

Properties of Pure Substance

Properties of pure substances are the unique physical and chemical characteristics that define a substance and distinguish it from other substances. The properties of pure substances important for the [GATE exam](#) include:

1. **Physical Properties:** These are the characteristics that can be observed without changing the identity of the substance. Examples include color, odor, density, boiling point, and melting point.
2. **Chemical Properties:** These characteristics describe a substance's behavior when it reacts with other substances. Examples include reactivity, flammability, and corrosiveness.
3. **Intensive Properties:** These properties do not depend on the amount of substance present and are the same for any amount of the substance. Examples include density, boiling point, and melting point.
4. **Extensive Properties:** These properties depend on the amount of substance present and change with the amount of substance. Examples include mass, volume, and heat capacity.
5. **Density:** The mass per unit volume of a substance, usually expressed in kilograms per cubic meter (kg/m^3) or grams per cubic centimeter (g/cm^3).
6. **Boiling Point:** The temperature at which a substance changes from a liquid to a gas.
7. **Melting Point:** The temperature at which a solid substance changes to a liquid.

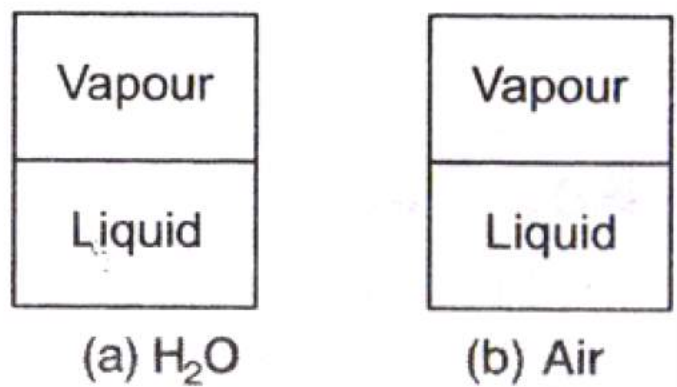
These properties of pure substances play a crucial role in understanding the behavior of substances and in a wide range of industrial and scientific applications.

What is a Pure Substance?

A pure substance is a material with a uniform and unchanging composition; its properties are the same throughout. There are two main types of pure substances: elements and compounds.

1. **Elements:** A substance that cannot be broken down into simpler substances by chemical reactions and is made up of only one type of atom. Examples include gold, silver, and iron.
2. **Compounds:** A substance of two or more elements combined in a specific ratio. Compounds can be broken down into simpler substances by chemical reactions. Examples include water (H_2O), salt (NaCl), and carbon dioxide (CO_2).

Pure substances have unique physical and chemical properties that can be used to identify and classify them. These properties include melting and boiling points, density, reactivity, and more. Understanding the properties of pure substances is crucial in a wide range of fields, including materials science, medicine, and the food and beverage industry.



Saturation Temperature and Saturation Pressure

Saturation temperature and saturation pressure are related concepts in thermodynamics that describe the state of a substance in a phase transition.

1. **Saturation Temperature:** The temperature at which a substance changes from a liquid to a gas (boiling point) or from a gas to a liquid (condensation point) at a constant pressure. At this temperature, the substance is said to be at its saturation temperature.
2. **Saturation Pressure:** The pressure at which a substance changes from a gas to a liquid (condensation pressure) or from a liquid to a gas (vapor pressure) at a constant temperature. At this pressure, the substance is said to be at its saturation pressure.

In thermodynamics, the relationship between saturation temperature and saturation pressure is described by the saturation curve. The saturation curve is a plot of saturation pressure versus saturation temperature for a substance, which is unique for each substance. This relationship between saturation temperature and saturation pressure is important in studying thermodynamics and is used in various applications, including refrigeration, power generation, and industrial processes.

Latent Heat of Pure Substance

Latent heat is the amount of heat energy required to change the state of a substance without causing a temperature change. This heat energy is called latent heat because it is hidden or latent within the substance and is not reflected in its temperature.

There are two main types of latent heat: latent heat of fusion and latent heat of vaporization.

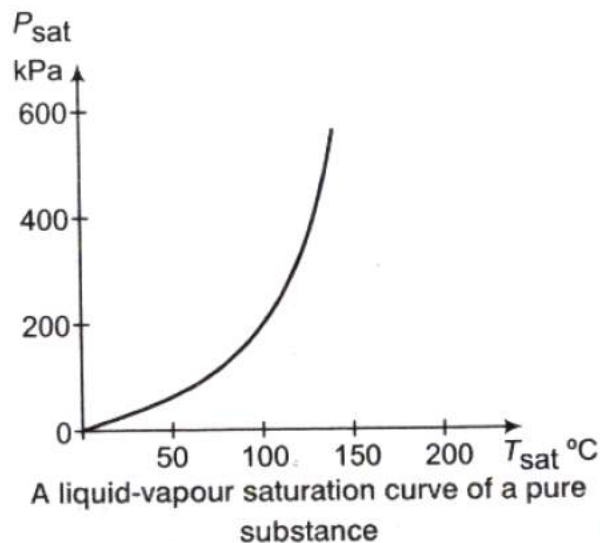
1. **Latent Heat of Fusion:** The heat energy required to change a substance from a solid to a liquid at its melting point.
2. **Latent Heat of Vaporization:** The heat energy required to change a substance from a liquid to a gas at its boiling point.

Latent heat is an important concept in thermodynamics and is used in various applications, including refrigeration, power generation, and industrial processes. Understanding the latent heat of a substance is crucial for the design and operation of energy-efficient systems, as well as for the optimization of industrial processes.

Liquid-Vapour Saturation Curve

From the following figure, it is clear that T_{sat} increases with p_{sat} . Thus, a substance at higher pressure will boil at higher temperatures.

$$T_{\text{sat}} = f(p_{\text{sat}})$$



- In the kitchen, a higher boiling temperature means shorter cooking time and energy savings.
- The atmospheric pressure, and thus the boiling temperature of the water, decreases with elevation. Therefore, it takes longer to cook at higher altitudes than at sea level.

Property Diagrams for Phase-change Process of Pure Substance

Property diagrams are graphical representations of the thermodynamic properties of a pure substance during a phase-change process, such as boiling or melting. They are used to understand the relationship between a substance's pressure, temperature, and enthalpy (heat content) during a phase change.

There are several types of property diagrams commonly used to represent phase-change processes, including:

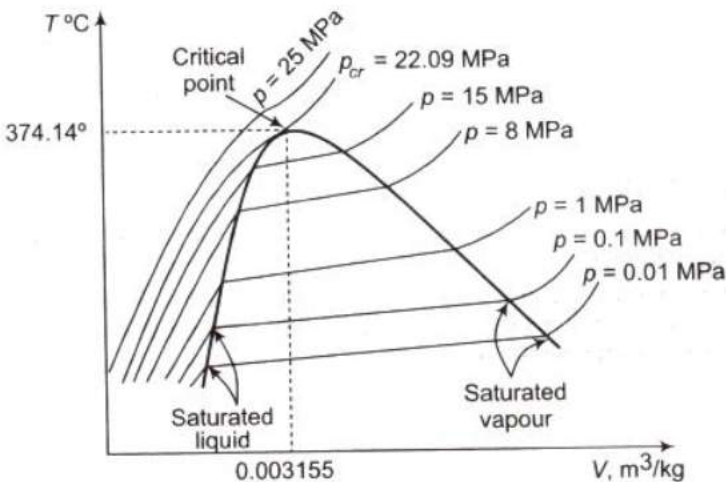
1. **Pressure-Temperature (P-T) diagram:** A plot of pressure versus temperature for a substance during a phase change. It shows the relationship between pressure and temperature at the saturation curve and helps to understand the behaviour of a substance during boiling or condensation.
2. **Pressure-Enthalpy (P-h) diagram:** A plot of pressure versus enthalpy for a substance during a phase change. It helps to understand the relationship between pressure and heat content during boiling or condensation.
3. **Temperature-Enthalpy (T-h) diagram:** A temperature plot versus enthalpy for a substance during a phase change. It helps to understand the relationship between temperature and heat content during melting or solidification.

Property diagrams provide a visual representation of the thermodynamic properties of a substance during a phase-change process and are used in a wide range of applications, including energy systems, refrigeration, and industrial processes. They help to understand the behaviour of a substance during phase changes, which is crucial for optimizing energy efficiency and industrial processes.

T-V Diagram of Pure Substance

The T-V diagram, also known as the Temperature-Volume diagram, is a graphical representation of the relationship between the temperature and volume of a pure substance. It is used to study the thermodynamic behaviour of a substance during changes of state, such as during heating and cooling, or during phase transitions such as melting and boiling. The T-V diagram can be used to determine the specific heat, latent heat, and other thermodynamic properties of a substance.

- Consider a piston-cylinder device containing liquid water at 20°C and 1 atm.
- Water will start boiling at a much higher temperature (179.9°C) at inside pressure of the cylinder reaches 1 MPa.
- The specific volume of the saturated liquid is larger, and the specific volume of the saturated vapour is smaller than the corresponding values at 1 atm pressure. That is, the horizontal line that connects the saturated liquid and saturated vapour states are much shorter.
- As the pressure is increased further, this saturation line will continue to get shorter, as shown in the figure, and it will become a point when the pressure reaches 22.09 MPa for the case of water. This point is called the critical point and it is defined as the point at which the saturated liquid and saturated vapour states are identical.
- At pressure above the critical pressure, there will not be a distinct phase change. Instead, the specific volume of the substance will continually increase, and at all times, there will be only one phase present. It is customary to refer to the substance as superheated vapour at temperatures above the critical temperature and as a compressed liquid below the critical temperature.



T - V diagram of constant pressure phase-change process of a pure substances at various pressures.

p-V Diagram of Pure Substance

The p-V diagram, also known as the Pressure-Volume diagram, is a graphical representation of the relationship between the pressure and volume of a pure substance. It is used to study the thermodynamic behaviour of a substance during changes of state, such as during heating and cooling, or during phase transitions such as melting and boiling. The p-V diagram can be used to determine the work done by a substance, the change in internal energy, and other thermodynamic properties.

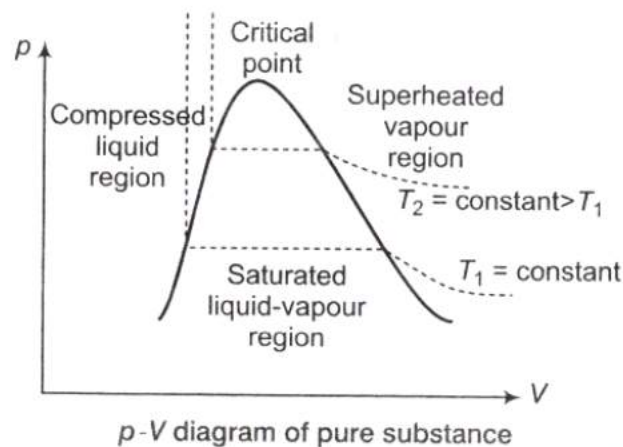
- The general shape of the p-V diagram of a pure substance is very much like the T-V diagram, but the $T = \text{constant}$ lines on this diagram have a downward trend.
- Consider again a piston-cylinder device that contains liquid water at 1 MPa, and 150°C; the water in this state exists as a compressed liquid. Now, the weights on top of the piston are removed one by one so that the pressure inside the cylinder decreases gradually.
- The water can exchange heat with the surroundings, so its temperature remains constant.
- As the pressure decreases, the volume of the water will increase slightly; when the pressure reaches the saturation pressure volume at a specific temperature, the water will start to boil.
- During this vaporization process, the temperature and the pressure remain constant, but the specific volume increases. Once the last drop of liquid is vaporized, further reduction in pressure results in a further increase in specific volume.
- If the process is repeated for other temperatures, similar paths will be obtained for the phase change processes.

Triple Point of Pure Substance

The triple point is a unique state in thermodynamics where three phases of a substance coexist in a stable equilibrium. It is a specific pressure and temperature condition where the solid, liquid, and gaseous phases of a substance are all in a state of balance, and

no phase change occurs. The triple point is an important concept in thermodynamics and is used as a reference point for defining temperature and pressure scales.

- When all three phases of a pure substance co-exist in equilibrium. It is called triple-phase.
- Triple-phase states form a line called the triple line.
- The triple line appears as a point on the p-T diagram and is often called the triple point.

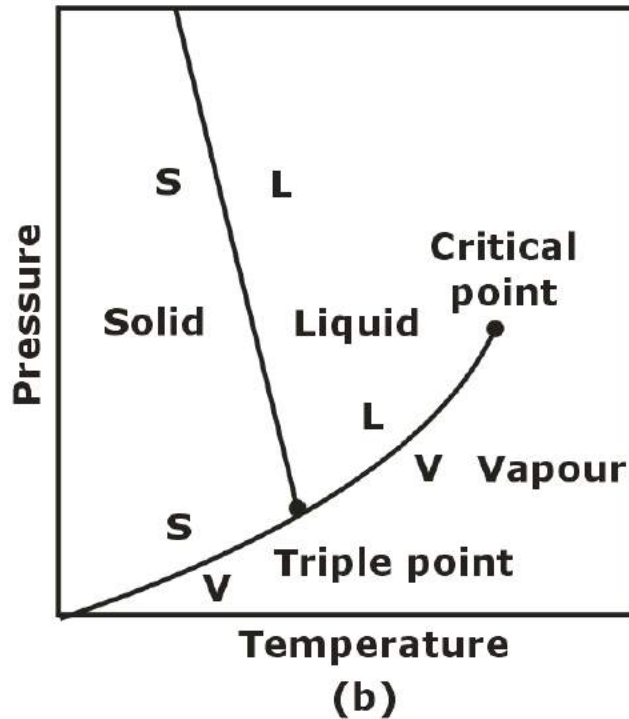


- No substance can exist in the liquid phase in stable equilibrium below the triple point pressure.
- The same can be said for the temperature of substances that contract on freezing.
- Substances at high pressure can exist in the liquid phase below the triple point temperature.

p-T Diagram

The p-T diagram, also known as the Pressure-Temperature diagram, is a graphical representation of the relationship between the pressure and temperature of a substance. It is used to study the thermodynamic behaviour of a substance during changes of state, such as during heating and cooling, or during phase transitions such as melting and boiling. The p-T diagram can be used to determine the critical point, the saturation line, and other thermodynamic properties.

- Solid – Liquid = Fusion
- Liquid – Vapour = Vaporisation
- Solid – Vapour = Sublimation



Enthalpy

Enthalpy is a measure of the total energy of a thermodynamic system. It includes the energy required to create a system and the amount required to make room for it by displacing its environment and establishing its volume and pressure. For certain types of processes, particularly in power generation and refrigeration.

$$\text{Enthalpy (H)} = U + pV (\text{kJ}) \text{ Or}$$

$$\text{per unit mass } h = u + pV (\text{kJ/kg})$$

Saturated Liquid and Saturated Vapour States:

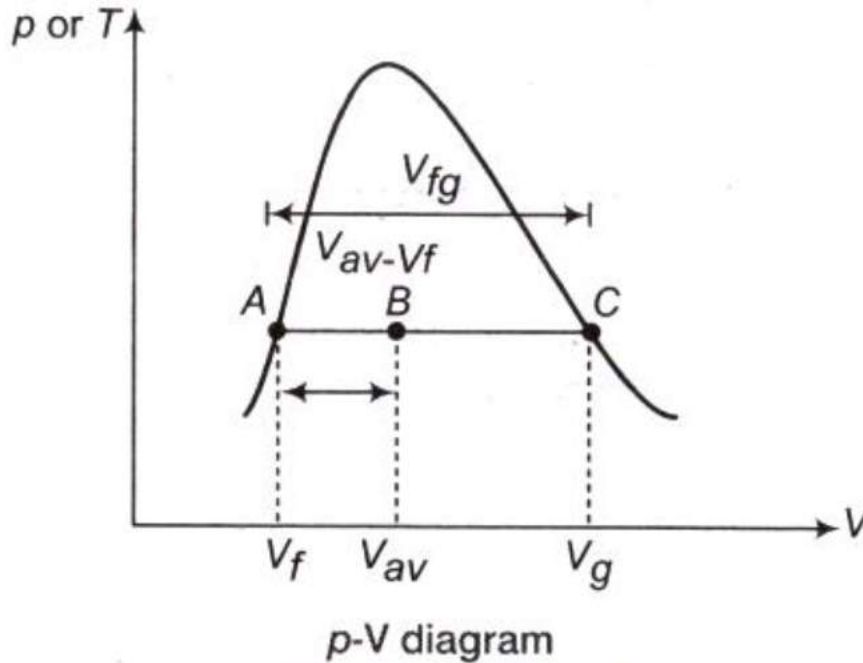
- Subscript f → properties of saturated liquid
- Subscript g → properties of saturated vapour
- V_f → specific volume of saturated liquid
- V_g → specific volume of saturated vapour
- V_{fg} → difference between V_g and V_f
- $V_{fg} = V_g - V_f$
- h_{fg} → enthalpy of vaporization or latent heat of vaporization (amount of energy needed to vaporize a unit mass of saturated liquid at a given pressure-temperature).
- The magnitude of latent heat depends on the temperature and pressure at which phase change occurs.
- For example, at 1 atm pressure, the latent heat of the fusion of water is 333.7 kJ/kg, and the latent heat of vaporization is 2257.1 kJ/kg.
- At below triple-point pressure, the substance begins to change directly to gas.

- The Enthalpy of vaporization decreases as the temperature or pressure increases and becomes zero at the critical point.

Saturated Liquid Vapour Mixture

- During vaporization, a substance exists as a part liquid and part vapour.
- A new property quality x is the ratio of the vapour's mass to the mixture's total mass.

Quality or dryness fraction: $x = m_{\text{vapour}}/m_{\text{total}}$



$$m_{\text{total}} = m_{\text{liquid}} + m_{\text{vapor}} = m_f + m_g$$

where, m_f = mass of the saturated liquid, and m_g = mass of the saturated vapour

- Quality has significance for saturated mixtures only.
- It has no meaning in the compressed liquid or superheated region.
- Its value lie between 0 (saturated liquid) and 1 (saturated vapour).
- The properties of the saturated liquid are the same whether it exists alone or in a mixture with saturated vapour.
- During the vaporization process, only the amount of saturated liquid changes, not its properties. The same can be said about saturated vapour.

Quality:

$$x = \frac{\overline{AB}}{\overline{AC}} \Rightarrow x = \frac{V_{av} - V_f}{V_{fg}}$$

- $V_{av} = (1-x)V_f + xV_g$ or $V_{av} = V_f + xV_g$
- $U_{av} = U_f + U_{fg}$
- $h_{av} = h_f + xh_{fg}$

Superheated Vapour

Since the superheated region is a single-phase region (vapour phase only), temperature and pressure are no longer dependent properties, and they can conveniently be used as two independent properties.

Superheated vapour is characterized by the following:

- Lower pressures ($p < p_{sat}$ at a given T)
- Higher temperatures ($T < T_{sat}$ at a given p)
- Higher specific volumes ($U > V_g$ at a given p or T)
- Higher internal energies ($U > U_g$ at a given p or T)
- Higher enthalpies ($h > h_g$ at a given p or T)

Compressed Liquid

- A compressed liquid may be approximated as a saturated liquid at a given temperature.
- This is because the compressed liquid properties depend on temperature much more strongly than they do on pressure.
 - $V \cong V_f$
 - $u \cong u_f$
 - $h \cong h_f$
- In general, a compressed liquid is characterized by:
 - Higher pressures ($p > p_{sat}$ at a given T)
 - Lower temperatures ($T < T_{sat}$ at a given p)
 - Lower specific volumes ($V < V_f$ at a given p or T)
 - Lower internal energies ($U < U_f$ at a given p or T)
 - Lower enthalpies ($h < h_f$ at a given p or T)

Ideal Gas Equation of State

The ideal gas law is an equation of state that describes the behaviour of an ideal gas. It states that at a constant temperature, the pressure times the volume of a gas is proportional to its number of molecules, or the gas constantly times its absolute temperature.

- Any equation that relates the pressure, temperature, and specific volume of a substance is called an equation of state.
- Property relations that involve other properties of a substance at equilibrium states are also referred to as equations of state.
- Ideal gas equation of state: $pV = RT$, where, p = Absolute pressure, T = Absolute temperature, and V = Specific volume
- Gas and vapour are often used as synonymous words.

- The vapour phase of a substance is customarily called a gas when it is above the critical temperature.
- Vapour usually implies a gas that is not far from a state of condensation.

Gas Constant

The gas constant (R) is a physical constant that appears in the ideal gas law and other equations that describe the behaviour of gases. It has a value of $8.31 \text{ J/mol}\cdot\text{K}$ in SI units and represents the ratio of the average kinetic energy of the gas molecules to the temperature. The gas constant is used to convert between the number of moles of gas and the pressure, volume, and temperature. Its value allows us to use the ideal gas law equation, $PV = nRT$, to calculate the properties of an ideal gas under given conditions. The gas constant is independent of the particular gas and is the same for all ideal gases.

$$R = R_u/M$$

where, R_u = Universal gas constant, M = Molar mass, R = Gas constant.

Compressibility Factor

- The compressibility factor (correction factor) is a measurement of the deviation of gases from ideal gas behaviour.
- Compressibility factor (z):

$$z = \frac{pV}{RT} \text{ or } pV = zRT$$

- It can also be expressed as

$$z = \frac{V_{\text{actual}}}{V_{\text{ideal}}}, \text{ where } V_{\text{ideal}} = \frac{RT}{p}$$

- For ideal gases $\Rightarrow z = 1$
- For real gases $\Rightarrow z$ is away from unity (> 1 or < 1)

Reduce Pressure and Temperature

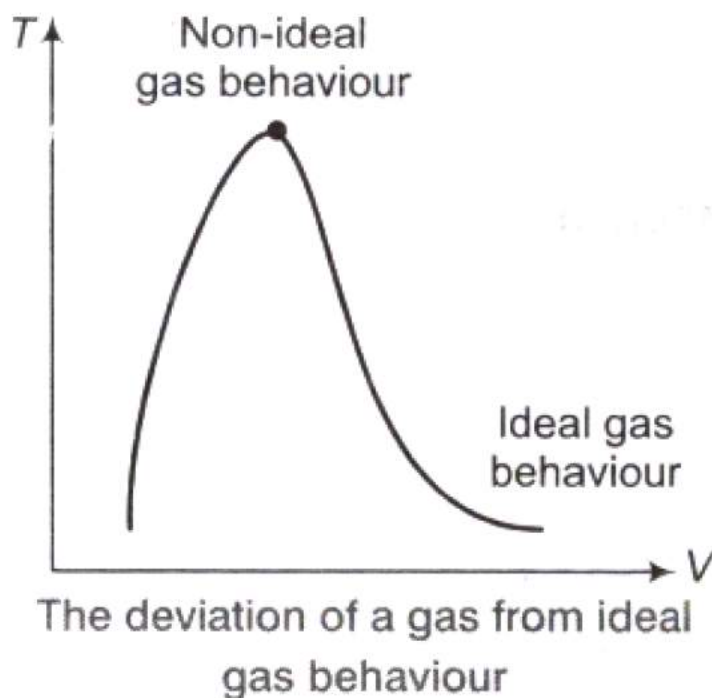
- Gases behave differently at a given temperature and pressure, but they behave very much the same at temperature and pressures normalized with respect to their critical temperatures and pressures.
- The normalization is done by introducing new terms,
 - Reduce pressure:

$$p_R = \frac{p}{p_c}$$

and reduce temperature:

$$T_R = \frac{T}{T_c}$$

where, T_{cr} = critical temperature, p_{cr} = critical pressure.



z factor for all gases is approximately the same at the same reduced pressure and temperature is greatest in the vicinity of the critical point.

- Gases deviate from the ideal gas behaviour most in the neighborhood of the critical point. So, we can say that at a critical point. The compressibility factor is constant for all substances.
- As mentioned above z factor for all gases is approximately the same at the same reduced pressure and temperature.
- Pseudo-reduced specific volume (V_R):

$$V_R = \frac{V_{actual}}{RT_{cr} / p_{cr}}$$

- VR is defined differently from pR and TR. It is related to Tcr and pcr instead of Vcr.
- All substances have the same critical compressibility factor

$$Z_c = \frac{p_c V_c}{RT_c}$$

- The experimental value of Zc for most substances falls within a narrow range of 0.20 – 0.33.
- Z the compressibility factor is the same function of pr and Tr for all gases.
- Specific heat all constant pressure and volume are the properties of the substances and are always properties.

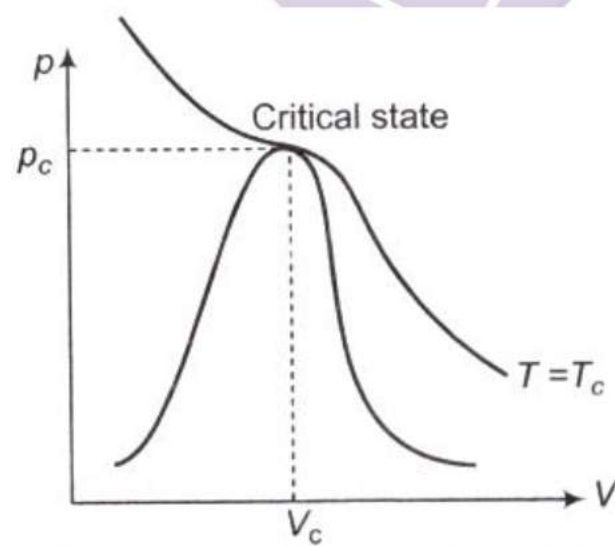
$$C_p > C_v, \frac{C_p}{C_v} > 1$$

Van der wall's Equation of State:

$$\left(p + \frac{a}{V^2}\right)(V - b) = RT$$

- Two effects: Intermolecular attraction forces:

$\frac{a}{V^2}$, and b accounts for the volume occupied by the gas molecules.



Critical properties on p-V diagram

Virial Equation of State

The virial equation of state is a modified form of the ideal gas law that takes into account the interactions between gas molecules. Unlike the ideal gas law, which assumes that gas molecules do not interact, the virial equation accounts for the attractive and repulsive forces between molecules. Van der Waal's equation of state can be expressed in the virial form as given below:

$$\left(p + \frac{a}{V^2}\right)(V - b) = RT$$

$$\left(pV + \frac{a'}{V}\right) = RT$$

$$pV + \frac{a}{V} = RT \left(1 - \frac{b}{V}\right)^{-1}$$

$$= RT \left(1 + \frac{b}{V} + \frac{b^2}{V^2} + \frac{b^3}{V^3} + \dots\right) \left(\text{where } \frac{b}{V} < 1\right)$$

$$pV = RT \left[1 + \left(b - \frac{a}{RT}\right) \frac{1}{V} + \frac{b^2}{V^2} + \frac{b^3}{V^3} + \dots\right]$$