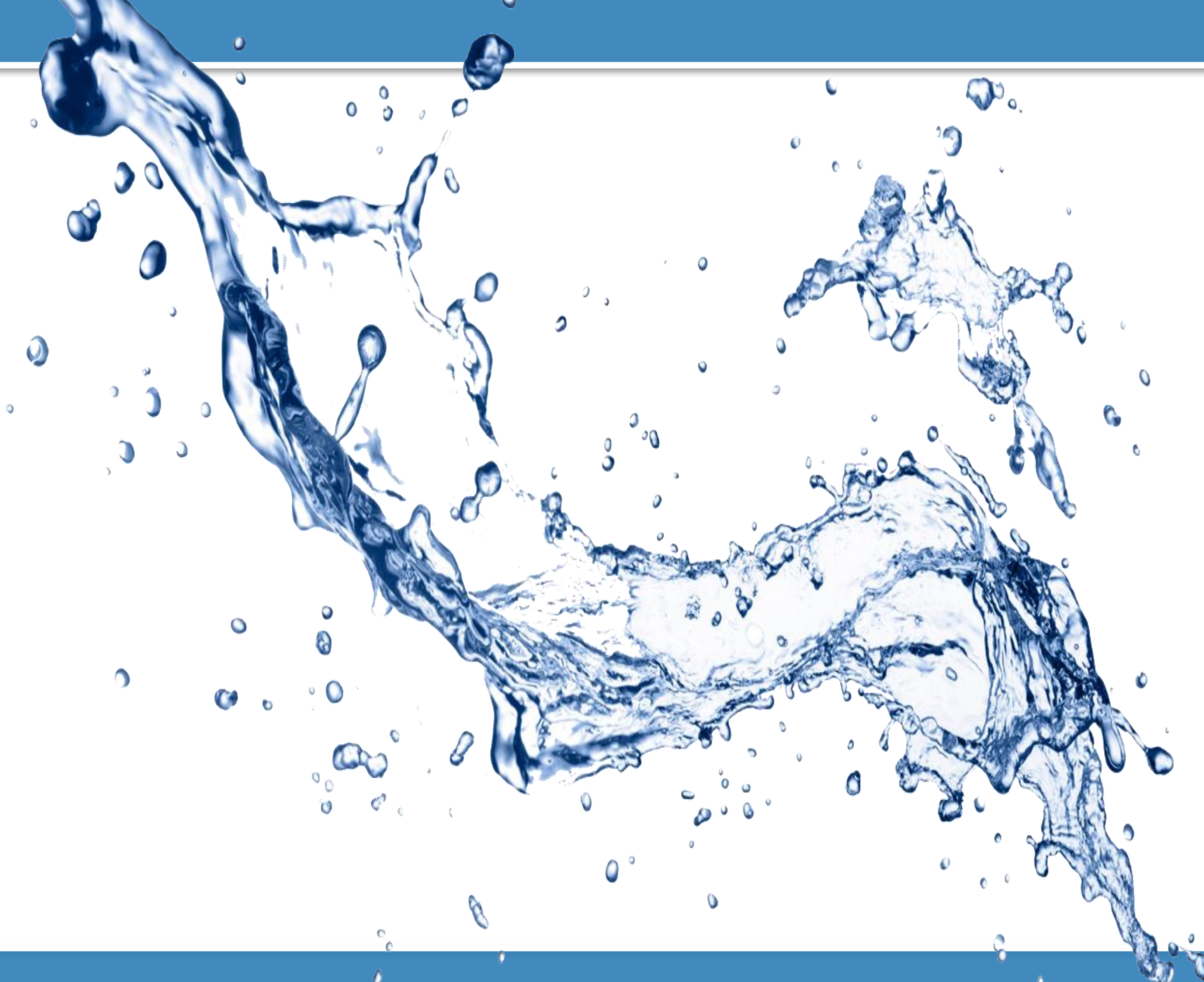
THERMODYNAMICS: PROPERTIES OF PURE SUBSTANCES



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THERMODYNAMICS: PROPERTIES OF PURE SUBSTANCES

For Polytechnic Approach

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Preface

بسم الله الرحمن الرحيم

In the name Allah S.W.T, the Most Gracious and the Most Merciful

Alhamdulillah,

With His abundant grace I was able to prepare this e-book titled "Thermodynamics: Properties of Pure Substances".

This e-book is written based on syllabus content in Thermodynamic course to help students understand this topic in more depth by providing concise notes and sample questions. This e-book also contains tutorial questions for students to test their understanding and the answers to the tutorial questions are provided to make it easier for students to check the correct answers.

I would like to take this opportunity to express my deep appreciation to my beloved family, my friends and everyone who is involved directly or indirectly in writing this e-book. May Allah S.W.T accept my effort, honor it with His pleasure, and make this e-book beneficial for all.

The Author,

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Dedication

This e-book is dedicated to my beloved family, my friends and everyone who is involved directly or indirectly in writing this e-book.

Abstract

This e-book is written based on the one topic in syllabus contents of Thermodynamics for second semester student of Mechanical Engineering Department, Malaysian Polytechnics. This chapter is carefully written with combinations of notes, examples and tutorial that are suitable for teaching and learning sessions.

Content

BASIC UNIT CONVERSION

Conversion of units is the conversion between different measurements that involves multiplication or division by a numerical factor for the same quantity.

Table 1.1: The Example of some Unit Conversions

Units	**Unit Conversions**
Mass	$1\ kg = 1000\ g = 0.001\ tonne = 2.205\ lb = 35.273\ oz$
Time	$1\ hour = 60\ minutes = 3600\ seconds$
Length	$1\ m = 100\ cm = 1000\ mm = 3.281\ ft = 1.094\ yd = 39.37\ in$ $1\ km = 1000\ m = 100\ 000cm$ @ $10^5\ cm = 10^6\ m = 0.6214\ miles$
Area Units	$1\ mm^2 = 0.01cm^2$ = $0.000001m^2 = 0.00155\ in^2 = 0.000011ft^2 = 0.000001\ yd^2$
Speed	$1m / \min = 0.06\ km/h = 0.05469\ ft/s = 0.0373\ miles/h$
Volume	$1m^3 = 1000\ litre$ = 100 0000 cm^3 = 61024 in^3 = 35 ft^3 = 264 US gal
Pressure	$1\ bar = 1x\ 10^5\ N/m^2 = 1x\ 10^2\ KN/m^2$ $1\ atm = 101.3\ kPa = 1.013\ bar = 14.70\ psi$
Density	$1\ kg/m^3 = 1\ g/ml = 0.0624\ lb/ft^3 = 0.000036\ lb/in^3$
Power	$1\ W = J/s = Nm/s = kg.m^2/s^2 = 0.000947\ Btu/s$ $1\ hp = 2544\ Btu/h$
Angular speed	$1\ rad/s = 9.549\ rpm = 0.159\ rev/s$
Mass Flow rate	$1\ kg/s = 2.205\ lb_m = 0.0685\ slug/s$
High Pressure	$1\ bar = 14.503\ psi = 100kPa = 0.1\ Mpa = 1.0196\ kgf/cm^2 = 750.0188\ mm\ Hg = 0.9872\ atm$

Using Units Fractions to convert Metric Units

Procedure : Convert units of Measure in Metric Units

Step 1 : Identify equal measures

Step 2 : Write the original quantity as a fraction. The word per indicates a fraction bar. Multiply by two units fractions.

Step 3 : Simplify

International Standard (SI) Prefix

SI prefixes are used to avoid very large or very small numeric values. The prefix showed directly to the name of a unit, and a prefix symbol directly to the symbol for a unit.

Table 1.2: SI Prefix

Decimal	Exponential	Prefix	Symbol
1.000,000,000,000	10^{12}	tera	T
1,000,000,000	10^{9}	giga	G
1,000,000	10^{6}	mega	M
1,000	10^{3}	kilo	k
100	10^{2}	hecto	h
10	10^{1}	deka	da
0.1	10^{-1}	deci	d
0.01	10^{-2}	centi	c
0.001	10^{-3}	milli	m
0.000001	10^{-6}	micro	µ
0.000000001	10^{-9}	nano	n
0.000000000001	10^{-12}	pico	p

Example 1.1

Convert 4 $\mathrm{km/hr}$ to $\mathrm{m/s}$

Solution:

1 km = 1000 m

1 hr = 3600s

$$= \frac{4\ \mathrm{km}}{\mathrm{hr}} \mathrm{x} \frac{1000\ \mathrm{m}}{1\ \mathrm{km}} \mathrm{x} \frac{1\ \mathrm{hr}}{3600\ \mathrm{s}}$$

$$= \frac{4000\ \mathrm{m}}{3600\ \mathrm{s}}$$

$$= \mathbf{1.11\ m/s}$$

Example 1.2

Convert 105 $\mathrm{g/mm^3}$to $\mathrm{kg/m^3}$

Solution:

1 m = 1000 mm

1 kg = 1000g

1 m^3 = 1000 x 1000 x 1000 mm^3

$$= \frac{105\ \mathrm{g}}{\mathrm{mm^3}} \mathrm{x} \frac{10^9\ \mathrm{mm^3}}{1\mathrm{m^3}} \mathrm{x} \frac{1\ \mathrm{kg}}{1000\ \mathrm{g}}$$

$$= \frac{105\ \mathrm{x}\ 10^9\ \mathrm{x}\ 1\ \mathrm{kg}}{1000\ \mathrm{m^3}}$$

$$= \mathbf{105 \times 10^6\ \ kg/m^3}$$

Example 1.3

Convert 28 $\mathrm{mg/liter}$ to $\mathrm{kg/m^3}$

Solution:

1 kg = 1000g = 1000 mg

1 m^3 = 1000 liter

$$= \frac{28\ \mathrm{mg}}{\mathrm{liter}} \mathrm{x} \frac{1000\ \mathrm{liter}}{1\mathrm{m^3}} \mathrm{x} \frac{1\ \mathrm{kg}}{10^6\ \mathrm{mg}}$$

$$= \frac{28\ \mathrm{x}\ 1000\ \mathrm{x}\ 1\ \mathrm{kg}}{10^6\ \mathrm{m^3}}$$

$$= \mathbf{28 \times 10^{-3}\ \ kg/m^3}$$

TUTORIAL 1

1) Convert 77 $\mathrm{m/s}$ to $\mathrm{km/hr}$

(277.2 km/hr)

Answer:

2) Convert 52 $\mathrm{N/cm^2}$ to $\mathrm{kN/m^2}$

$(520\ \mathrm{kN/m^2})$

Answer:

3) Convert 65 $\mathrm{kg/m^3}$ to $\mathrm{g/mm^3}$

$(6.5\ \times 10^{-5}\mathrm{g/mm^3})$

Answer:

4) Convert 200 $\mathrm{MN/m^2}$ to $\mathrm{N/mm^2}$

$(200\ \mathrm{N/mm^2})$

Answer:

PROPERTIES OF PURE SUBSTANCES

Pure substances are substances that are made up of ***only one kind of particle*** and have a fixed or constant structure. Pure substances are further classified as **elements and compounds.**

An element is a substance that consists of only one type or kind of atom. An element is a pure substance as it cannot be broken down or transformed into a new substance even by using some physical or chemical means. Elements are mostly metals, non-metals or metalloids.

Compounds, on the other hand, are also pure substances when two or more elements are combined chemically in a fixed ratio. However, these substances can be broken down into separate elements by chemical methods.

All elements are mostly pure substances. A few of them include gold, copper, oxygen, chlorine, diamond, etc. Compounds such as water, salt or crystals, baking soda amongst others are also grouped as pure substances.

However, 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 chemical composition of all phases is the same *(homogenous).*

For example, like ice and water (solid and liquid) or water and steam (liquid and gas).

- A mixture of ice (solid) and water (liquid) is a pure substance because both phases have the same chemical composition.
- Air is a mixture of several gases, but it is often considered to be a pure substance because it has a uniform chemical composition.

a) Water b) Air

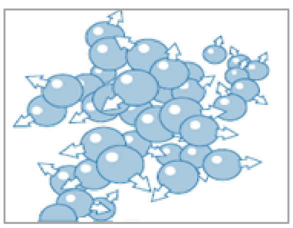
2.1 Phase – Change Processes of Pure Substances

There are **THREE (3)** phases of pure substances:

What Is Phase?

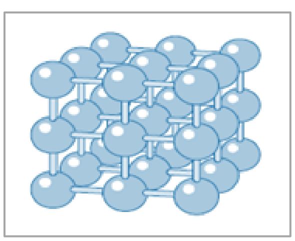
A phase is identified as having a distinct molecular arrangement that is homogeneous throughout and separated from the others (if any) by easily identifiable boundary surfaces.

Solid Phase



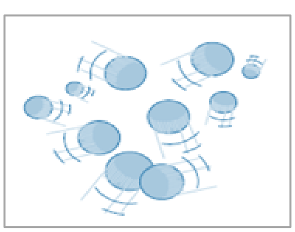
In the solid phase the molecules are closely bound, therefore relatively dense. The molecules are arranged in a rigid three dimensional pattern so that they do not easily deform. An example of pure solid state is ice.

Liquid Phase



In the liquid phase the molecules are closely bound, therefore also relatively dense and unable to expand to fill a space. They are no longer rigidly structured so much so that they are free to move within a fix volume. An example is a pure liquid state.

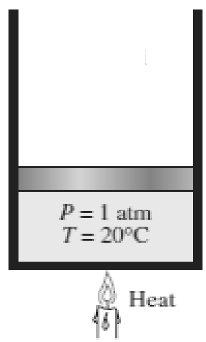
Steam Phase



In the steam phase the molecules are virtually do not attract each other. The distance between the molecules are not as close as those in the solid and liquid phases. The molecules are not arranged in a fixed pattern. There is neither a fixed volume nor a fixed shape for steam.

Phase-Change Processes

State 1



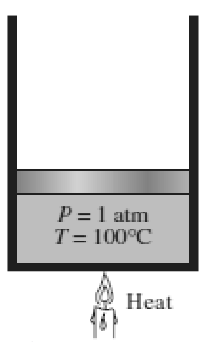
At 1 atm and 20°C, water exists in the liquid phase (*Compressed liquid*).

At these conditions, water exists in the liquid phase, and it is called a *compressed liquid*, or a *sub cooled liquid*. Which is it is not about to vaporize.

Heat is now transferred to the water until its temperature rises. When the temperature rises, the liquid water expands slightly, and so its specific volume increases. The piston moves up slightly to accommodate this expansion. The pressure remains constant at 1 atm during this process since it depends on the outside barometric pressure and the weight of the piston, both of which are constant.

Water is still a compressed liquid at this state since it has not started to vaporize.

State 2

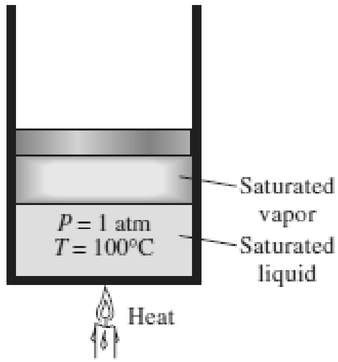


At 1 atm pressure and 100°C, water exists as a liquid that is ready to vaporize (*Saturated liquid*)

As more heat is transferred, the temperature keeps rising until it reaches 100°C. At this point water is still a liquid, but any heat addition will cause some of the liquid to vaporize.

That is, a phase-change process from liquid to vapor is about to take place. A liquid that is *about to vaporize* is called a *saturated liquid.*

State 3



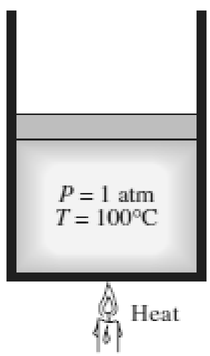
As more heat is transferred, part of the saturated liquid vaporizes (*Saturated liquid–vapor mixture*)

Once boiling starts, the temperature stops rising until the liquid is completely vaporized.

During a boiling process, the only change we will observe is a large increase in the volume and a steady decline in the liquid level as a result of more liquid turning to vapor.

Midway about the vaporization line, the cylinder contains equal amounts of liquid and vapor.

State 4



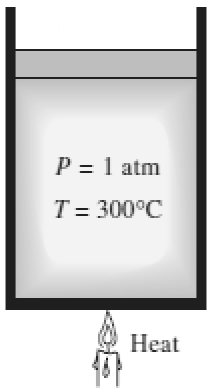
At 1 atm pressure, the temperature remains constant at 100°C until the last drop of liquid is vaporized (*Saturated vapor*)

The vaporization process continues until the last drop of liquid is vaporized (state 4), as we continue transferring heat. At this point, the entire cylinder is filled with vapor that is on the borderline of the liquid phase. Any heat loss from this vapor will cause some of the vapor to condense (phase change from vapor to liquid).

A vapor that is *about to condense* is called a *saturated vapor*.

A substance at states between 2 and 4 is referred to as a *saturated liquid–vapor mixture* since the *liquid and vapor phases coexist* in equilibrium at these states.

State 5

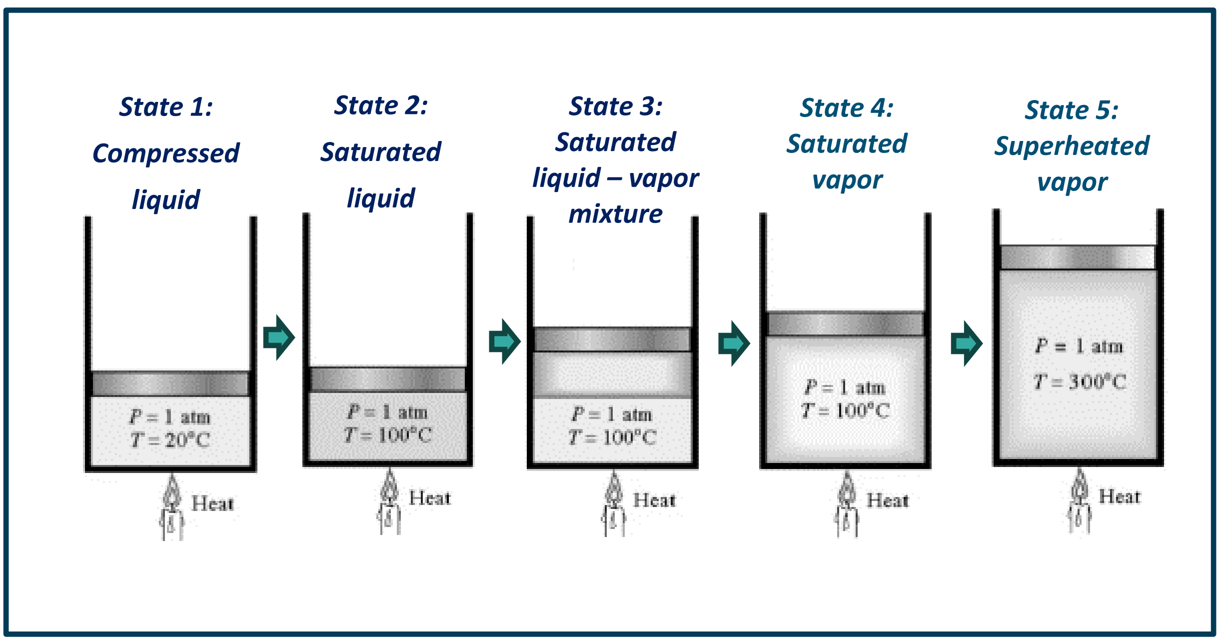


As more heat is transferred, the temperature of the vapor starts to rise (*Superheated vapor*)

Once the phase-change process is completed, we are back to a single phase region again (this time vapor), and further transfer of heat results in an increase in both the temperature and the specific volume.

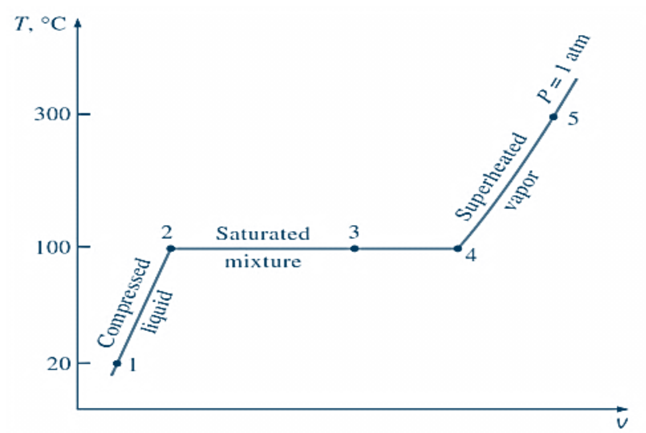
At state 5, the temperature of the vapor is, let us say, 350°C; and if we transfer some heat from the vapor, the temperature may drop somewhat but no condensation will take place as long as the temperature remains above 100°C (for *P* _ 1 atm).

A vapor that is *not about to condense* (i.e., not a saturated vapor) is called a *superheated vapor* (state 5).



2.2 Property Diagram for Phase – Changes Process

The variations of properties during phase-change processes are best studied and understood with the help of property diagrams. The phase-change process of water at 1 atm was described in the last section and the T-v diagram was plotted.



T-v Diagram for Heating Process at Constant Pressure

- **Compressed or sub cooled liquid (between state 1&2):**
  Water exists in the liquid phase and it is called a compressed liquid or sub cooled liquid, meaning that it is not about to vaporize.

- **Saturated liquid (state 2):**
  All fluid is in the liquid state. However, even the slightest addition of energy would result in the in the formation of some vapor.

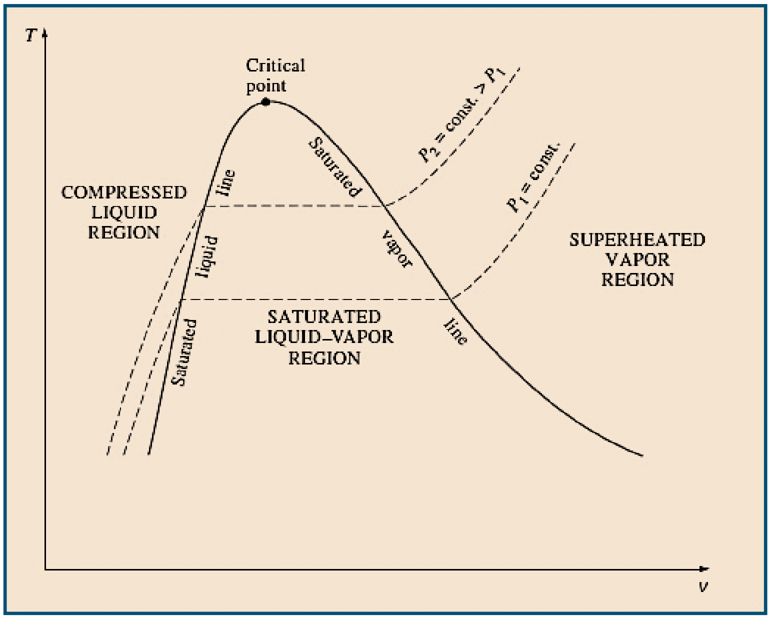
- **Saturated liquid-vapor or wet steam region (between states 2 &3):**
  Liquid and steam exist together in a mixture.

- **Saturated vapor (state 4):**
  All fluid is in the steam state, but even the slightest loss of energy from the system would result in the formation of some liquid.

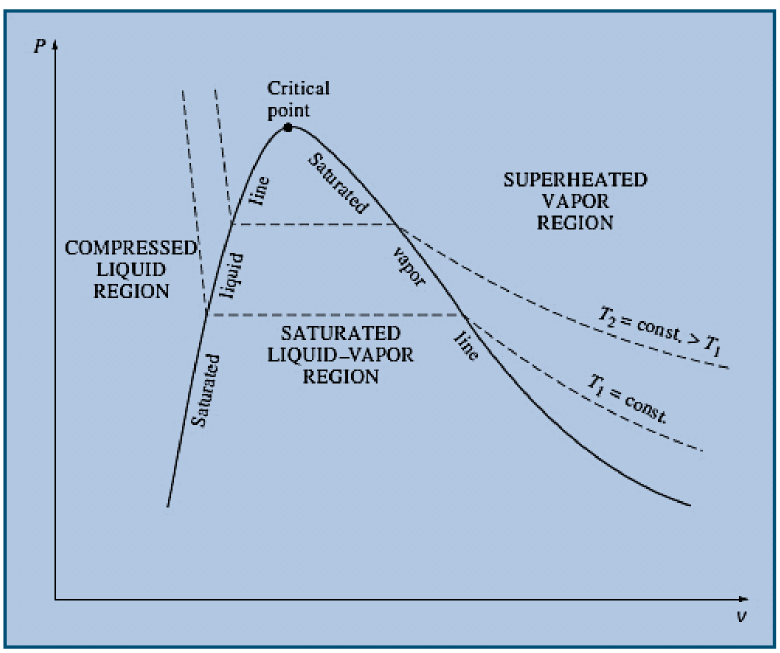
- **Superheated vapor (the right of state 4):**
  All fluid is in the steam state and above the saturation state. The superheated steam temperature is greater than the saturation temperature corresponding to the pressure.

The variations of properties during phase-change processes are best studied and understood with the help of property diagrams. There are 3 types of diagrams for pure substances:

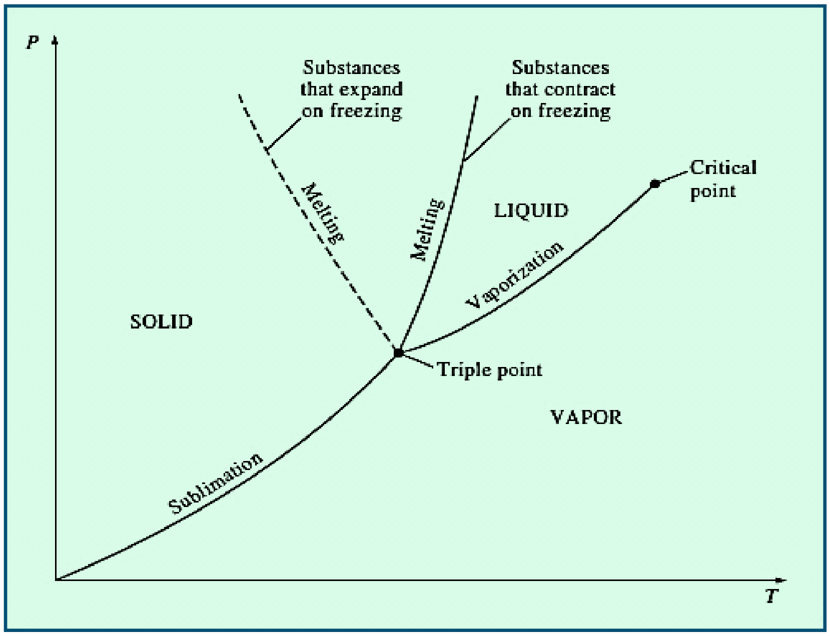
1. T-v Diagram



2. P-v Diagram



3. **P-T Diagram**

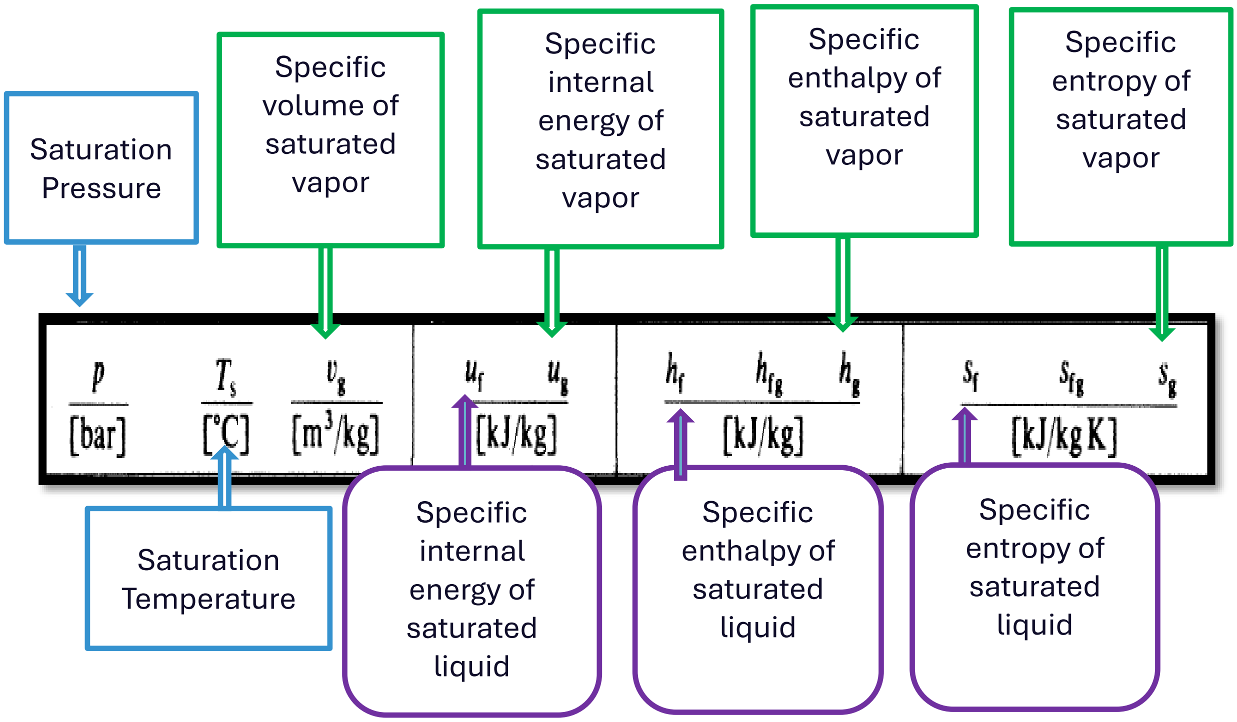


2.3 Property Tables

Property table also known as thermodynamic tables, are tables that will provide information for temperature, pressure, specific volume, internal energy, enthalpy, and entropy at a certain value of temperature or pressure.

Thermodynamics properties are frequently presented in the form of tables in a convenient format. A separate table is prepared for each region of interest. Such as the saturated liquid, saturated vapour, superheated vapour, compressed liquid, and saturated (mixture) regions.

Two new properties: *enthalpy* (*h) and entropy (s).* Entropy is a property associated with the second law of thermodynamics.



Subscripts;

f - refers to a property of the saturated liquid, or to a value of formation

g - refers to a property of the saturated vapour

fg - refers to a change of phase at constant P

Source: Thermodynamics and Transport Properties of fluids Si Units arranged by G. F. C. Rogers and Y. R. Mayhew, Fifth Edition

2.3.1 Saturated Water and Steam Tables

The table of the saturation condition is divided into two parts:

Part 1: Saturated Water - Temperature Table

Refer to the value of temperature from 0.01 °C to 100 °C.

Example 2.1:

Saturated liquid and steam at temperature of 10 °C.

Solution:

t	P_s	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
°C	bar	m³/kg	kJ/kg			kJ/kg.K		
10	0.01227	106.4	42.0	2477.2	2519.2	0.151	8.749	8.900

Example 2.2:

Saturated liquid and steam at temperature of 50 °C.

Solution:

t	P_s	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
°C	bar	m^3/kg	kJ/kg			kJ/kg.K		
50	0.1233	12.04	209.3	2382.1	2591.4	0.704	7.371	8.075

Part 2: Saturated Water – Pressure Table

Part 2 refers to the values of pressure from 0.006112 bar to 221.2bar

Example 2.3:

Saturated liquid and steam at a pressure of 2.5 bar.

Solution:

P	t_s	v_g	u_f	u_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
bar	°C	m^3/kg	kJ/kg		kJ/kg			kJ/kg.K		
2.5	127.4	0.7186	535	2537	535	2182	2717	1.607	5.446	7.053

Example 2.4:

Saturated liquid and steam at a pressure of 40 bar.

Solution:

P	t_s	v_g	u_f	u_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
bar	°C	m^3/kg	kJ/kg		kJ/kg			kJ/kg.K		
40	250.3	0.04977	1082	2602	1087	1714	2801	2.797	3.273	6.070

Saturation Pressure (P_s) and Saturation Temperature (T_s)

The temperature at which water starts boiling depends on the pressure. Therefore, if the pressure is fixed, so is the boiling temperature.

At a given pressure, the temperature at which a pure substance changes phase is called **saturation temperature (T_s).**

At a given temperature, the pressure at which a pure substance changes phase is called **saturation pressure (P_s).**

2.3.2 Compressed Liquid

Below the saturation state, a liquid state in which the fluid remains entirely within the liquid state. A substance is said to be a compressed liquid when the pressure is greater than the saturation pressure for the temperature ($P > P_s$).

Compressed Water

p/[bar] (T_s/[°C])	T/[°C]	0.01	100	200	250	300	350	374.15
	p_s	0.006112	1.01325	15.55	39.78	85.92	165.4	221.2
	$v_f/10^{-2}$	0.1000	0.1044	0.1157	0.1251	0.1404	[illegible]	0.317
	h_f	0	419	852	1086	1345	1671	2084
	s_f	0	1.307	2.331	2.793	3.255	3.779	4.430
100 (311.0)	$(v - v_f)/10^{-2}$	−0.0005	−0.0006	−0.0009	−0.0011	−0.0007	[illegible]	[illegible]
	$(h - h_f)$	+10	+7	+4	0	−2	[illegible]	[illegible]
	$(s - s_f)$	0.000	−0.008	−0.013	−0.014	−0.007	[illegible]	[illegible]
221.2 (374.15)	$(v - v_f)/10^{-2}$	−0.0011	−0.0012	−0.0020	−0.0029	−0.0051	[illegible]	[illegible]
	$(h - h_f)$	+22	+17	+9	+1	−12	[illegible]	[illegible]
	$(s - s_f)$	+0.001	−0.017	−0.031	−0.040	−0.053	[illegible]	[illegible]
500	$(v - v_f)/10^{-2}$	−0.0023	−0.0024	−0.0042	−0.0064	−0.0117	[illegible]	[illegible]
	$(h - h_f)$	+49	+38	+23	+8	−21	−94	−369
	$(s - s_f)$	0.000	−0.037	−0.068	−0.091	−0.134	−0.235	−0.670
1000	$(v - v_f)/10^{-2}$	[illegible]	−0.0044	−0.0075	−0.0111	−0.0191	−0.0427	−0.180
	$(h - h_f)$	+96	+76	+51	+28	−17	−119	−415
	$(s - s_f)$	[illegible]	−0.070	−0.124	−0.164	−0.235	−0.385	−0.853

Note:
v_f is too small
Assume.
$v_f = 0.001\ m^3/kg$

Note: $v_f \times 10^{-2}$

2.3.3 Saturated Liquid & Saturated Vapor States

Saturated Liquid

All fluid is in the liquid state. A liquid is about to vaporized or begin to boil. Which is, even the slightest addition of energy would result in the in the formation of some vapor. The subscript ***f*** is used to denote properties of a **saturated liquid**.

Saturated Vapor

A vapor that is about to condense or vaporization is complete. All fluid is in the vapor state, but even the slightest loss of energy from the system would result in the formation of some liquid. The subscript ***g*** is to denote the properties of **saturated vapor**.

Another subscript commonly used is ***fg***, which denotes the **difference between the saturated vapor and saturated liquid** values of the same property.

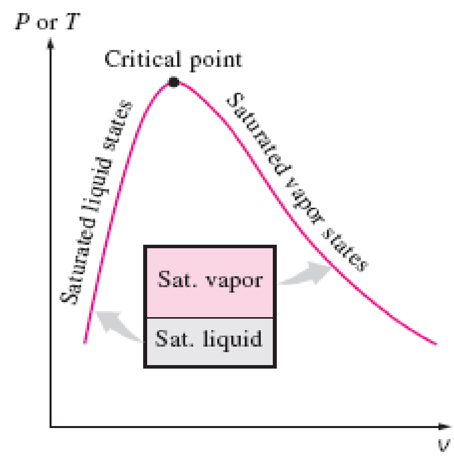
For example for specific internal energy:

u_f = specific internal energy of **saturated liquid**

u_g = specific internal energy of **saturated vapor**

u_{fg} = difference between $u_g - u_f$ (that is $u_{fg} = u_g - u_f$)

p [bar]	t_s [°C]	v_g [m³/kg]	u_f [kJ/kg]	u_g [kJ/kg]
1.0	99.6	1.694	417	2506
1.1	102.3	1.549	429	2510
1.2	104.8	1.428	439	2512
1.3	107.1	1.325	449	2515
1.4	109.3	1.236	458	2517
1.5	111.4	1.159	467	2519



Specific internal energy of saturated liquid

Specific internal energy of saturated vapor

Example 2.5:

Determine the volume, internal energy and entropy of the saturated liquid state at P = 20 bar.

Solution:

From saturated water and steam table:

At 20 bar saturated liquid state;

Volume, $v_f = 0.001\ m^3/kg$

Internal energy, $u_f = 907$ kJ/kg

Entropy, $s_f = 2.447$ kJ/kg.K

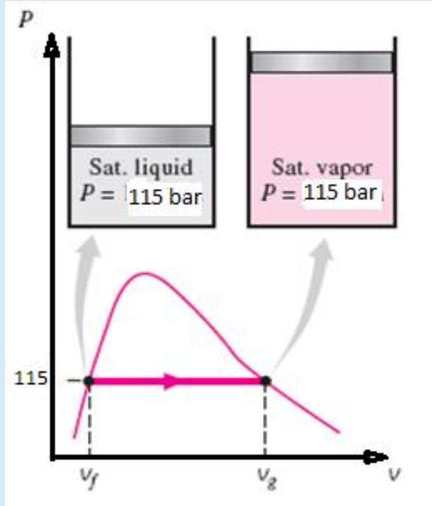
Example 2.6:

Determine the volume and internal energy of the saturated state at P = 115 bar.

Solution:

From saturated water and steam table:

At 115 bar saturated liquid state;



Volume, $v_f = 0.001\ m^3/kg$

Internal energy, $u_f = 1454$ kJ/kg

At 115 bar saturated vapor state;

Volume, $v_g = 0.01508\ m^3/kg$

Internal energy, $u_g = 2522$ kJ/kg

Example 2.7:

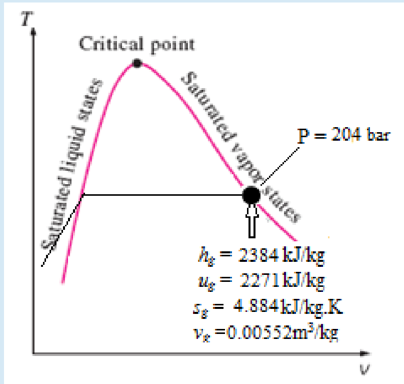
Determine the phase, internal energy, volume and entropy for steam at 204 bar with 2384 kJ/kg of enthalpy. Plot the T-v diagram.

Solution:

From saturated water and steam table:

Enthalpy h = 2384 kJ/kg is h_g. Therefore the phase is at **saturated vapour state**.

At 204 bar the;



Internal energy, u_g = 2271 kJ/kg

Volume, $v_g = 0.00552\ m^3/kg$

Entropy, s_g = 4.884 kJ/kg.K

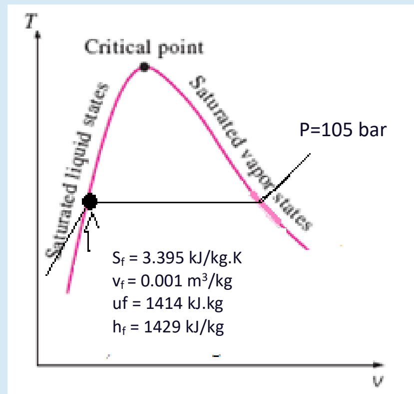
Example 2.8:

Determine the phase, internal energy, volume and enthalpy for steam at 105 bar with 3.395 kJ/kg.K of entropy. Plot the T-v diagram.

Solution:

From saturated water and steam table:

Entrophy, s = 3.395 kJ/kg.K is s_f. Therefore the phase is at **saturated liquid state.**



At 100 bar the;

Internal energy, u_f = 1414 kJ/kg
Volume, v_f = 0.001 m^3/kg
Enthalpy, h_f = 1429 kJ/kg

Example 2.9:

Determine the phase, entropy, volume and enthalpy for steam at 65 bar with 2586 kJ/kg of internal energy.

Solution:

From saturated water and steam table:

Internal energy, u = 2586 kJ/kg is u_g. Therefore the phase is at **saturated vapor state.**

At 100 bar the;

Entropy, s_g = 5.851 kJ/kg.K
Volume, v_g = 0.02972 m^3/kg
Enthalpy, h_g = 2779 kJ/kg

TUTORIAL 1

1) Complete the following table for saturated water and steam.

Answer:

t	***P_s***	***v_g***	***h_f***	***h_fg***	***h_g***	***s_f***	***s_fg***	***s_g***
°C	bar	m^3/kg	kJ/kg			kJ/kg.K		
6		137.8						
			62.9			0.224		
	0.03166							8.557
		13.23			2587.9			
80			334.9					

2) Complete the following table for saturated water and steam.

Answer:

P_s	***t***	***v_g***	***u_f***	***u_g***	***h_f***	***h_fg***	***h_g***	***s_f***	***s_fg***	***s_g***
bar	°C	m^3/kg	kJ/kg		kJ/kg			kJ/kg.K		
0.05		28.20								
	147.9					2121				
		0.06665						2.645		
95										5.647
		0.00479						4.131		

3) Determine the volume, internal energy, enthalpy and entropy of the saturated vapour state at pressure 110 bar.
Answer:
4) A steam at 12 bar with 2.216 kJ/kg.K of entropy, determine the phase, internal energy, volume and enthalpy. Plot the T-v diagram.
Answer:

2.3.4 Saturated Liquid-Vapor Mixture (Wet Steam)

During a vaporization process, a substance exists as part liquid and part vapor. It is a mixture of saturated liquid and saturated vapour. To analyse this mixture properly, we need to know the proportions of the liquid and vapour phases in the mixture.

This is done by defining a new property called the **dryness fraction (x)** as the ratio of the mass of vapor to the total mass of the mixture.

$$x = \frac{m_{vapor}}{m_{total}}$$

where: $m_{total} = m_{liquid} + m_{vapor} = m_f + m_g$

Therefore for **saturated liquid-vapor region (wet steam)**;

$$\boldsymbol{v = x\, v_g}$$
$$\boldsymbol{h = h_f + x\, h_{fg}}$$
$$\boldsymbol{u = u_f + x\,(u_g - u_f)}$$
$$\boldsymbol{s = s_f + x\, s_{fg}}$$

Example 2.10:

For a steam at 8 bar with dryness fraction of 0.86, calculate the:

i. specific volume
ii. specific internal energy

Solution:

From the steam tables:

P	t_s	v_g	u_f	u_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
8	170.4	0.2403	720	2577	721	2048	2769	2.046	4.617	6.663

i. Specific volume (v)

$$v = x\, v_g$$
$$= 0.86\,(0.2403)$$
$$= \mathbf{0.207\ m^3/kg}$$

ii. Specific internal energy (u)

$$u = u_f + x\, u_{fg}$$
$$= 720 + 0.86\,(2577 - 720)$$
$$= \mathbf{2317.02\ kJ/kg}$$

Example 2.11:

Find the dryness fraction, specific volume, specific entropy and specific enthalpy of steam at 42 bar and specific internal energy 2550 kJ/kg.

Solution:

An extract from the steam tables:

At 42 bar, u_g= 2601 kJ/kg, since the actual specific internal energy is given as 2530 kJ/kg, the steam must be in wet steam state ($u < u_g$).

P	t_s	v_g	u_f	u_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
42	253.2	0.04732	1097	2601	1102	1698	2800	2.823	3.226	6.049

Internal energy (u)

$$u = u_f + x\,(u_g - u_f)$$
$$2530 = 1097 + x\,(2601 - 1097)$$
$$\boldsymbol{x = 0.953}$$

Specific volume (v)

$$v = x\,vg$$
$$= 0.953\,(0.04732)$$
$$= \mathbf{0.045}\,\boldsymbol{m^3}/\mathbf{kg}$$

Specific entropy (s)

$$s = s_f + x\,s_{fg}$$
$$= 2.823 + 0.953\,(3.226)$$
$$= \mathbf{5.897k\,J/kg.K}$$

Specific enthalpy (h)

$$h = h_f + x\,h_{fg}$$
$$= 1102 + 0.953\,(1698)$$
$$= \mathbf{2720.19\ k\,J/kg}$$

Example 2.12:

Find the dryness fraction, specific volume, specific internal energy, specific entropy of steam at 110 bar and specific enthalpy 2450 kJ/kg.

Solution:

An extract from the steam tables:

At 110 bar, h_g= 2705 kJ/kg, since the actual specific enthalpy is given as 2450 kJ/kg, the steam must be in wet steam state ($h < h_g$).

P	t_s	v_g	u_f	u_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
110	318.0	0.01598	1434	2529	1450	1255	2705	3.430	2.123	5.553

Specific enthalpy (h)

$$2450 = h_f + x\,h_{fg}$$
$$2450 = 1450 + x\,(1255)$$
$$\boldsymbol{x = 0.797}$$

Specific volume (v)

$$v = x\,vg$$
$$= 0.797\,(0.01598)$$
$$= \mathbf{0.0127\,m^3/kg}$$

Internal energy (u)

$$u = u_f + x\,(u_g - u_f)$$
$$= 1434 + 0.797\,(2529 - 1434)$$
$$= \mathbf{2306.72\ kJ/kg}$$

Specific entropy (s)

$$s = s_f + x\,s_{fg}$$
$$= 3.430 + 0.797\,(2.123)$$
$$= \mathbf{5.122\ kJ/kg.K}$$

TUTORIAL 2

1) The internal energy of wet steam is 2360 kJ/kg. If the pressure is 20 bar, what is the value of dryness fraction?

(Ans: x = 0.858)

Answer:

2) Determine the specific volume, specific enthalpy and specific internal energy of wet steam at 5.5 bar if the dryness fraction is 0.73.

(Ans: v = 0.250 m^3/kg, h = 2186.81 kJ/kg, u = 2049.3 kJ/kg)

Answer:

3) Find the dryness fraction, specific volume and specific internal energy of steam at 145 bar and specific enthalpy 2300 kJ/kg. *(Ans: x = 0.686, v = 7.477 x 10^{-3} m^3/kg, u = 2184.4 kJ/kg)*
Answer:
4) Determine the dryness fraction, specific volume and specific enthalpy for wet steam at 140 kN/m^2 and specific entropy is 5.580kJ/kg.K *(Ans: x = 0.714, v = 0.883 m^3/kg, h = 2051.65 kJ/kg)*
Answer:

2.3.5 Superheated Vapor

The second part of the table is the superheated steam tables. A steam is called superheated when its temperature is greater than the saturation temperature corresponding to the pressure (**$T > t_s$**).

The equation of degree of superheat is:

$$Degree\ of\ superheat = T_{superheat} - t_{saturation}$$

For example, steam at 30 bar and 350°C is superheated since the saturation temperature at 30 bar is 233.8 °C.

The steam at this state has a **degree of superheat** of **350 °C – 233.8 °C = 116.2 °C.**

The tables of properties of **superheated steam** range in pressure from **0.006112 bar** to the critical pressure of **221.2 bar**.

Superheated Steam†

p/[bar] (T_s/[°C])		T [°C]	50	100	150	200	250	300	400	500
0	$u = h - RT$ at $p = 0$	v								
		u	2446	2517	2589	2662	2737	2812	2969	3132
		h	2595	2689	2784	2880	2978	3077	3280	3489
		s								
0.006112 (0.01)	v_g 206.1	v	243.9	281.7	319.5	357.3	395.0	432.8	508.3	583.8
	u_g 2375	u	2446	2517	2589	2662	2737	2812	2969	3132
	h_g 2501	h	2595	2689	2784	2880	2978	3077	3280	3489
	s_g 9.155	s	9.468	9.739	9.978	10.193	10.390	10.571	10.897	11.187

Superheated Steam*

p/[bar] (T_s/[°C])		T [°C]	350	375	400	425	450	500	600	700
210	v_g 0.00498	$v/10^{-2}$		0.650	0.908	1.064	1.187	1.390	1.719	2.003
(369.8)	h_g 2336	h		2500	2781	2928	3041	3225	3528	3799
	s_g 4.803	s		5.050	5.484	5.699	5.859	6.105	6.474	6.768
220	v_g 0.00368	$v/10^{-2}$		0.450	0.825	0.987	1.111	1.312	1.632	1.906
(373.7)	h_g 2178	h		2300	2738	2900	3020	3210	3519	3793
	s_g 4.552	s		4.725	5.409	5.645	5.813	6.068	6.444	6.742
221.2	v_c 0.00317	$v/10^{-2}$	0.163	0.351	0.816	0.978	1.103	1.303	1.622	1.895
(374.15)	h_c 2084	h	1637	2139	2733	2896	3017	3208	3518	3792
	s_c 4.406	s	3.708	4.490	5.398	5.638	5.807	6.064	6.441	6.739

For the **pressure above 80 bar**, the **specific internal energy (u) is not tabulated**.

Superheated Steam*

p/[bar] (T_s/[°C])		T [°C]	350	375	400	425	450	500	600	700
80	v_g 0.02352	$v/10^{-2}$	2.994	3.220	3.428	3.625	3.812	4.170	4.839	5.476
(295.0)	h_g 2758	h	2990	3067	3139	3207	3272	3398	3641	3881
	s_g 5.744	s	6.133	6.255	6.364	6.463	6.555	6.723	7.019	7.279
90	v_g 0.02048	$v/10^{-2}$	2.578	2.794	2.991	3.173	3.346	3.673	4.279	4.852
(303.3)	h_g 2743	h	2959	3042	3118	3189	3256	3385	3633	3874
	s_g 5.679	s	6.039	6.171	6.286	6.390	6.484	6.657	6.958	7.220
100	v_g 0.01802	$v/10^{-2}$	2.241	2.453	2.639	2.812	2.972	3.275	3.831	4.353
(311.0)	h_g 2725	h	2926	3017	3097	3172	3241	3373	3624	3868
	s_g 5.615	s	5.947	6.091	6.213	6.321	6.419	6.596	6.902	7.166

The **specific internal energy** is calculated using the equation:

$$u = h - Pv$$

where:

P = (kN/m²)

v x 10^{-2} = (m³/kg)

h = (kJ/kg)

Example 2.13:

Steam at 90 bar has a specific volume of 0.02645 m^3/kg at 400°C. Find the degree of superheat and the specific internal energy.

Solution:

At 90 bar, v_g = 0.02048 m^3/kg. This is less than the actual specific volume of 0.02645 m^3/kg $\{v > v_g\}$. Hence, the steam is superheated.

P bar ***(t_s °C)***			**400**
90 (303.3)	v_g 0.02048	$v \times 10^{-2}$	2.991
	h_g 2743	h	3118
	s_g 5.679	s	6.286

$$\text{Degree of superheat} = T_{superheat} - t_{saturation}$$
$$= 400\ ^\circ\text{C} - 303.3\ ^\circ\text{C}$$
$$= \mathbf{96.7\ ^\circ C}$$

So, at 90 bar and 400 °C, we have;

$$v = 2.991 \times 10^{-2}\ \text{m}^3/\text{kg}$$
$$h = 3118\ \text{kJ/kg}$$

∴ From equation

$$u = h - Pv$$
$$= 3118\ \text{kJ/kg} - (90 \times 10^2 \text{kN/m}^2)(2.991 \times 10^{-2}\ \text{m}^3/\text{kg})$$
$$= \mathbf{2848.81\ kJ/kg}$$

Example 2.14:

Steam at 200 bar has a specific volume of 1.815 m^3/kg at 600 °C. Find the temperature, degree of superheat, specific enthalpy and specific internal energy.

Solution:

At 200 bar, v_g = 0.00585 m^3/kg. This is less than the actual specific volume of 1.815 x 10^{-2} m^3/kg {$v > v_g$}. Hence, the steam is superheated. The state of the steam is at point A in the diagram below.

P bar (t$_s$ °C)			**600**
200 (365.7)	v_g 0.00585	v x 10^{-2}	1.815
	h_g 2411	h	3537
	s_g 4.928	s	6.505

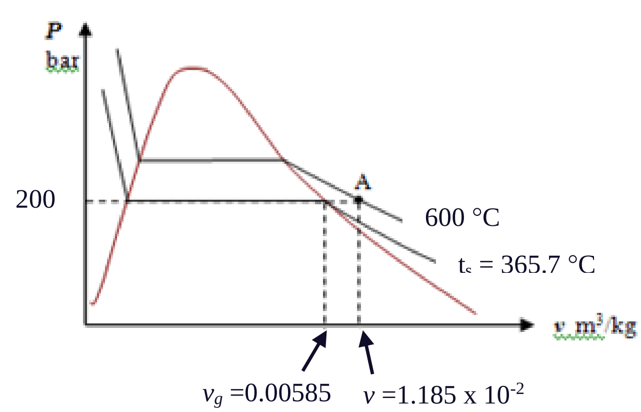
$$\text{Degree of superheat} = T_{superheat} - t_{saturation}$$
$$= 600\ ^0C - 365.7\ ^0C$$
$$\mathbf{= 234.3\ °C}$$

So, at 200 bar and 600 °C, we have;

$$v = 1.815 \text{ x } 10^{-2} \text{ m}^3/\text{kg}$$
$$h = 3537 \text{ kJ/kg}$$

∴ From equation

$$u = h - Pv$$
$$= 3537 \text{ kJ/kg} - (200 \text{ x } 10^2 \text{kN/m}^2)(1.815 \text{ x } 10^{-2} \text{ m}^3/\text{kg})$$
$$\mathbf{= 3174 \ kJ/kg}$$



TUTORIAL 3

1) Steam at 15 bar is at 300 °C. Find the degree of superheat, specific volume, specific enthalpy and specific internal energy.

(Ans: DOS = 101.7 ℃, v = 0.1697 m^3/kg, h = 3039 kJ/kg, u = 2784 kJ/kg)

Answer:

2) Steam at 120 bar has a specific enthalpy of 3348 kJ/kg. Find the temperature, degree of superheat, specific volume and specific internal energy.

(Ans: T = 500 ℃, DOS = 175.4 ℃, v = 2.677 x10^{-2} m^3/kg, u = 3026.76 kJ/kg)

Answer:

2.4 Interpolation

There two methods **to solve the problem that one or two values is not tabulated**:

a) Single Interpolation

b) Double Interpolation

2.4.1 Single Interpolation

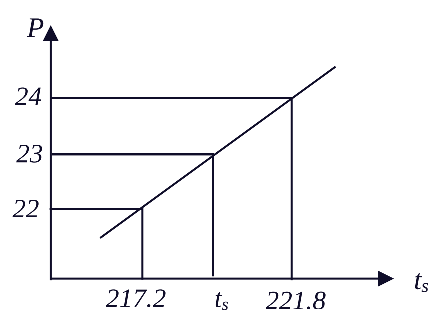
Single interpolation is used to find the values in the table when one of the values is not tabulated.

Example 2.15:

Determine the saturation temperature at 23 bar.

Solution:

The values of saturation temperature at a pressure of 23 bar are not tabulated in the Steam Tables. So, we need to interpolate between the two nearest values that are tabulated in the Steam Tables.



$$\frac{t_s - 217.2}{221.8 - 217.2} = \frac{23 - 22}{24 - 22}$$

$$t_s = \frac{1\,(4.6)}{2} + 217.2$$

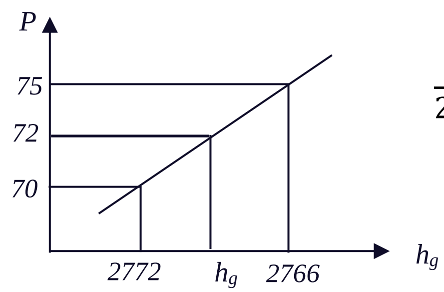
$$\boldsymbol{t_s = 219.5\,°C}$$

Example 2.16:

Determine the specific enthalpy of dry saturated steam at 72 bar.

Solution:

The values of specific enthalpy of dry saturated steam at a pressure of 72 bar are not tabulated in the Steam Tables. So, we need to interpolate between the two nearest values that are tabulated in the Steam Tables.



$$\frac{h_g - 2772}{2766 - 2772} = \frac{72 - 70}{75 - 70}$$

$$h_g = \frac{2\,(-6)}{5} + 2772$$

$$\boldsymbol{h_g = 2769.6\ \mathrm{kJ/kg}}$$

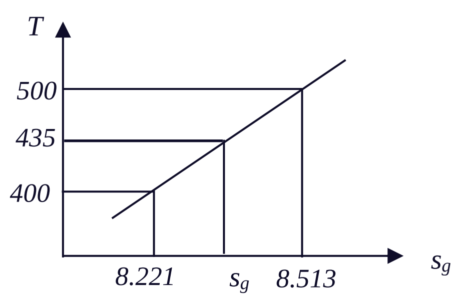
Example 2.17:

Determine the specific entropy of steam at 2 bar and 435 °C.

Solution:

The steam pressure of 2 bar is tabulated in the steam table, but the temperature of 435 °C is not tabulated. To find the values of specific entropy, we need to interpolate between the two nearest values that are tabulated in the Steam Tables.

At P = 2 bar;



$$\frac{s_g - 8.221}{8.513 - 8.221} = \frac{435 - 400}{500 - 400}$$

$$s_g = \frac{35\,(0.292)}{100} + 8.221$$

$$\boldsymbol{s_g = 8.3232\ \mathrm{kJ/kg.K}}$$

Example 2.18:

Determine the specific internal energy of steam at 95 bar and 500 °C.

Solution:

The steam pressure of 95 bar is not tabulated in the steam table, but the temperature of 500 °C is tabulated. To find the values of specific internal energy, we need to find the specific internal energy at 90 bar and 100 bar.

From the superheated steam table;

At P = 90 bar, T = 500 °C; h = 3385 kJ/kg
v = 3.673 x 10^{-2} m^3/kg

The specific internal energy, $u_1 = h - Pv$

$$= 3385\,\frac{kJ}{kg} - \left(90x10^2\,\frac{kN}{m^2}\right)\left(3.673x10^{-2}\,\frac{m^3}{kg}\right)$$

u_1 = 3054.43 kJ/kg

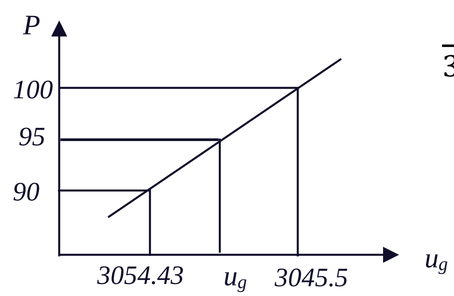
At P = 100 bar, T = 500 °C; h = 3373 kJ/kg
v = 3.275 x 10^{-2} m^3/kg

The specific internal energy, $u_2 = h - Pv$

$$= 3373\,\frac{kJ}{kg} - \left(100x10^2\,\frac{kN}{m^2}\right)\left(3.275x10^{-2}\,\frac{m^3}{kg}\right)$$

u_2 = 3045.5 kJ/kg

Now interpolate between u_1 at 90 bar, 500 °C, and u_2 at 100 bar, 500 °C in order to find u_g at 95 bar and 500 °C.



$$\frac{u_g - 3054.43}{3045.5 - 3054.43} = \frac{95 - 90}{100 - 90}$$

$$u_g = \frac{5\,(-8.93)}{10} + 3054.43$$

$$\boldsymbol{u_g = 3049.97\ \mathrm{kJ/kg.K}}$$

TUTORIAL 4

1) Determine the saturation temperature at 77 bar.

(Ans: t_s = 292.3 ℃)

2) Determine the specific enthalpy of steam at 117 bar and dryness fraction 0.87.

(Ans: h = 2533.44 kJ/kg)

3) Determine the specific internal energy of steam at 165 bar and 700 °C. *(Ans: u = 3401.39kJ/kg)*

2.4.2 Double Interpolation

In some cases, a double interpolation is necessary and it's usually used in the **Superheated Steam Table**.

Double interpolation must be used when **two of the properties** (eg. temperature and pressure) are **not tabulated** in the Steam Tables.

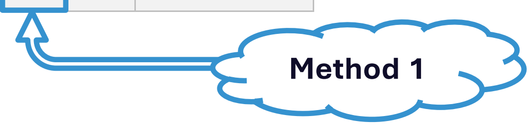
Example 2.19:

Determine the specific enthalpy of superheated steam at pressure of 4.5 bar and temperature of 320 °C.

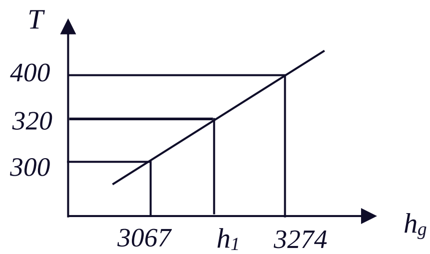
Solution 1:

An extract from the Superheated Steam Tables:

T (°C) / *P (bar)*	*300*	*320*	*400*
4	*3067*	h_1	*3274*
4.5	h_3	h	h_4
5	*3065*	h_2	*3272*



Find the specific enthalpy (h_1) at 4 bar and 320 °C;

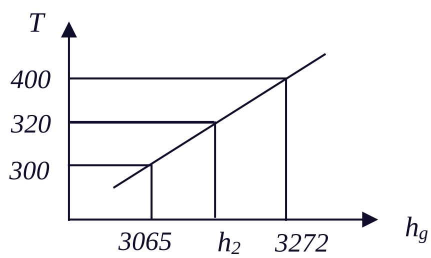


$$\frac{h_1 - 3067}{3274 - 3067} = \frac{320 - 300}{400 - 300}$$

$$h_1 = \frac{20\,(207)}{100} + 3067$$

$$\boldsymbol{h_1 = 3108.4\ \mathbf{kJ/kg}}$$

Find the specific enthalpy (h_2) at 5 bar and 320 °C;

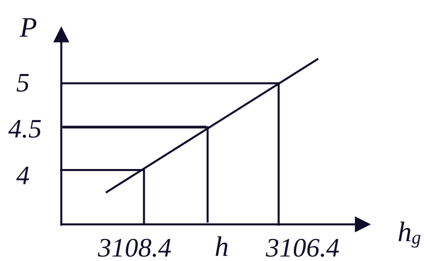


$$\frac{h_2 - 3065}{3272 - 3065} = \frac{320 - 300}{400 - 300}$$

$$h_2 = \frac{20\,(207)}{100} + 3065$$

$$\boldsymbol{h_2 = 3106.4\ \mathbf{kJ/kg}}$$

Now interpolate between h_1 at 4 bar, 320 °C, and h_2 at 5 bar, 320 °C in order to find h at 4.5 bar and 320 °C.



$$\frac{h - h_1}{h_2 - h_1} = \frac{4.5 - 4}{5 - 4}$$

$$\frac{h - 3108.4}{3106.4 - 3108.4} = \frac{4.5 - 4}{5 - 4}$$

$$\boldsymbol{h = 3107.4\ \mathbf{kJ/kg}}$$

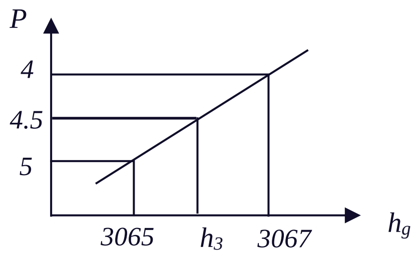
Solution 2:

An extract from the Superheated Steam Tables:

T (℃) / P (bar)	300	320	400
4	3067	h_1	3274
4.5	h_3	h	h_4
5	3065	h_2	3272

Method 2

Find the specific enthalpy (h_3) at 4.5 bar and 300 °C;

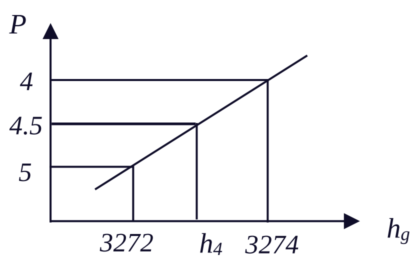


$$\frac{h_3 - 3065}{3067 - 3065} = \frac{4.5 - 5}{4 - 5}$$

$$h_3 = \frac{-0.5\ (2)}{-1} + 3065$$

$$\boldsymbol{h_3 = 3066\ \mathrm{kJ/kg}}$$

Find the specific enthalpy (h_4) at 4.5 bar and 400 °C;

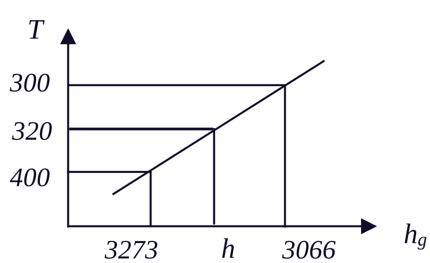


$$\frac{h_4 - 3272}{3274 - 3272} = \frac{4.5 - 5}{4 - 5}$$

$$h_4 = \frac{-0.5\ (2)}{-1} + 3272$$

$$\boldsymbol{h_4 = 3273\ \mathrm{kJ/kg}}$$

Now interpolate between h_3 at 4.5 bar, 300 °C, and h_4 at 4.5 bar, 400 °C in order to find h at 4.5 bar and 320 °C.



$$\frac{h - h_3}{h_4 - h_3} = \frac{320 - 400}{300 - 400}$$

$$\frac{h - 3273}{3066 - 3273} = \frac{320 - 400}{300 - 400}$$

$$\boldsymbol{h = 3107.4\ \mathrm{kJ/kg}}$$

TUTORIAL 5

1) A superheated steam at 53 bar is at 415 °C. Determine the specific volume.

(Ans: v = 0.056216 m^3/kg)

2) A superheated steam at 17.5 MN/m^2 is at 625 °C. Determine the specific enthalpy.

(Ans: h = 3625 kJ/kg)

3) A superheated steam at 62 bar is at 375 °C. Determine the specific entropy.

(Ans: s = 6.4187 kJ/kg.K)

4) A superheated steam at 15 bar and 400 °C expands at constant volume until the pressure becomes 12 bar and the dryness fraction is 0.83. Calculate the changes in the internal energy of steam. Sketch the process in the form of a *T-v* diagram.

(Ans: dU = - 668.47 kJ/kg)

5) A superheated steam at 21.5 MN/m^2 is at 470^0C. Determine the specific internal energy.

(Ans: u = 2841.085 kJ/kg)

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