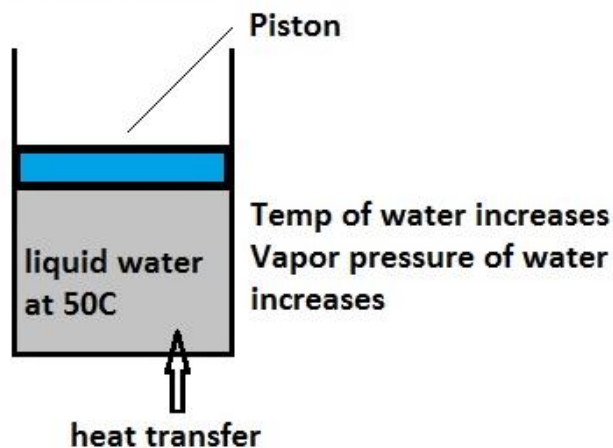


The pressure above liquid water is not atmospheric pressure, it is piston pressure.

We are expecting that at high pressure boiling point of water is high, if you compare with the boiling temperature at 101.3 kPa which is 100°C.

Under 200 kPa pressure water boils at 120°C (saturation temperature).

Pressure exerted by the piston is 500 kPa



The pressure above liquid water is not atmospheric pressure, it is piston pressure.

We are expecting that at high pressure boiling point of water is high, if you compare with the boiling temperature at 101.3 kPa which is 100°C.

Under 500 kPa pressure water boils at 151.8°C.

The state of water on Pv diagram

We need at least two properties to locate state of water.

On saturated liquid line we need a property and a statement

Example: saturated liquid water at 100 kPa

From saturated water table; v_f , u_f , h_f and T_s can be written

Example: saturated water vapor at 200 kPa

From saturated water table; v_g , u_g , h_g and T_s can be written

Example: liquid water at 60°C and 200 kPa

State liquid water: from saturated water table at 60°C, the pressure of water is 20 kPa

200 kPa given must be the piston or external pressure, not water pressure.

Water is cold liquid water. State can be located left side of the saturated liquid water and these properties show the compressed liquid water.

Between saturated liquid and saturated vapor line we need to know two properties

P and T values show infinite points between saturated liquid and saturated vapor

Example: water at 101.3 kPa and 100°C

Saturated liquid has these properties, mixture and saturated vapor also.

These properties may be;

P or T and v

P or T and u

P or T and h

P or T and s

P or T and dryness fraction

P or T and amount of saturated liquid-saturated vapor to find dryness fraction

Example:

Water at 200 kPa with a specific volume of 0.50 m³/kg.

First of all, values given should be compared with the values on saturated water table

From saturated water table-pressure table, find 200 kPa

Saturated water—Pressure table

Press., P kPa	Sat. temp., T _{sat} °C	Specific volume, m ³ /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
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
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

v_f : 0.001061 m³/kg v_g : 0.88578 m³/kg, specific volume in problem is smaller than v_g (saturated vapor) and bigger than v_f (saturated liquid). It must be mixture.

Now we know the state of water but still we need dryness fraction to locate exact point on

P-v diagram. We have specific volume of the mixture, 0.50 m³/kg

Equation: v = v_f + x*v_{fg} or v = x*v_g since v_f is very small and negligible

$$0.50 = x \cdot 0.88578 \quad x = 0.5645$$

Example: water at 250 kPa with an internal energy of 2300 kJ/kg.

using saturated steam table, $u_f = 535$ kJ/kg and $u_g = 2537$ kJ/kg

internal energy in the problem lies between sat liquid and sat vapor, it is mixture.

$$\text{Equation: } u = u_f + x \cdot u_{fg} \quad 2300 = 535 + x \cdot 2002 \quad x = 0.88$$

Example: water at 200 kPa and 200°C

Using saturated water table: at 200 kPa saturation temperature is 120°C. Temperature value in the problem is higher than the saturation temperature. State of water must be superheated water vapor. Using superheated water vapor table: 200 kPa = 0.2 MPa

Under 0.2 MPa pressure, find 200°C

Superheated water

T °C	v m ³ /kg	u kJ/kg	h kJ/kg	s kJ/kg·K	v m ³ /kg	u kJ/kg	h kJ/kg	s kJ/kg·K	v m ³ /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. ^f	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

Now v , u , h and s values can be read.

Example: water at 200 kPa with a specific volume of 1.2 m³/kg

Using saturated water table: at 200 kPa v_g value is 0.88578 m³/kg. Specific volume in the problem is bigger than the v_g value. State of water must be superheated water vapor. Using superheated water vapor table: 200 kPa = 0.2 MPa

Under 0.2 MPa pressure, try to find 1.2 m³/kg (250°C) and read u , h and s

Similar procedure can be applied for internal energy and enthalpy.