Engineering Thermodynamics I

Lecture 6

Properties of Pure Substances

Lecturer: Dr. Melaku Desta

Lecture learning outcomes:

At the end of this lecture, you will be able to:

i. Explain the concept of vapor pressure and its role in phase equilibrium.

ii. Utilize property tables to determine thermodynamic properties.

iii. Apply the ideal gas equation to solve basic gas law problems.

iv. Understand the compressibility factor and its significance in real gas behavior.

v. Solve practical problems using theoretical concepts and tutorials.

Content

1. Vapor pressure and phase equilibrium

- Vapor pressure and phase equilibrium concepts are fundamental in understanding boiling, condensation, and how substances behave at different pressures and temperatures
- **Vapor pressure** is the pressure exerted by a vapor in equilibrium with its liquid (or solid) phase at a given temperature.
- It represents the tendency of the liquid's molecules to escape into the vapor phase.
- A substance with higher vapor pressure evaporates more readily, indicating greater volatility.

1. Vapor pressure and phase equilibrium Cont…

- **Phase equilibrium** refers to the state in which multiple phases (e.g., liquid, vapor, solid) of a substance coexist without a net change, as their rates of interconversion are equal.
- At this point, the rate of molecules evaporating from the liquid equals the rate of molecules condensing back into the liquid.
- This dynamic process maintains a constant vapor pressure as long as temperature and conditions remain steady.
- For example, in a closed container with water, the rate at which water evaporates equals the rate at which vapor condenses, maintaining equilibrium.

2. Thermodynamics Tables

- The relationship among thermodynamic properties are too complex to be expressed in simple equations and thus, properties are measured and/or calculated and then presented in a tabulated form.
- Thermodynamic tables are reference materials that provide the thermodynamic properties of substances under various conditions of temperature and pressure. These properties include, but are not limited to:

Pressure (P)	Internal Energy (u)
Temperature (T)	Enthalpy (h)
Specific Volume (v)	Entropy (s)

2. Thermodynamics Tables

Cont…

- In single-phase regions, any two properties will fix the state.
- In two phase regions, any two properties (except P and T) will fix the state.
- P and T are dependent on each other.

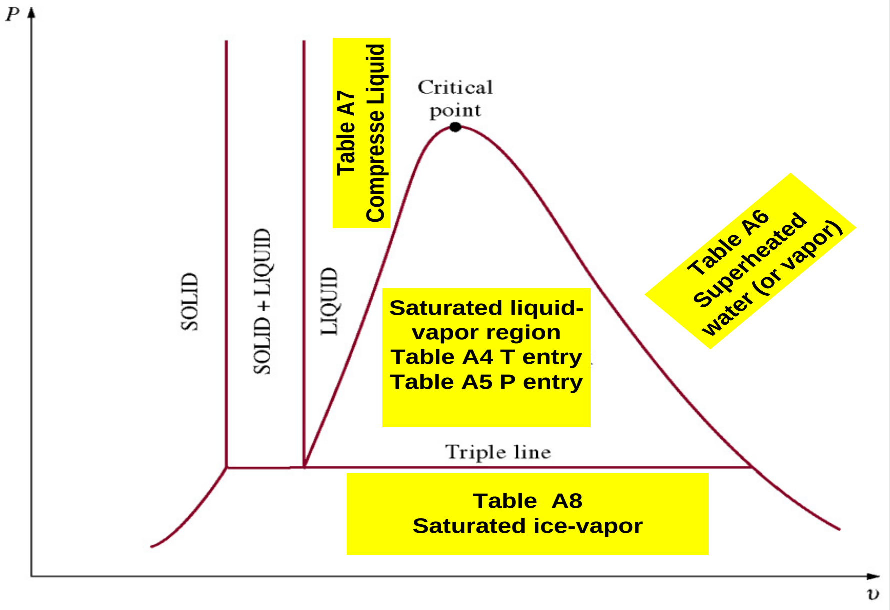


Figure 1: P-v Diagram of a Pure Substance

url: https://image.slideserve.com/485693/regions-on-a-pv-diagram-l.jpg

2. Thermodynamics Tables

Cont…

Enthalpy – A Combination Property

- In the analysis of certain types of processes, particularly in power generation and refrigeration, we frequently encounter the combination of internal energy U, and pressure-volume product PV. That is

$$H = U + PV \qquad h = u + Pv$$

- Before 1930, h was referred to as heat content or total heat.
- After 1930, it is referred to as *enthalpy* (from the Greek word enthalpien which means to heat)

2. Thermodynamics Tables

Cont…

Saturated Liquid and Saturated Vapor States

- Both saturated liquid and saturated vapor states are crucial in thermodynamics for understanding phase transitions, energy transfer during boiling or condensation, and the behavior of substances at varying pressures and temperatures.
- **Saturated liquid state** refers to a liquid at its boiling point.
- At this state, the liquid is in equilibrium with its vapor.
- Any small addition of heat will begin converting the liquid into vapor without raising its temperature.
- It's the precise threshold before a phase change begins.

2. Thermodynamics Tables **Cont…**

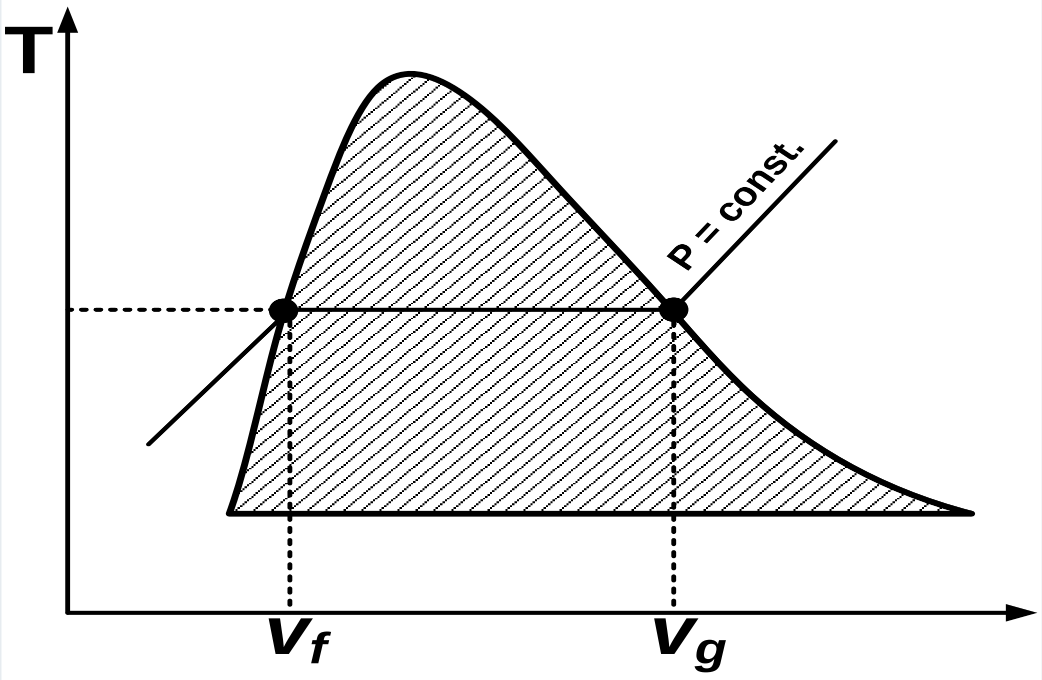
- **Saturated vapor state** describes a vapor at its condensation point. Here, the vapor is in equilibrium with its liquid counterpart.
- If heat is removed, condensation will begin, but the temperature remains constant during the process.
- Saturated liquid-vapor mixture falls under the P-v (or T-v) dome.
- Its properties can be obtained from Water Tables A-4 and A-5

2. Thermodynamics Tables

Cont…

Table A-4

Temperature is listed in the left column as the independent variable.



2. Thermodynamics Tables

Cont…

Saturated Water Table A-4 [2]

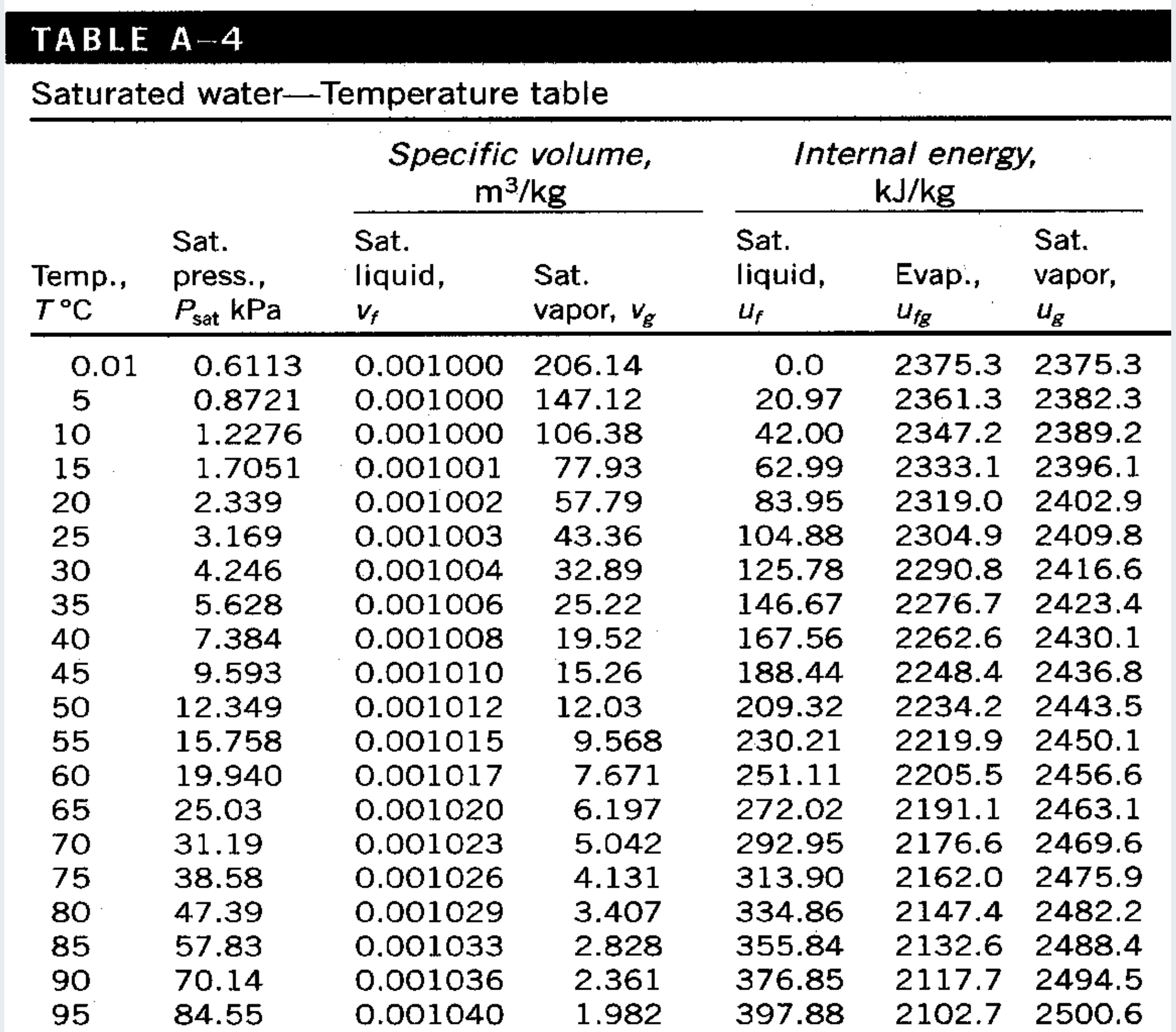


TABLE A–4

Saturated water—Temperature table

Temp., T °C	Sat. press., P_{sat} kPa	Specific volume, m³/kg Sat. liquid, v_f	Specific volume, m³/kg Sat. vapor, v_g	Internal energy, kJ/kg Sat. liquid, u_f	Internal energy, kJ/kg Evap., u_{fg}	Internal energy, kJ/kg Sat. vapor, u_g
0.01	0.6113	0.001000	206.14	0.0	2375.3	2375.3
5	0.8721	0.001000	147.12	20.97	2361.3	2382.3
10	1.2276	0.001000	106.38	42.00	2347.2	2389.2
15	1.7051	0.001001	77.93	62.99	2333.1	2396.1
20	2.339	0.001002	57.79	83.95	2319.0	2402.9
25	3.169	0.001003	43.36	104.88	2304.9	2409.8
30	4.246	0.001004	32.89	125.78	2290.8	2416.6
35	5.628	0.001006	25.22	146.67	2276.7	2423.4
40	7.384	0.001008	19.52	167.56	2262.6	2430.1
45	9.593	0.001010	15.26	188.44	2248.4	2436.8
50	12.349	0.001012	12.03	209.32	2234.2	2443.5
55	15.758	0.001015	9.568	230.21	2219.9	2450.1
60	19.940	0.001017	7.671	251.11	2205.5	2456.6
65	25.03	0.001020	6.197	272.02	2191.1	2463.1
70	31.19	0.001023	5.042	292.95	2176.6	2469.6
75	38.58	0.001026	4.131	313.90	2162.0	2475.9
80	47.39	0.001029	3.407	334.86	2147.4	2482.2
85	57.83	0.001033	2.828	355.84	2132.6	2488.4
90	70.14	0.001036	2.361	376.85	2117.7	2494.5
95	84.55	0.001040	1.982	397.88	2102.7	2500.6

2. Thermodynamics Tables

Cont…

Table A-5

- Pressure is listed in the left column as the independent variable.

  Use whichever table is convenient

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

$$h_{fg} = h_g - h_f$$

- Enthalpy of vaporization or latent heat - the amount of energy needed to vaporize a unit mass of saturated liquid at a given temperature or pressure

2. Thermodynamics Tables

Cont…

Saturated Water Table A-5 [2]

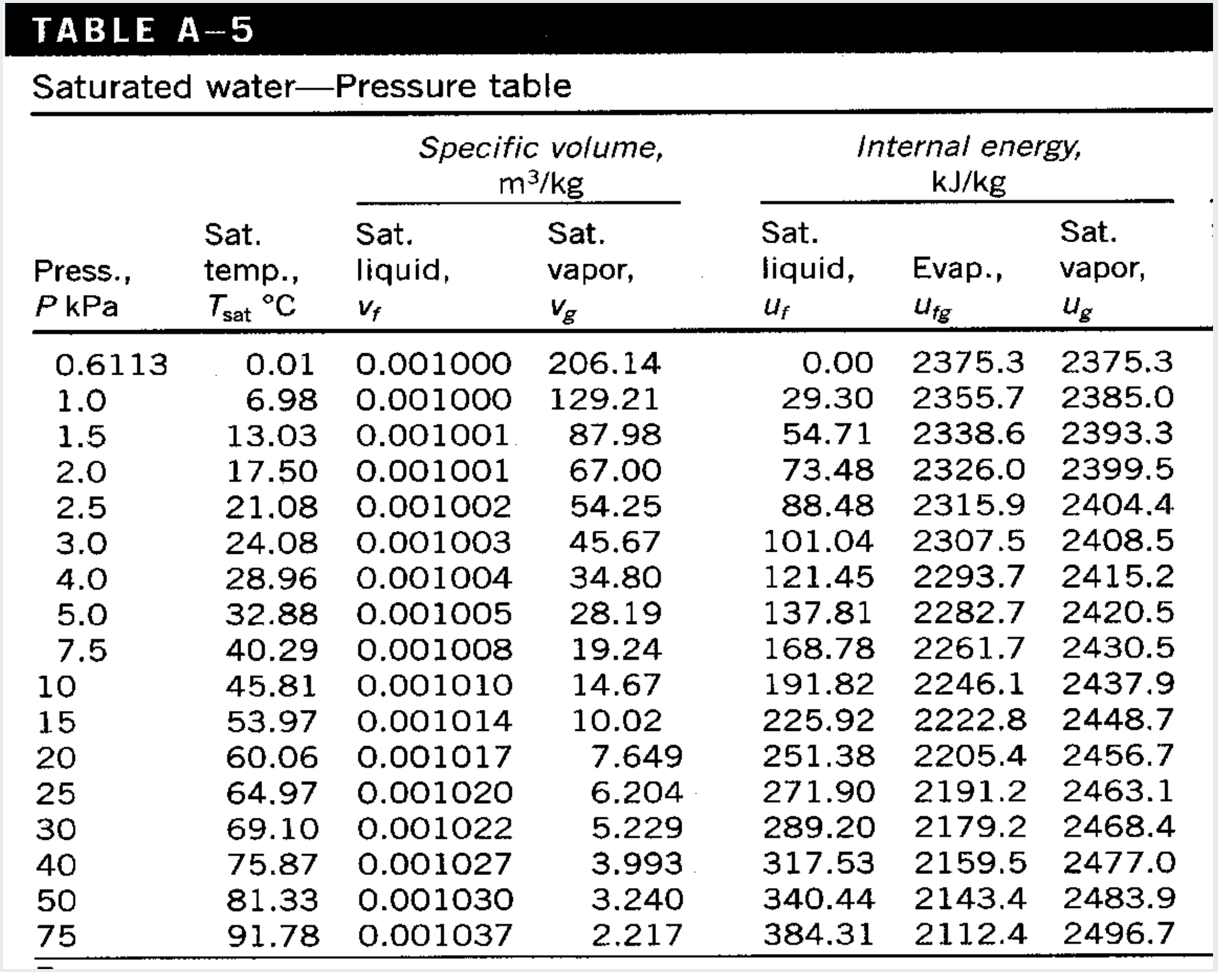


TABLE A–5

Saturated water—Pressure table

		Specific volume, m^3/kg		Internal energy, kJ/kg		
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g
0.6113	0.01	0.001000	206.14	0.00	2375.3	2375.3
1.0	6.98	0.001000	129.21	29.30	2355.7	2385.0
1.5	13.03	0.001001	87.98	54.71	2338.6	2393.3
2.0	17.50	0.001001	67.00	73.48	2326.0	2399.5
2.5	21.08	0.001002	54.25	88.48	2315.9	2404.4
3.0	24.08	0.001003	45.67	101.04	2307.5	2408.5
4.0	28.96	0.001004	34.80	121.45	2293.7	2415.2
5.0	32.88	0.001005	28.19	137.81	2282.7	2420.5
7.5	40.29	0.001008	19.24	168.78	2261.7	2430.5
10	45.81	0.001010	14.67	191.82	2246.1	2437.9
15	53.97	0.001014	10.02	225.92	2222.8	2448.7
20	60.06	0.001017	7.649	251.38	2205.4	2456.7
25	64.97	0.001020	6.204	271.90	2191.2	2463.1
30	69.10	0.001022	5.229	289.20	2179.2	2468.4
40	75.87	0.001027	3.993	317.53	2159.5	2477.0
50	81.33	0.001030	3.240	340.44	2143.4	2483.9
75	91.78	0.001037	2.217	384.31	2112.4	2496.7

2. Thermodynamics Tables

Cont…

Saturated Liquid-Vapor Mixture

A saturated liquid-vapor mixture refers to a thermodynamic state where both liquid and vapor phases coexist in equilibrium at a given pressure and temperature.

  - The liquid is at its saturated liquid condition (ready to evaporate if heat is added).
  - The vapor is at its saturated vapor condition (ready to condense if heat is removed).
- This mixture represents an intermediate state during phase transition.

2. Thermodynamics Tables

Cont…

Saturated Liquid-Vapor Mixture

For example:

- When a saturated liquid starts boiling, it forms a saturated liquid-vapor mixture until all the liquid becomes vapor.
- Similarly, when a saturated vapor starts condensing, the mixture forms until the entire vapor turns into liquid.

2. Thermodynamics Tables

Cont…

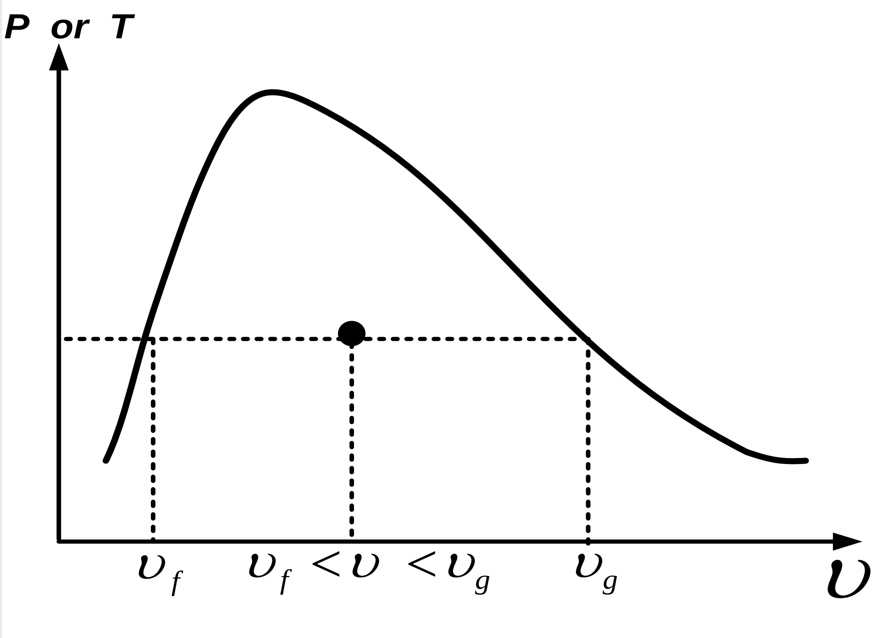
- In the saturated liquid-vapor mixture, the mass fraction of vapor is called the Quality (x) and is expressed as:

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

where:

f *stands for saturated liquid and*

g *for saturated vapor*



x =0: Saturated liquid

x =1: Saturated vapor

0< x <1: Liquid-vapor mixture

2. Thermodynamics Tables

Cont…

- Derivation

$$V = V_f + V_g$$

$$mv = m_f v_f + m_g v_g$$

$$mv = (m - m_g)v_f + m_g v_g$$

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

$$v = v_f + x(v_g - v_f)$$

$$v = v_f + x v_{fg}$$

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

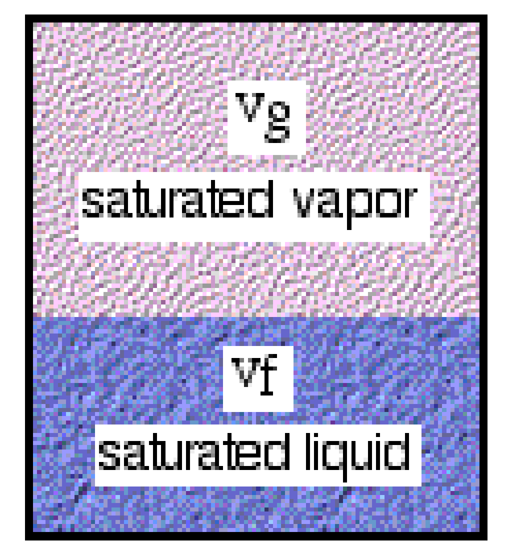


Figure 2: Saturated Liquid-Vapor Mixture

url:https://people.ohio.edu/trembly/mechanical/thermo/Intro/Chapt.1_6/pure_fluid/quality_eqns.gif

2. Thermodynamics Tables

Average Properties

- For saturated liquid-vapor mixtures, average (or mixture) properties are calculated using quality (x) to interpolate between saturated liquid and saturated vapor states.
- In the saturated mixture region, the average value of any intensive property y is given as: $y = y_f + x(y_g - y_f)$

$$y = y_f + xy_{fg}$$

- The average properties of the mixtures are always between the values of the saturated liquid and the saturated vapor properties.

That is $y_f \leq y_{avg} = y_g$

2. Thermodynamics Tables

Cont…

Average Properties

- For saturated liquid-vapor mixtures,
  - **Using Quality (x):**
    - Specific Volume: $v = v_f + xv_{fg}$
    - Enthalpy: $h = h_f + xh_{fg}$
    - Entropy: $s = s_f + xs_{fg}$
    - Specific Internal Energy: $u = u_f + xu_{fg}$
  - **Subscripts:**

    f: Saturated liquid.
    g: Saturated vapor.
    fg: Difference between vapor and liquid.

2. Thermodynamics Tables

Cont…

The T-v diagram

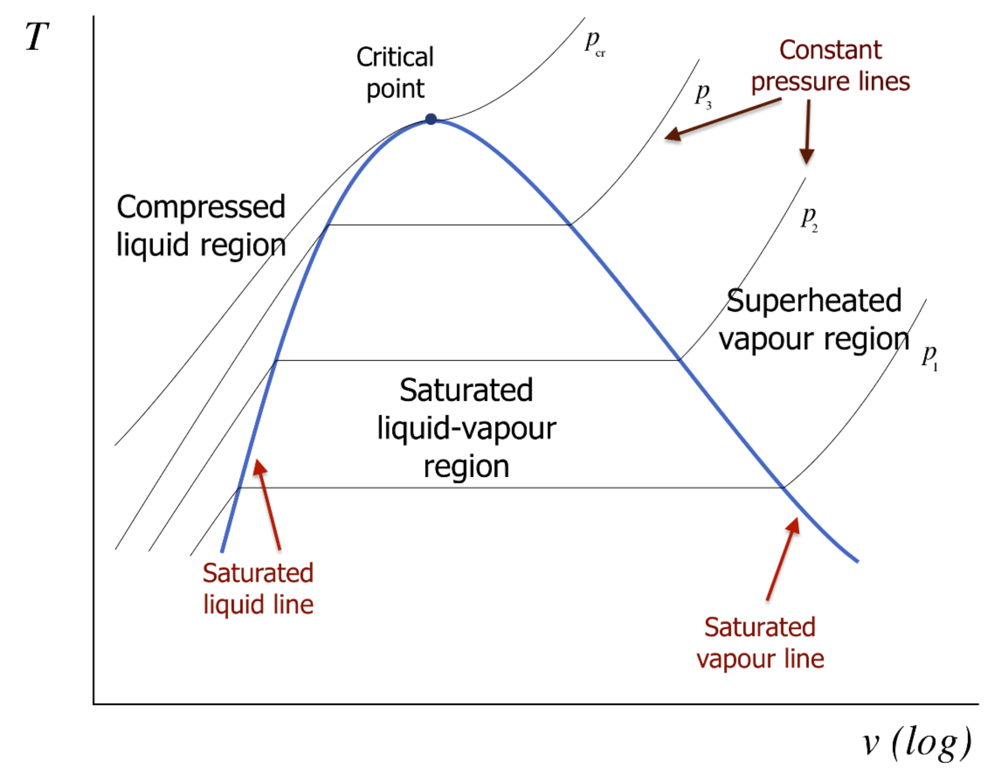


Figure 3: T-v Diagram of a Pure Substance

url:https://pressbooks.bccampus.ca/thermo1/wp-content/uploads/sites/499/2021/06/Fig.-2-8_T-v_diagram_for_a_liquid_vapor-copy.svg_.png

2. Thermodynamics Tables

Cont…

Example:

- A closed container holds 5 kg of water at 200 kPa with a quality (x) of 0.6. Determine:
  - a. The mass of liquid and vapor present
  - b. The specific volume (v) of the mixture
  - c. The total enthalpy (H) of the mixture
  - d. The temperature of the mixture

2. Thermodynamics Tables

Cont…

Solution

Step 1: Identify Given Data

Pressure, P=200 kPa

Quality, x =0.6 (60% vapor by mass)

Total mass, m=5 kg

Step 2: Find Saturation Properties at 200 kPa

From **saturated water tables** at P=200 kPa

Property	Saturated Liquid (f)	Saturated Vapor (g)
Temperature, Tsat	120.21°C	
v (m^3/kg)	0.001061	0.8857
h (kJ/kg)	504.68	2706.3

2. Thermodynamics Tables

Cont…

Step 3: Calculate Mass of Liquid and Vapor

Mass of vapor, $m_g = x * m = 0.6 * 5 = 3\ kg$

Mass of liquid, $m_f = m - m_g = 5 - 3 = 2\ kg$

Step 4: Determine Specific Volume of Mixture

Using the quality formula: $v = v_f + xv_{fg}$

$$v = 0.001061 + 0.6(0.8857 - 0.001061) = 0.5317\ {}^{m^3}/_{kg}$$

Step 5: Calculate Total Enthalpy

First, find enthalpy per unit mass: $h = h_f + xh_{fg}$

$$\mathrm{h} = 504.68 + 0.6(2706.3 - 504.68) = 1824.9\ {}^{\mathrm{kJ}}/_{\mathrm{kg}}$$

2. Thermodynamics Tables

Cont…

Now, total enthalpy:

$$H = m * h = 5 * 1824.9 = 9124.5\ kJ$$

Step 6: Determine Temperature

Since it's a saturated mixture, the temperature equals the saturation temperature at 200 kPa:

$$T = T_{sat} = 120.1°C$$

2. Thermodynamics Tables

Cont…

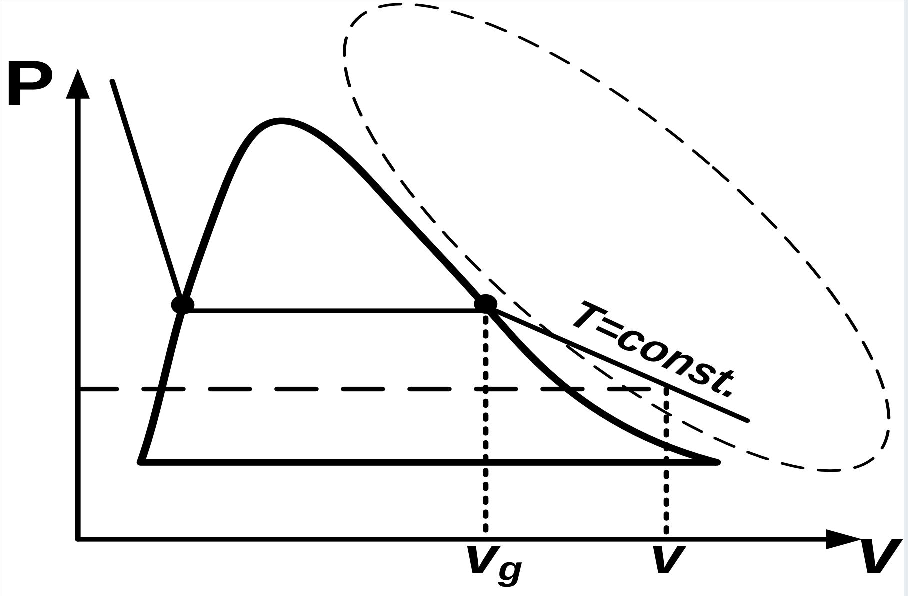
Superheated Vapor

- A superheated vapor is a pure gaseous phase that exists at a temperature higher than the saturation temperature (T>Tsat) for a given pressure.
- Unlike saturated vapor (which is at the boiling point), superheated vapor has no liquid phase present and behaves more like an ideal gas.
- To identify superheated vapor in thermodynamic tables, check if T>Tsat for a given P.

2. Thermodynamics Tables

Cont…

- In the region to the right of the saturated vapor line, a substance exists as superheated vapor (single phase).



2. Thermodynamics Tables

Cont…

Superheated Vapor Table: A-6 [2]

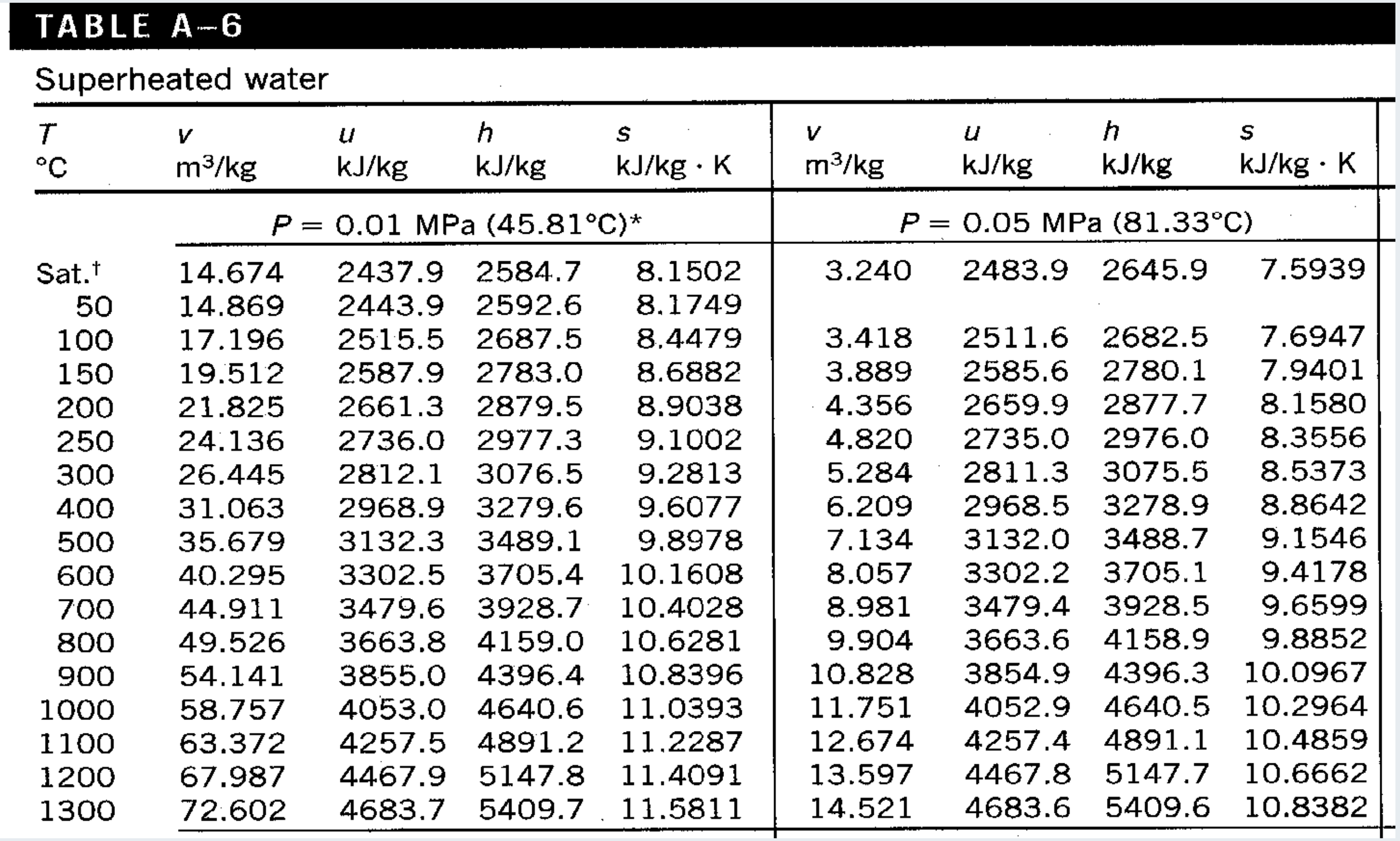


TABLE A–6

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
	P = 0.01 MPa (45.81°C)*				P = 0.05 MPa (81.33°C)			
Sat.†	14.674	2437.9	2584.7	8.1502	3.240	2483.9	2645.9	7.5939
50	14.869	2443.9	2592.6	8.1749				
100	17.196	2515.5	2687.5	8.4479	3.418	2511.6	2682.5	7.6947
150	19.512	2587.9	2783.0	8.6882	3.889	2585.6	2780.1	7.9401
200	21.825	2661.3	2879.5	8.9038	4.356	2659.9	2877.7	8.1580
250	24.136	2736.0	2977.3	9.1002	4.820	2735.0	2976.0	8.3556
300	26.445	2812.1	3076.5	9.2813	5.284	2811.3	3075.5	8.5373
400	31.063	2968.9	3279.6	9.6077	6.209	2968.5	3278.9	8.8642
500	35.679	3132.3	3489.1	9.8978	7.134	3132.0	3488.7	9.1546
600	40.295	3302.5	3705.4	10.1608	8.057	3302.2	3705.1	9.4178
700	44.911	3479.6	3928.7	10.4028	8.981	3479.4	3928.5	9.6599
800	49.526	3663.8	4159.0	10.6281	9.904	3663.6	4158.9	9.8852
900	54.141	3855.0	4396.4	10.8396	10.828	3854.9	4396.3	10.0967
1000	58.757	4053.0	4640.6	11.0393	11.751	4052.9	4640.5	10.2964
1100	63.372	4257.5	4891.2	11.2287	12.674	4257.4	4891.1	10.4859
1200	67.987	4467.9	5147.8	11.4091	13.597	4467.8	5147.7	10.6662
1300	72.602	4683.7	5409.7	11.5811	14.521	4683.6	5409.6	10.8382

2. Thermodynamics Tables

Cont…

Compressed Liquid

- A compressed liquid (also called subcooled liquid) refers to water (or any liquid) that is not about to vaporize
- It is at a higher pressure than its saturation pressure (P>Psat) for a given temperature, or at a lower temperature than its saturation temperature (T<Tsat) for a given pressure.
- Unlike saturated liquid (which is at boiling point), compressed liquid is fully liquid with no bubbles.

2. Thermodynamics Tables

Compressed Liquid

- Since liquids are nearly incompressible, properties like v, u, h, s are close to saturated liquid values at the same temperature.

  $v \approx v_f$ (specific volume)

  $h \approx h_f$ (enthalpy)

  $u \approx u_f$ (internal energy)

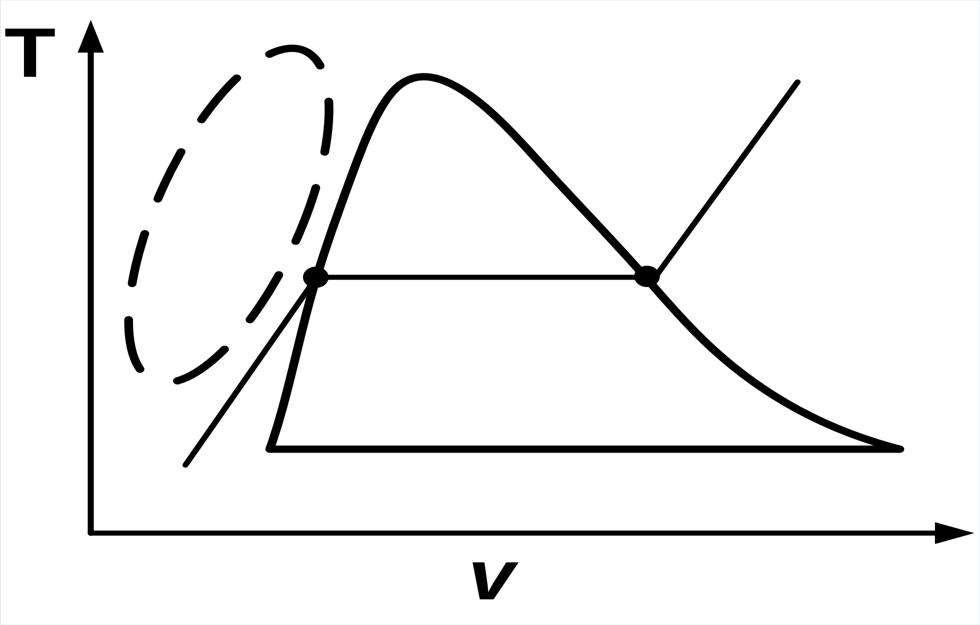
- Water as a compressed liquid does not obey $Pv = RT$ (unlike superheated vapor at low pressure).

2. Thermodynamics Tables

Cont…

Compressed Liquid

In the region to the left of the saturated liquid line, a substance exists as compressed liquid.



2. Thermodynamics Tables

Cont…

Compressed Liquid Water Table A-7 [2]

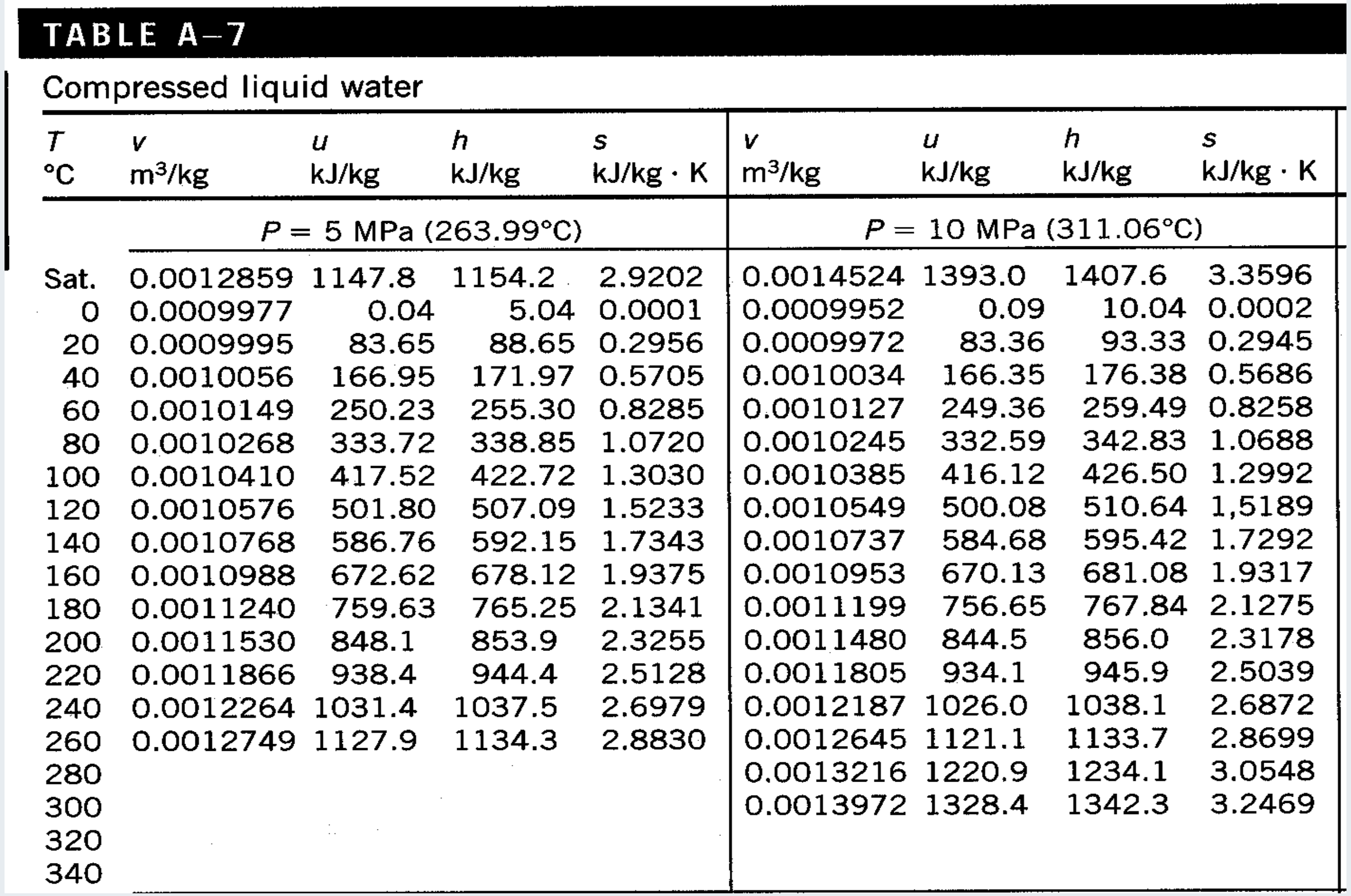


TABLE A–7

Compressed liquid 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
	P = 5 MPa (263.99°C)				*P* = 10 MPa (311.06°C)			
Sat.	0.0012859	1147.8	1154.2	2.9202	0.0014524	1393.0	1407.6	3.3596
0	0.0009977	0.04	5.04	0.0001	0.0009952	0.09	10.04	0.0002
20	0.0009995	83.65	88.65	0.2956	0.0009972	83.36	93.33	0.2945
40	0.0010056	166.95	171.97	0.5705	0.0010034	166.35	176.38	0.5686
60	0.0010149	250.23	255.30	0.8285	0.0010127	249.36	259.49	0.8258
80	0.0010268	333.72	338.85	1.0720	0.0010245	332.59	342.83	1.0688
100	0.0010410	417.52	422.72	1.3030	0.0010385	416.12	426.50	1.2992
120	0.0010576	501.80	507.09	1.5233	0.0010549	500.08	510.64	1,5189
140	0.0010768	586.76	592.15	1.7343	0.0010737	584.68	595.42	1.7292
160	0.0010988	672.62	678.12	1.9375	0.0010953	670.13	681.08	1.9317
180	0.0011240	759.63	765.25	2.1341	0.0011199	756.65	767.84	2.1275
200	0.0011530	848.1	853.9	2.3255	0.0011480	844.5	856.0	2.3178
220	0.0011866	938.4	944.4	2.5128	0.0011805	934.1	945.9	2.5039
240	0.0012264	1031.4	1037.5	2.6979	0.0012187	1026.0	1038.1	2.6872
260	0.0012749	1127.9	1134.3	2.8830	0.0012645	1121.1	1133.7	2.8699
280					0.0013216	1220.9	1234.1	3.0548
300					0.0013972	1328.4	1342.3	3.2469
320								
340								

2. Thermodynamics Tables Cont…

Linear Interpolation

- Linear interpolation is a mathematical technique used to estimate unknown property values (like v, h, s, u) between two known data points in thermodynamic tables.
- Since tables provide discrete values, interpolation helps find precise values at intermediate states.

A	B
100	5
130	y
200	10

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

2. Thermodynamics Tables

Cont…

Example 1: Interpolating for Superheated Vapor Table: A-6

Find the specific enthalpy (h) of water vapor at **P = 1.5 MPa** and **T = 320°C** using the table below.

Temp. (°C)	h (kJ/kg) at 1.0 MPa	h (kJ/kg) at 2.0 MPa
300	3051.2	3024.2
350	3157.7	3137.0

Solution:

1. Interpolate for 1.5 Mpa at 300°C

$$h_{300°C,1.5MPa} = 3024.2 + \left(\frac{1.5 - 1.0}{2.0 - 1.0}\right)(3051.2 - 3024.2) = 3037.7\, {}^{kJ}/_{kg}$$

2. Thermodynamics Tables

Cont…

2. Interpolate for 1.5 Mpa at 350°C

$$h_{350°C,1.5MPa} = 3137.0 + \left(\frac{1.5 - 2.0}{1.0 - 2.0}\right)(3157.7 - 3137.0) = 3147.35\, {}^{kJ}/_{kg}$$

3. Now interpolate for 320°C at 1.5 MPa

$$h_{320°C} = 3037.7 + \left(\frac{320 - 300}{350 - 300}\right)(3147.35 - 3037.7) = 3081.5\, {}^{kJ}/_{kg}$$

2. Thermodynamics Tables

Example 2:

A piston-cylinder device contains 1 kg of water at 200°C and 500 kPa. The water is heated until its temperature reaches 400°C.

Determine:

a. The initial state (saturated, superheated, or compressed liquid).

b. The specific volume (v) and enthalpy (h) at the initial state.

c. The final specific volume (v) and enthalpy (h) after heating.

d. The total work done (W) if the pressure remains constant.

2. Thermodynamics Tables

Cont…

Solution:

Step 1: Identify the Initial State

$P = 500\ kPa$

$\mathrm{T}_{initial} = 200°C$

Check Saturation Temperature at $500\ kPa$:

From **saturation tables for water**, at $P = 500\ kPa$:

$\mathrm{T}_{sat} = 151.86°C$

Since 200°C>151.86°C,

the water is **superheated vapor** initially.

2. Thermodynamics Tables

Cont…

Step 2: Find Initial Properties ($\boldsymbol{v_1, h_1}$)

Use Superheated Steam Tables (500 kPa):

Temp. (°C)	$\boldsymbol{v(m^3/kg)}$	**h (kJ/kg)**
150	0.001093 (compressed liquid)	632.20
200	0.4249	2855.8
250	0.4744	2961.3

At **200°C and 500 kPa**:

$$v_1 = 0.4249\ {m^3}/{kg}$$

$$h_1 = 2855.8\ {kJ}/{kg}$$

2. Thermodynamics Tables

Cont…

Step 3: Find Final Properties (v_2, h_2)

Final State: $T_2 = 400°C$ (still at P=500 kPa)

From **superheated steam tables (500 kPa):**

Temp. (°C)	v (m3/kg)	h (kJ/kg)
400	0.6173	3278.2

Thus:

$$v_2 = 0.6173\ {}^{m^3}/_{kg}$$

$$h_2 = 3278.2\ {}^{kJ}/_{kg}$$

2. Thermodynamics Tables

Cont…

Step 4: Calculate Work Done (Constant Pressure Process)

Work Formula for Constant Pressure:

$$\mathrm{W} = \mathrm{P}(v_2 - v_1)$$ (per kg)

$$\mathrm{W} = 500\mathrm{kPa} * (0.6173 - 0.4249)$$

$$\mathrm{W} = 500{*}0.1924 = 96.2\ \mathrm{Kj/kg}$$

Total Work (for 1 kg):

$$W_{total} = 96.2\ kJ$$

2. Thermodynamics Tables Cont…

Reference State and Reference Values

- In thermodynamics, a **reference state** (or **reference condition**) is a standardized baseline used to define **zero values** for properties like enthalpy (h), entropy (s), and internal energy (u).
- These reference values simplify calculations by providing a consistent starting point for measuring changes in a system.
- The values of u, h, and s *cannot be measured directly*, and they are calculated from *measurable properties* using the relations between thermodynamic properties.
- However, those relations give the changes in properties, not the values of properties at specified state.

2. Thermodynamics Tables

Cont…

Reference State and Reference Values

- In thermodynamics we are concerned with the changes in properties, and the reference chosen has no consequences in the calculations [3].
- For water, the state saturated liquid at 0.01ºC is taken as the reference state, and the internal energy and entropy are assigned zero values at that sate.
- For refrigerant 134a, the state saturated liquid at -40ºC is taken as the reference state, and the enthalpy and entropy are assigned zero values at that state.
- Always check the reference state in your thermodynamic tables before solving problems!

3. The Ideal Gas Equation of State

- Property tables provide very accurate information about the properties. ***But***, They are bulky and vulnerable (exposed) to typographical errors.
- A more practical and desirable approach would be to have some simple relations among the properties that are sufficiently general and accurate.
- Any equation that relates P-v-T is called Equation of state.
- The ideal gas equation of state is a fundamental relationship in thermodynamics that describes the behavior of an ideal gas. It is expressed as:

$$Pv = RT$$

- It is the simplest and best known equation of state

3. The Ideal Gas Equation of State Cont…

- The vapor phase of a substance is called gas when it is above the critical temperature.
- Vapor implies a gas that is not far from a state of condensation.

$$Pv = RT$$

R is the Gas Constant

$$R = {R_u}/{M}$$

R_u *the universal gas constant*

$$R_u = 8.314 \frac{kJ}{kmol\ K}$$

M is Molar Mass of the gas (Molecular Weight)

But, $v = \frac{V}{M}, then\ PV = MRT$

3. The Ideal Gas Equation of State

Cont…

- The properties of an ideal gas for a fixed mass at two different states are related to each other by:

$$m = \frac{PV}{RT} \qquad m_1 = m_2 \qquad \frac{P_1V_1}{RT_1} = \frac{P_2V_2}{RT_2} \qquad \frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

- An ideal gas is an imaginary substance that obeys the P-v-T relation.
- An ideal gas is a hypothetical gas whose molecules occupy negligible space and have no interactions, and which consequently obeys the gas laws exactly [4].
- At low pressure and high temperature, the density of a gas decreases, and the gas behaves like an ideal gas.

3. The Ideal Gas Equation of State

Cont…

- Many familiar gases such as Air, Nitrogen, Oxygen, Hydrogen, Helium, Argon, Neon, Krypton, and even heavier gases such as Carbon dioxide can be treated as ideal gases with negligible error.
- However, dense gases such as water vapor in steam power plants and refrigerant vapor in refrigerators, however, should not be treated as ideal gases.
- At pressure below 10 KPa, water vapor can be treated as an ideal gas, regardless of its temperature, with negligible error (less than 0.1%).
- At higher pressures, however, the ideal-gas assumption

yields unacceptable errors.

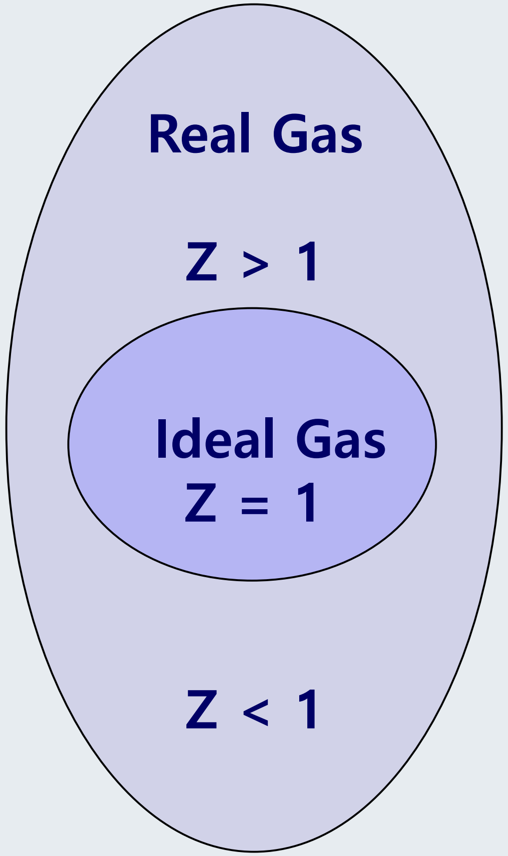
4. Compressibility Factor

- Real gases deviate from ideal-gas behavior significantly at state near the saturation region and the critical point.
- This deviation at a given temperature and pressure can accurately accounted for by introducing a correction factor called the compressibility factor.
- The **compressibility factor**, often denoted by Z, is a dimensionless number that measures how much a real gas deviates from ideal gas behavior [5].
- It is defined as:

$$Z = \frac{PV}{MRT}$$

4. Compressibility Factor

- The compressibility factor is a correction factor applied to the ideal gas law to account for deviations from ideal behavior in real gases.
- For real gases Z can be greater than or less than unity.
- The farther away *Z* is from unity, the more the gas deviates from ideal-gas behaviour.



4. Compressibility Factor

Generalized Compressibility Chart

- This chart can be done if the coordinates are modified such that $P_R = {}^{P}/_{P_{cr}}$ and $T_R = {}^{T}/_{T_{cr}}$ where P_R and T_R are the reduced pressure and reduced temperature.

- **The Z factor is the same for all gases at the same reduced pressure and temperature.**
- **This is called the *principle of corresponding states*.**

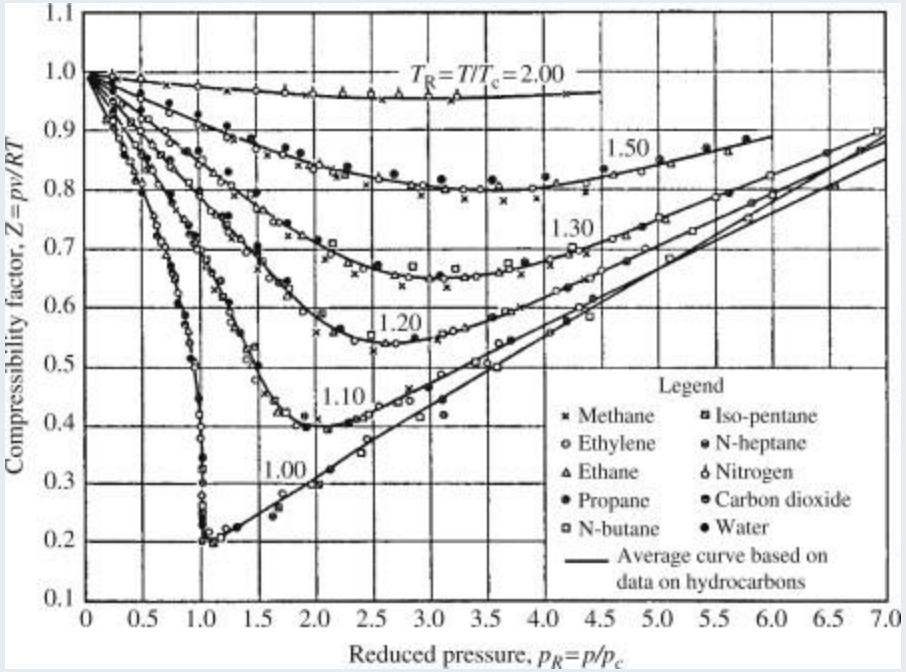


Figure 4: Generalized Compressibility Chart

[url:https://ars.els-cdn.com/content/image/3-s2.0-B9780123749963000117-f11-02-9780123749963.jpg](https://ars.els-cdn.com/content/image/3-s2.0-B9780123749963000117-f11-02-9780123749963.jpg)

Summary

- Vapor pressure is the pressure exerted by a vapor in equilibrium with its liquid or solid phase; phase equilibrium occurs when phase change rates, like evaporation and condensation, are balanced.
- Thermodynamic tables provide key data, including enthalpy, entropy, and specific volume, aiding in the analysis of real substances under varying conditions.
- Ideal Gas Equation of State: $Pv = RT$ models ideal gas behavior, assuming no intermolecular interactions and negligible molecular volume, working well at high temperatures and low pressures.
- Compressibility Factor (Z): $\mathrm{Z} = \frac{PV}{mRT}$, quantifies how real gases deviate from ideal behavior; ideal gases have Z=1, while real gases vary based on temperature and pressure.
- Generalized Compressibility Chart: A versatile tool for estimating Z, using reduced pressure and temperature to simplify analyses across a variety of gases.

'

References

[1]. Thermodynamics – An Engineering Approach, Cengel Y A.,Bole M A., McGraw-Hill Education, 8th edition 2015.

[2]. Introduction to Thermodynamics and Heat Transfer, Cengel, McGraw-Hill Education, Second edition, 2008.

[3]. Thermodynamic Aspects of Energy, Ibrahim Dincer, Calin Zamifirescu, 2018, Pages 153-211, https://doi.org/10.1016/B978-0-12-809597-3.00105-X.

[4]. Fundamentals of Thermal and Nuclear Power Generation, Tomio Okawa, Hitoshi Asano, JSME Series in Thermal and Nuclear Power Generation, Volume 1, 2021, Pages 77-226, https://doi.org/10.1016/B978-0-12-820733-8.00003-0.

[5]. Gas Turbine Engineering Handbook, Meherwan P. Boyce, 2012, Pages 139-176, https://doi.org/10.1016/B978-0-12-383842-1.00003-2.

Thank you !