

AMME2262 THERMAL ENG 1 NOTES

“thermodynamics, an engineering approach” 7th Ed SI units McGraw-Hill 2011.

“Fundamentals of Heat and Mass Transfer”; 7th edition Wiley. Frank P. Incropera; David P. Dewitt

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Assessments:

10% tute assignments (8/12)

30% 3 quizzes (5,8,11 on Wednesday)

10% labs

50% final

Course aims:

- Fundamental thermodynamics applied to open and closed systems
- Understanding basic thermodynamic properties of substances
- Ability to analyse in term of 1st and 2nd law of thermodynamics
- Calculate gas and multiphase power and refrigeration cycles

Introductory concepts:

Pressure:

$$P = \frac{F}{A} \quad (\text{N/m}^2 ; Pa)$$

Absolute pressure:

- Measured relative to absolute zero pressure

Gage/vacuum pressure:

- Measured relative to atmospheric pressure

$$P_{abs} = P_{guage} + P_{atm}$$

Pascal's Law:

$$P_1 = P_2$$

Temperature:

- Kelvin (K)

Celsius/Kelvin conversion

$$T(K) = T(^{\circ}C) + 273.15$$

Density:

$$\rho = \frac{m}{V}$$

Specific volume:

$$v = \frac{V}{m} = \frac{1}{\rho}$$

Specific gravity:

$$SG = \frac{\rho}{\rho_{H_2O}}$$

Specific weight:

$$\rho g$$

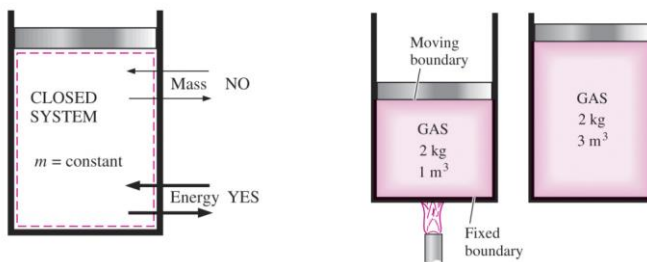
Properties per unit mole:

Are denoted with an overbar:

$$\bar{v} = \frac{m^3}{kmol}$$
$$\bar{u} = \frac{kJ}{kmol}$$
$$\bar{h} = \frac{kJ}{kmol}$$

Thermodynamics system:

Could be either **closed** or **open**



Closed system:

Fixed amount of mass, and has no mass flow across boundary. (can have a moving system boundary though).

Referred to as **control mass**.

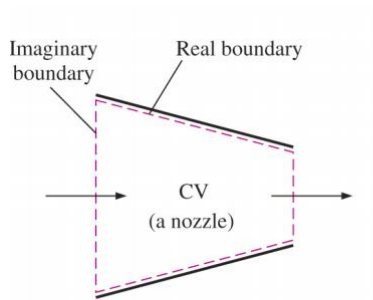
Eg: closed tank or piston cylinder.

Open system:

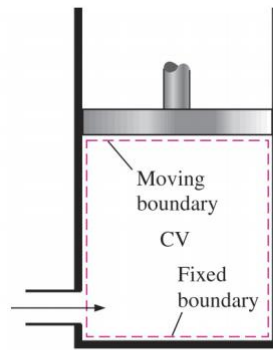
Involves mass flow across boundary.

Referred to as **control volume**.

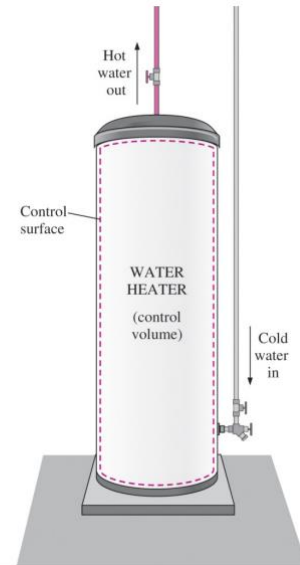
Eg: turbine, nozzle, compressor



(a) A control volume with real and imaginary boundaries



(b) A control volume with fixed and moving boundaries



Continuum assumption applied to system

Matter is made up of atoms that are widely spaced in the gas phase. Yet it is very convenient to disregard the atomic nature of a substance and view it as a continuous, homogeneous matter with no holes, that is, a continuum. Despite the large gaps between molecules, a substance can be treated as a continuum because of the very large number of molecules even in an extremely small volume.

Intensive properties:

Independent of size of system:

- Temperature
- Pressure
- Density

Extensive property:

Dependent on size of system:

- Mass
- Volume
- Energy

Specific property

Extensive properties per unit mass are **specific properties**, and are intensive.

- Mass
- Specific volume: $\frac{V}{m} = v$
- Specific internal energy: $\frac{U}{m} = u$
- Specific energy: $\frac{E}{m} = e$

Thermal equilibrium:

A system is in thermodynamic equilibrium if it is in thermal, mechanical, phase and chemical equilibrium. When a system in an equilibrium state the properties of a system do not change and are constant over the entire system.

0th law of thermodynamics:

The Zeroth law of thermodynamics states that if two bodies are in thermal equilibrium with a third body, they also are in thermal equilibrium with each other. This validates temperature measurements in that if two bodies have the same temperature, they are in thermal equilibrium. (Fowler 1931) Two bodies reaching thermal equilibrium after being brought into contact in an isolated enclosure. By replacing the third body with a thermometer, the zeroth law can be restated as two bodies are in thermal equilibrium if both have the same temperature reading even if they are not in contact.

Equation of state

An equation of state is any equation that relates pressure, temperature and specific volume of a substance.

Ideal gas equation:

Ideal gas assumptions:

- The gas is composed of a large amount of small molecules.
- The gas molecules are elastic
- The size and total volume of the molecules is small relative to the volume
- Thermal motions of the gas are random
- ->real gases can be approximated by an ideal gas at "low" densities: "low" pressures and "high" temperatures.

$$PV = nR_u T$$

$$P = \text{Pressure}; V = \text{Volume}; n = \text{mols}; R_u = 8.314 \left(\frac{J}{K \cdot mol} \right); T = \text{temperature (K)}$$

BUT- better to use mass than mols:

So:

$$PV = mRT$$

Cannot use ideal gas equation for steam or refrigerant

$$P = (\mathbf{kPa}); V = (m^3); m = (kg); R = \text{gas constant} = \frac{R_u}{\text{molecular weight}} \left(\frac{\mathbf{kJ}}{\mathbf{K} \cdot \mathbf{kg}} \right); T = (K)$$

List of some gas constants:

| Gas | J/(kgK) | kJ/(kgK) |
|--|---------|----------|
| Argon, Ar | 208 | 0.208 |
| Acetylene | 319 | 0.319 |
| Ammonia | 488 | 0.488 |
| Carbon Dioxide, CO ₂ | 188.9 | 0.1889 |
| Carbon Monoxide, CO | 297 | 0.297 |
| Carbonic acid | 189 | 0.189 |
| Helium, He | 2077 | 2.077 |
| Hydrogen, H ₂ | 4124 | 4.124 |
| Methane - natural gas, CH ₄ | 518.3 | 0.5183 |
| Nitrogen, N ₂ | 296.8 | 0.2968 |
| Oxygen, O ₂ | 259.8 | 0.2598 |
| Propane, C ₃ H ₈ | 189 | 0.189 |
| Sulfur dioxide, SO ₂ (sulfuric acid) | 130 | 0.13 |
| Air | 286.9 | 0.2869 |
| Water vapor | 461.5 | 0.4615 |

State postulate:

The state of a simple* compressible system is completely specified by two independent, intensive properties. (i.e- hold one constant and change another property)

*simple compressible system:

No:

- Electrical
- Magnetic
- Gravitational
- Motion

- Surface tension

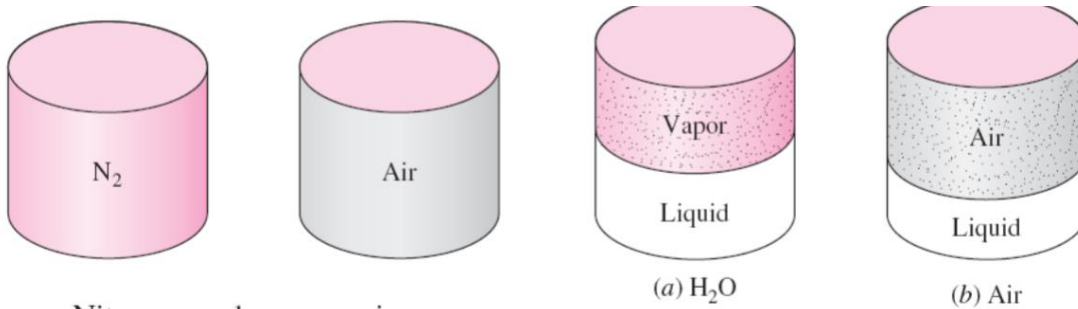
Eg: piston

If $T = 25^\circ\text{C}$; $v = 0.9 \frac{\text{m}^3}{\text{kg}}$: This is state postulate

Pure substances:

Have a fixed chemical composition throughout:

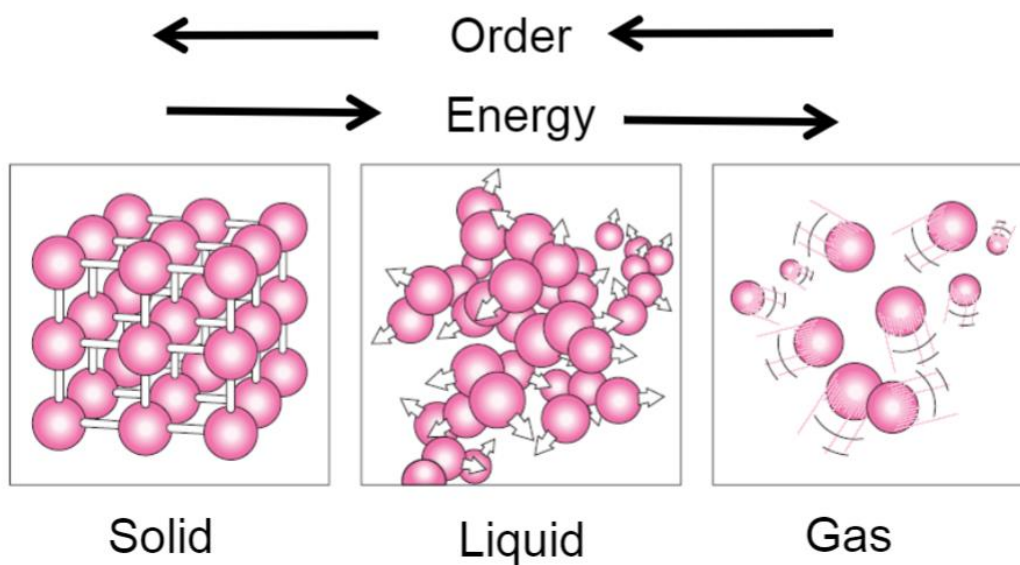
- Air is a pure substance at atmospheric pressure and temperature (fixed mixture throughout)



Nitrogen and gaseous air are pure substances.

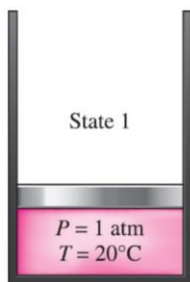
A mixture of liquid and gaseous water is a pure substance, but a mixture of liquid and gaseous air is not.

Phases of pure substances:



Compressed liquid (subcooled liquid):

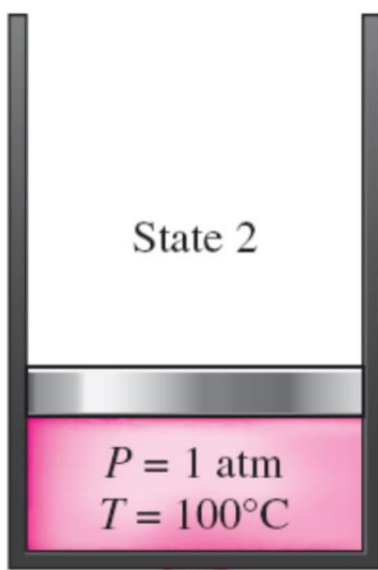
A substance that is **not** about to vaporize



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

Saturated Liquid:

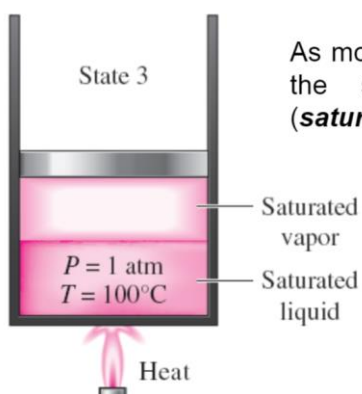
Liquid is about to vaporize



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

Saturated liquid-vapor mix:

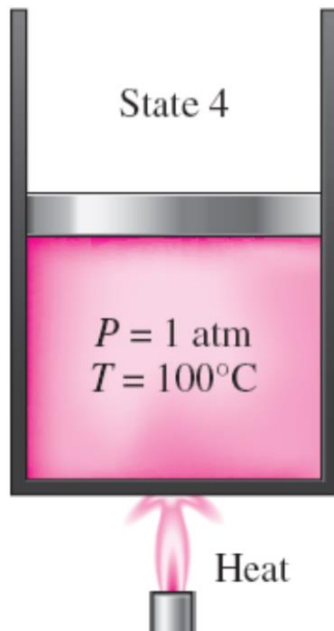
State at which liquid and vapour coexist in equilibrium (but temperature is not rising, as energy is used to vaporize liquid)



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

Saturated Vapor

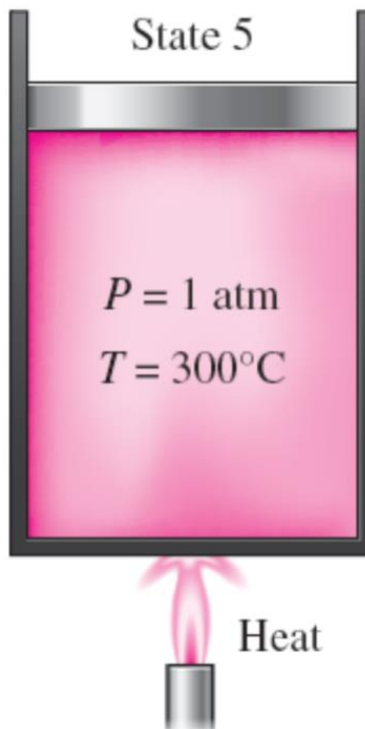
Vapour is about to condense:



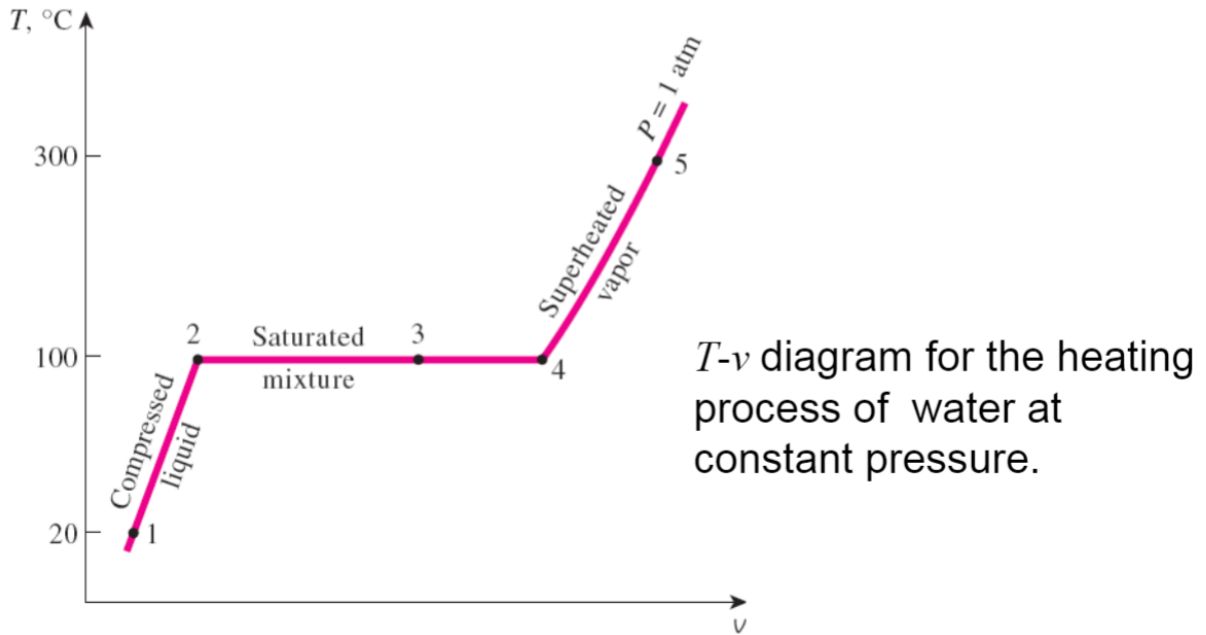
At 1 atm pressure, the temperature remains constant at 100°C until the last drop of liquid is vaporized (**saturated vapor**).

Superheated vapour:

- Too much energy (temperature increases); vapour is NOT about to condense



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



Reversing the process following the same path releases the same amount of heat as was added in the forward process.

Saturation Temperature and pressure:

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

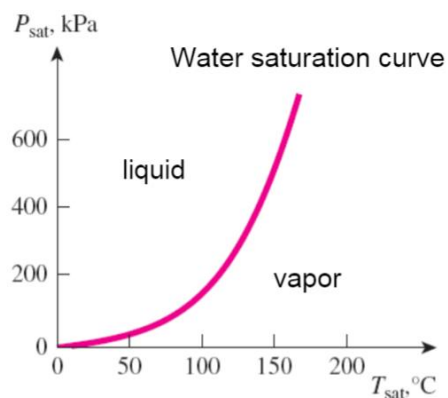
T_{SAT} :

The temperature at which a pure substance changes phase at a given pressure

P_{SAT} :

The Pressure at which a pure substance changes phase at given temperature

Water Saturation curve:



Latent heat:

The amount of energy absorbed or released during a phase change process

Latent heat of fusion:

The amount of energy absorbed during melting (equivalent to amount released in freezing)

Latent heat of vaporisation

The amount of energy absorbed during vaporisation (equivalent to released in condensation)

- Depends on temperature and pressure at which the phase occurs

At 1 atm:

Latent heat of fusion of water = 333.7 kJ/kg

Latent heat of vaporisation = 2265.5 kJ/kg

Isobaric process:

- Constant pressure

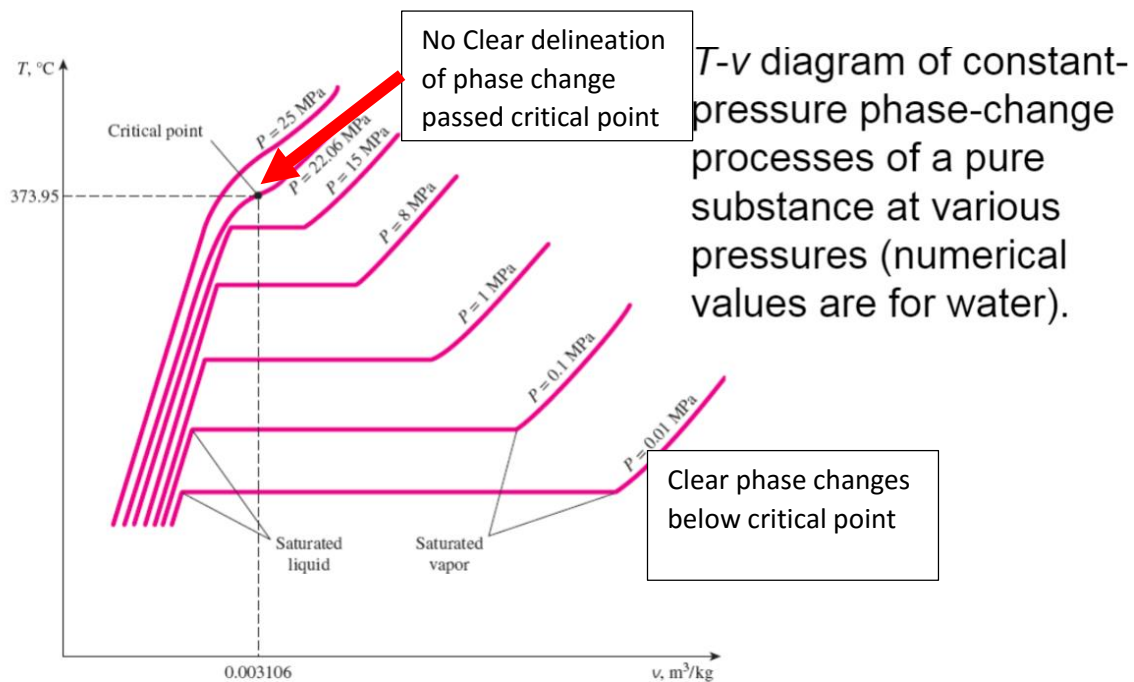
Isothermal process:

Constant temperature:

Phase diagrams

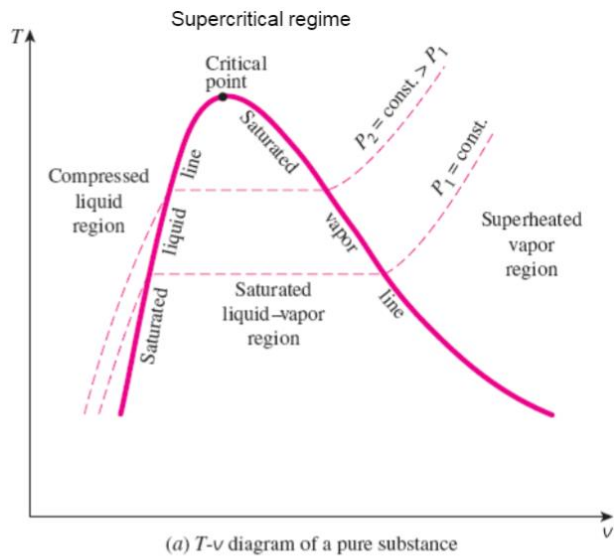
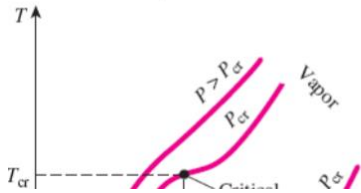
Critical point:

The point at which the saturated liquid and saturated vapour states are identical.

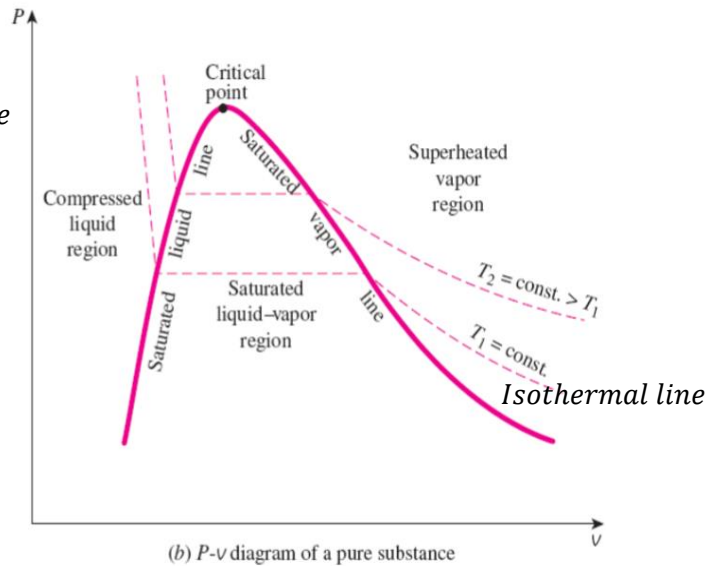
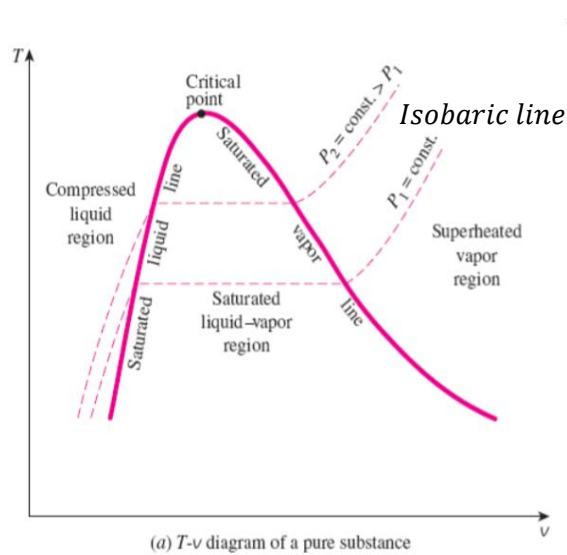


Phase Diagrams

- saturated liquid line
- saturated vapor line
- compressed liquid region
- superheated vapor region
- saturated liquid–vapor mixture region (wet region)
- Supercritical region



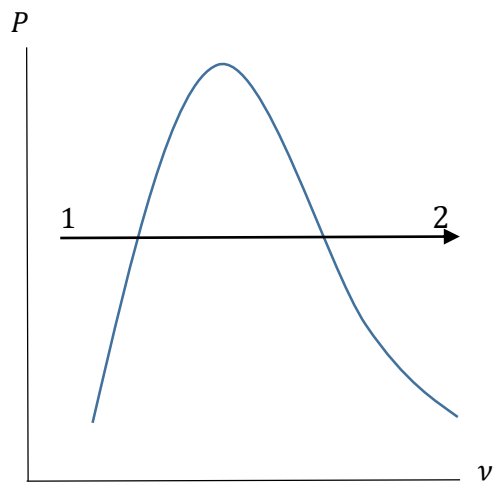
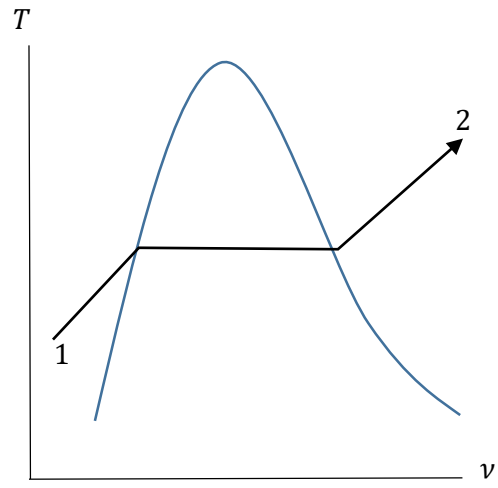
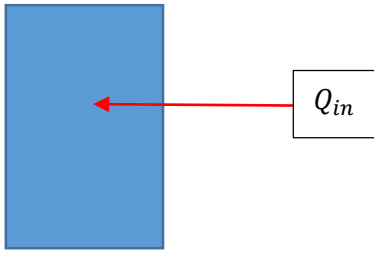
Pv and Tv Phase diagrams:



Notes: line left of critical is saturated liquid line; right is saturated vapour line

Example: drawing Pv ; Tv diagrams

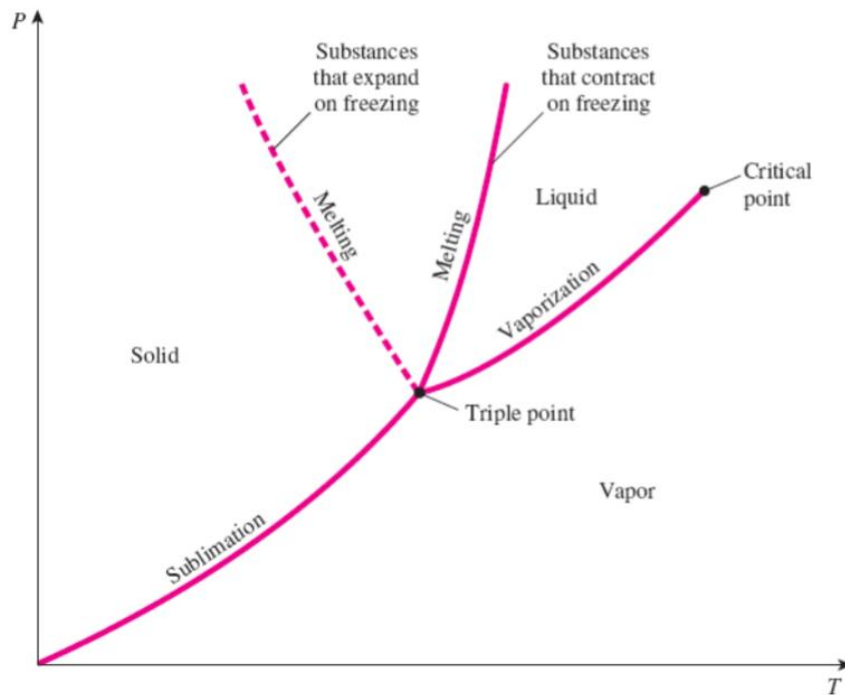
Constant pressure process; water; heat is added to water from a compressed liquid till the water is a superheated vapour. Show on $T - v$; $P - v$ diagrams. (Heat added, pressure constant)



Three phase diagrams:

PT diagram of pure substance:

P-T diagram of pure substances.



Triple point:

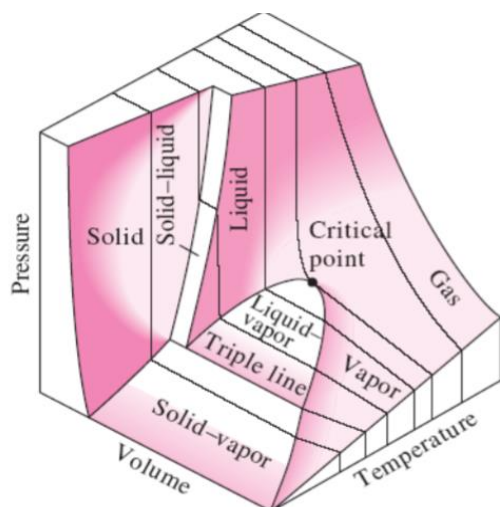
Critical point for 3 states (solid/liquid/gas coexist at same time)

Sublimation:

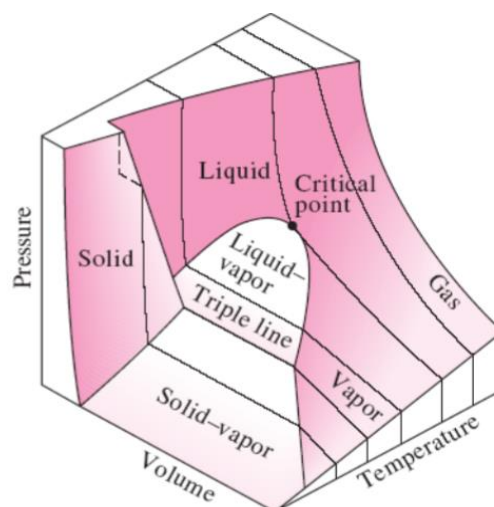
Sublimation: Passing from the solid phase directly into the vapor phase.

PvT surfaces:

Too much info on one diagram:



P-v-T surface of a substance that contracts on freezing.



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

Internal Energy:

Internal energy is the sum of all microscopic forms of energy related to molecular structure and activity (nuclear, thermal, electrical, etc)

Can be either Intensive:

$$u: \left(\frac{kJ}{kg}\right)$$

Extensive:

$$U \text{ (kJ)}$$

Enthalpy:

Enthalpy is internal energy + Pressure energy:

Intensive:

$$h = u + Pv \text{ Units: kJ/kg}$$

Extensive:

$$H = U + PV \text{ kJ}$$

Entropy:

- 2nd law of thermodynamics; associated as a measure of disorder

Intensive:

$$s: \text{kJ/kg} \cdot \text{K}$$

Extensive:

$$S: \text{kJ/K}$$

Saturated liquid-vapor mix:

We are given either pressure or temperature

We are given one of the following: v , u , h or s

Ratio of mass:

$$x = \frac{\text{mass of vapor}}{\text{total mass}} = \frac{m_g}{m_{total}}$$

$$\therefore m_t = m_f + m_g$$

Average specific volume

$$v_{av} = v_f + xv_{fg}$$

Volume:

$$V = v_{av}m_t$$

Average enthalpy/internal energy

$$u_{av} = u_f + xu_{fg}$$

$$h_{av} = h_f + xh_{fg}$$

Average quantity:

This works for any physical quantity:

$$y = y_{av} = y_f + xy_{fg} \quad (\text{where } y_{fg} = y_g - y_f)$$

Example: Saturated liquid-vapor mix

A rigid container contains 2 kg of vapor and 8 kg of liquid water at 90°C. Determine the volume of the container

Given: $T = 90^\circ\text{C}$

$$m_g = 2\text{kg}$$

$$m_f = 8\text{kg}$$

Assume a saturated mixture:

Determine $V_{\text{container}}$

$$V = v_{av} \times m_{\text{total}}$$

$$m_t = m_f + m_g = 10\text{kg}$$

$$v_{av} = v_f + xv_{fg} = v_f + \frac{m_g}{m_t}(v_g - v_f)$$

Saturated water temperature table A4:

$$v_f = 0.001836 \text{ m}^3/\text{kg}$$

$$v_g = 2.3593 \text{ m}^3/\text{kg}$$

$$\therefore v_{av} = 0.47269 \rightarrow V = 4.73 \text{ m}^3$$

Superheated vapour:

Compared to saturated vapor, superheated vapor is characterized by:

- Lower pressure ($P < P_{sat}$)
- Higher temperature ($T > T_{sat}$)
- Higher specific volume ($v > v_g$)
- Higher internal energy ($u > u_g$)
- Higher enthalpy ($h > h_g$)

Compressed liquids:

Compared to saturated vapor, superheated vapor is characterized by

- higher pressure ($P > P_{sat}$)
- lower temperature ($T < T_{sat}$)
- lower specific volume ($v < v_g$)

- lower internal energy ($u < u_g$)
- lower enthalpy ($h < h_g$)

The properties of compressed liquids vary strongly with temperature and in many cases negligibly with pressure

Compressed liquid property approximations:

$$y \approx y_{f@T}$$

So: the property $y = v, u, h$ can be approximated by using a saturated liquid property at same temperature

Tables

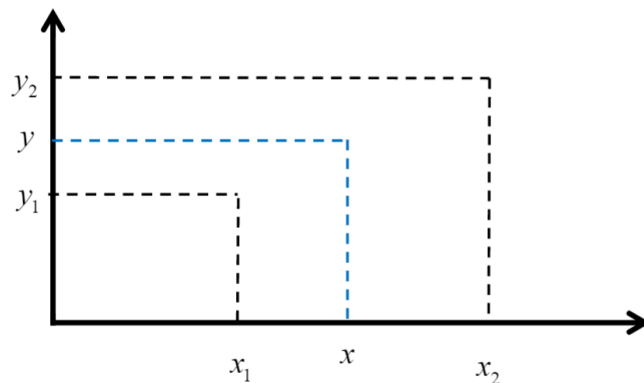
The values of $u, h, and s$ cannot be measured directly, and they are calculated from measurable properties using the relations between properties.

However, those relations give the changes in properties, not the values of properties at specified states.

Therefore, we need to **choose a convenient reference state and assign a value of zero** for a convenient property or properties at that state.

The reference state for water is 0.01°C and for R-134a is -40°C in tables. Some properties may have negative values as a result of the reference state chosen.

Interpolation/extrapolation:



$$y = mx + b$$

$$y = \frac{y_2 - y_1}{x_2 - x_1}(x - x_1) + y_1$$

Using tables examples:

- What is the difference between treating water at 100°C with the exact value and saturated conditions for the specific volume and internal energy at 5 MPa and 50 MPa?

- ANSWER:

Looking at table A4: pressure well above saturation pressure at 100C ∴ Compressed liquid

Approximating : $v_{CL} \approx v_{sat @T}$

$$v = 0.0010410 \frac{m^3}{kg}$$
$$u = 417.65 \frac{kJ}{kg}$$

Looking at table A7 for compressed liquids:

$$v = 0.00102 \frac{m^3}{kg}$$
$$u = 405.94 \frac{kJ}{kg}$$

∴ quite small % error

QUESTION 2:

Steam is at 750 kPa and 500°C, what is the entropy (s) of the steam?

Temperature above saturation pressure → Superheated vapour

| | T | s |
|---------|-----|-----|
| 600 kPa | | |
| 750 kPa | | |
| 800 kPa | | |

Processes and cycles:

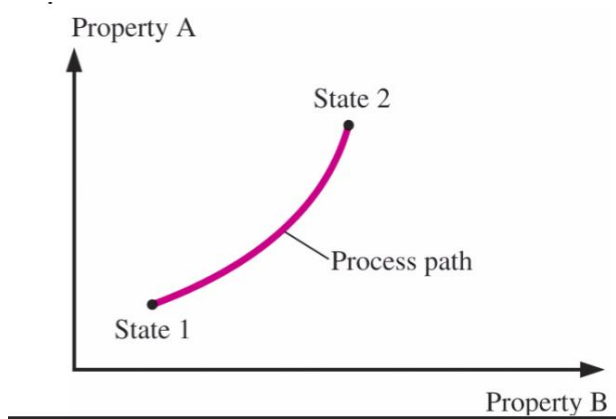
Process:

Any change that a system undergoes from one equilibrium state to another.

Path

The series of states through which a system passes during a process

To describe a process completely, one should specify the initial and final states, as well as the path it follows, and the interactions with the surroundings.



Quasistatic process:

When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times.

Nonquasistatic process

When a process proceeds very fast at that any instant the system state is far from equilibrium



(a) Slow compression
(quasi-equilibrium)



(b) Very fast compression
(nonquasi-equilibrium)

Isothermal process:

A process during which the temperature T remains constant.

Isobaric process:

A process during which the pressure P remains constant.

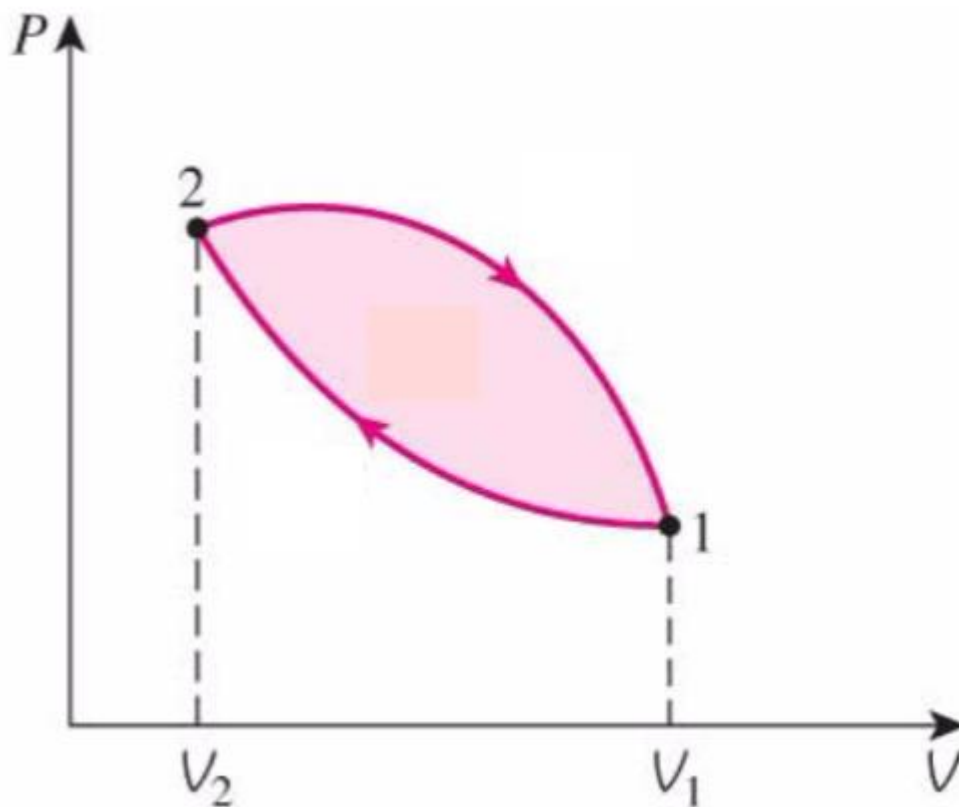
Isochoric (or isometric) process:

A process during which the specific volume v remains constant. Cycle: A process during which the initial and final states are identical.

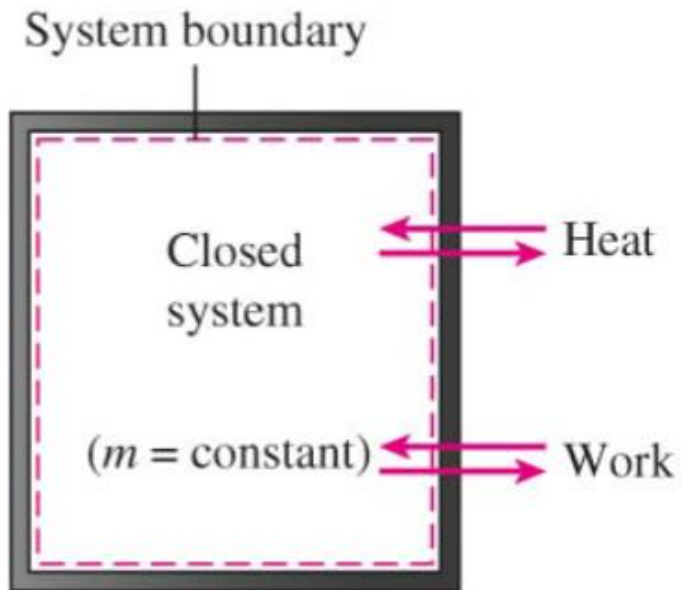
Cycle:

A process during which the initial and final states are identical.

Cycle diagram example:



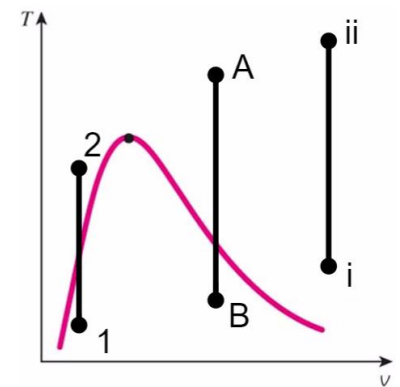
Example Process path: rigid container



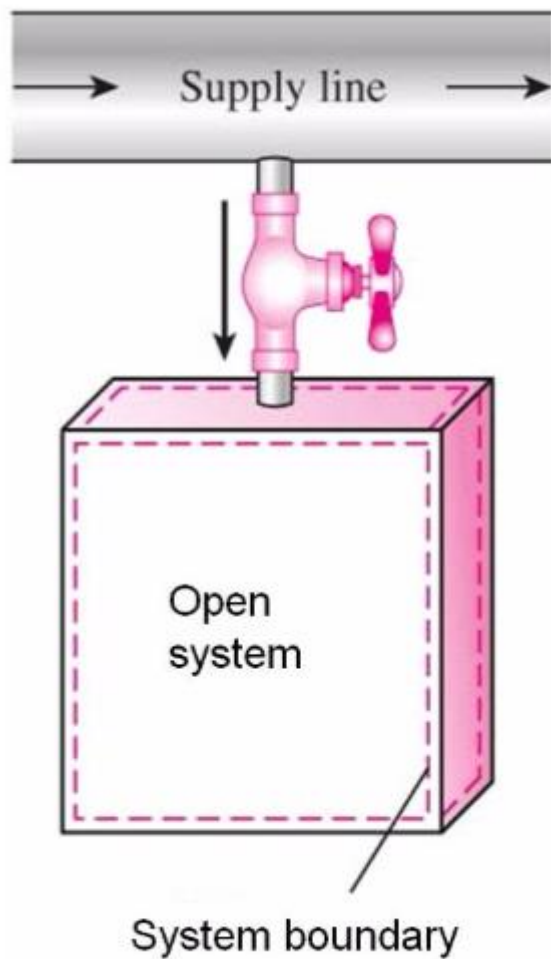
Isochoric process (as rigid container, with mass and volume staying same as control mass)

Therefore pressure and temperature not constant

\therefore vertical path on Tv or Pv diagram



Example 2: open system



As open system, not isochoric → pressure and temperature will be curves in Pv or Tv diagrams

Piston cylinder closed system example:

Closed system:

Volume not constant, mass constant, pressure constant if a free piston- no external pressure)

∴ Horizontal process in Pv diagram

Follows an isobar in Tv diagrams

Example: Process path in rigid container

A rigid container of volume 40 L contains water initially at a pressure of 10 kPa. Energy is added to the water until the pressure at the final state is 50 MPa.

1. Determine the initial and the final temperatures

$$V = 40L = 0.04m^3; P_1 = 10kPa; P_2 = 50MPa$$
$$m_{total} = 7kg \rightarrow v = \frac{0.04}{7}$$

table A5: $T_{sat@10kPa} = 45.81^\circ$
 $v_f = 0.00101; v_g = 14.67$
 \therefore as $v_g > v > v_f$ saturated liquid.
therefore $v = v_f + xv_{fg} \rightarrow x = 3.207 \times 10^{-4}$
 $\rightarrow u = u_f + xu_{fg} = 192.51 \frac{kJ}{kg}$

2. ii. Determine the percentage of the volume in the vapor phase at the initial and final state

$$\therefore V_{vap} = m_{total} x v_{vap} = 0.032932 \text{ m}^3$$

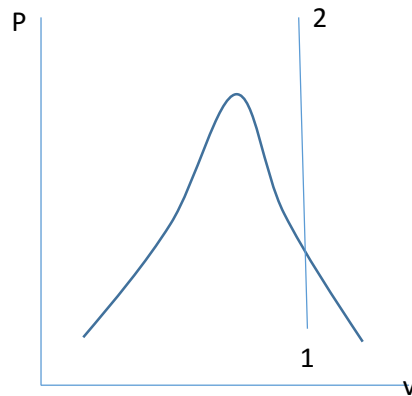
$$\therefore V_{vap} \% = \frac{0.0329}{0.04} = 82.3\%$$

3. iii. Determine the change in internal energy of the water through the process (in kJ).

$$P_2 = 50 \text{ MPa}; v_2 = v_1 = 0.0057132$$

$$P_{cr} = 22 \text{ MPa}; v_{cr} = 0.003106 \rightarrow \text{superheated vapour}$$

| T | v | u |
|--------|-----------|---------------|
| 550 | .005118 | 2769.5 |
| 580.12 | 0.0057143 | 2876.1 |
| 600 | 0.006108 | 2947.1 |



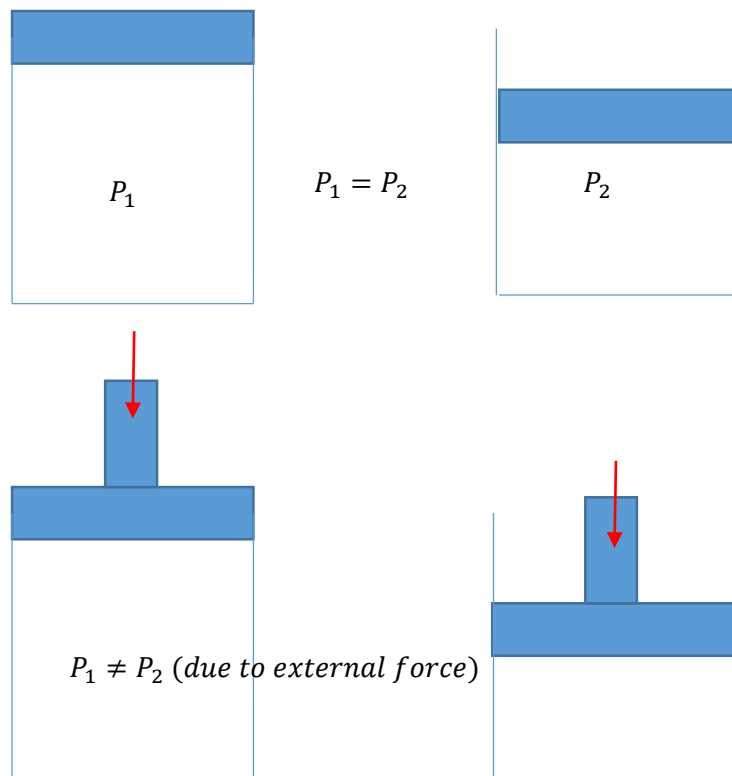
4. iv. Show the process on T-v and P-v diagrams with respect to the initial and final states and the saturation curve.

Example 2:

A rigid container of volume 60 000 cm³ contains water initially at a temperature of 53.1°C. Initially 61% of volume is in the vapor phase and remainder in the liquid phase. Energy is added to the water until the temperature at the final state is 440°C. i. Determine the initial and the final Pressures ii. Determine the percentage of the mass the vapor phase at the initial and final state iii. Determine the change in internal energy of the water through the process (in kJ). iv. Show the process on T-v and P-

v diagrams with respect to the initial and final states and the saturation curve. 5 A very difficult question with lots of interpolation: Final pressure close to 44.8 Mpa...

Process path: Piston cylinders



Compressibility factor:

Compressibility factor Z : A factor that accounts for the deviation of real gases from ideal-gas behavior at a given temperature and pressure.

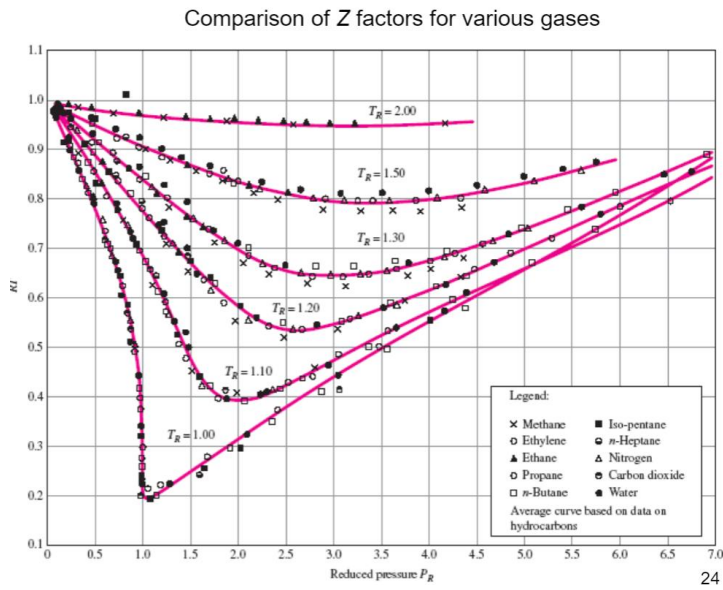
$$Z = \frac{v_{actual}}{v_{ideal}} = \frac{Pv}{RT}$$

for $Z \approx 1$; approximately ideal gas
 further Z is from away from 1, less ideal gas like

$$Pv = ZRT$$

NOTE: Z is not a fixed value.

The farther away Z is from unity, the more the gas deviates from ideal-gas behavior. Gases behave as an ideal gas at low densities (i.e., low pressure, high temperature).



Where

Reduced pressure:

$$P_R = \frac{P}{P_{CR}}$$

Reduced temperature

$$T_R = \frac{T}{T_{CR}}$$

Pseudo Reduced specific volume

$$v_R = \frac{v}{\left(\frac{RT_{CR}}{P_{CR}}\right)} = \frac{vP_{CR}}{RT_{CR}}$$