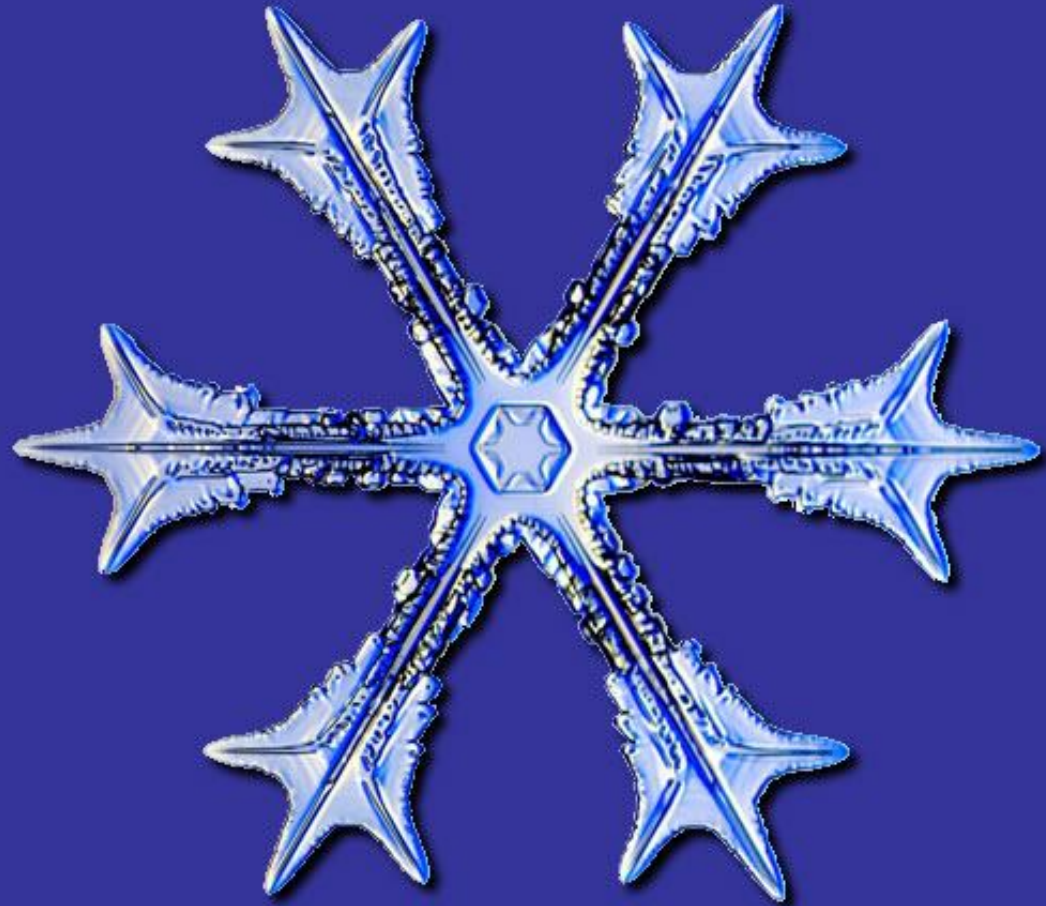


Thermodynamic Properties of Pure Substances




STATE PRINCIPLE

Any two independent intensive thermodynamic properties are sufficient to describe the state of a system containing a single pure substance.

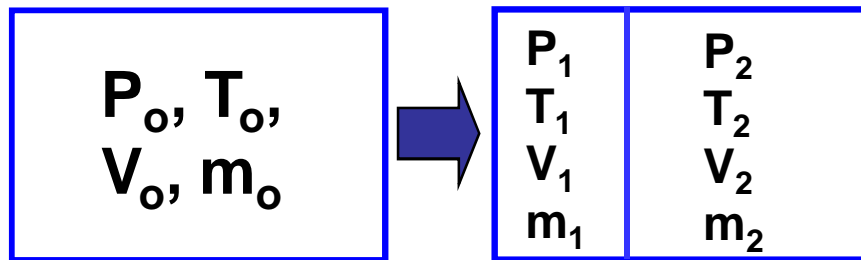
Table of Steam Properties

P (kPa)	T (°C)	v (m ³ /kg)
100	100	1.696
100	120	1.793
100	160	1.984



Intensive and Extensive Properties

- The value of an **extensive** property is **dependent** of the mass of the system.
- The value of an **intensive** property is **independent** of the mass of the system.
- Partition box



$P_0 = P_1 = P_2 \rightarrow$ **Intensive Prop**

$T_0 = T_1 = T_2 \rightarrow$ **Intensive Prop**

$V_0 \neq V_1 \neq V_2 \rightarrow$ **Extensive Prop**

$m_0 \neq m_1 \neq m_2 \rightarrow$ **Extensive Prop**

- Try specific volume:

$$v = V/m \rightarrow v_0 = v_1 = v_2 \rightarrow \text{Intensive Property}$$

Intensive and Extensive Properties

Property	Extensive	Intensive
Mass	m	-
Temperature	-	T
Pressure	-	P
Volume	V	$v = V/m$ (specific volume)
Internal Energy	U	$u = U/m$ (specific internal energy)
Enthalpy	H	$h = H/m$ (specific enthalpy)

- Any extensive property can be made intensive (specific) by dividing by mass.

Pure Substances

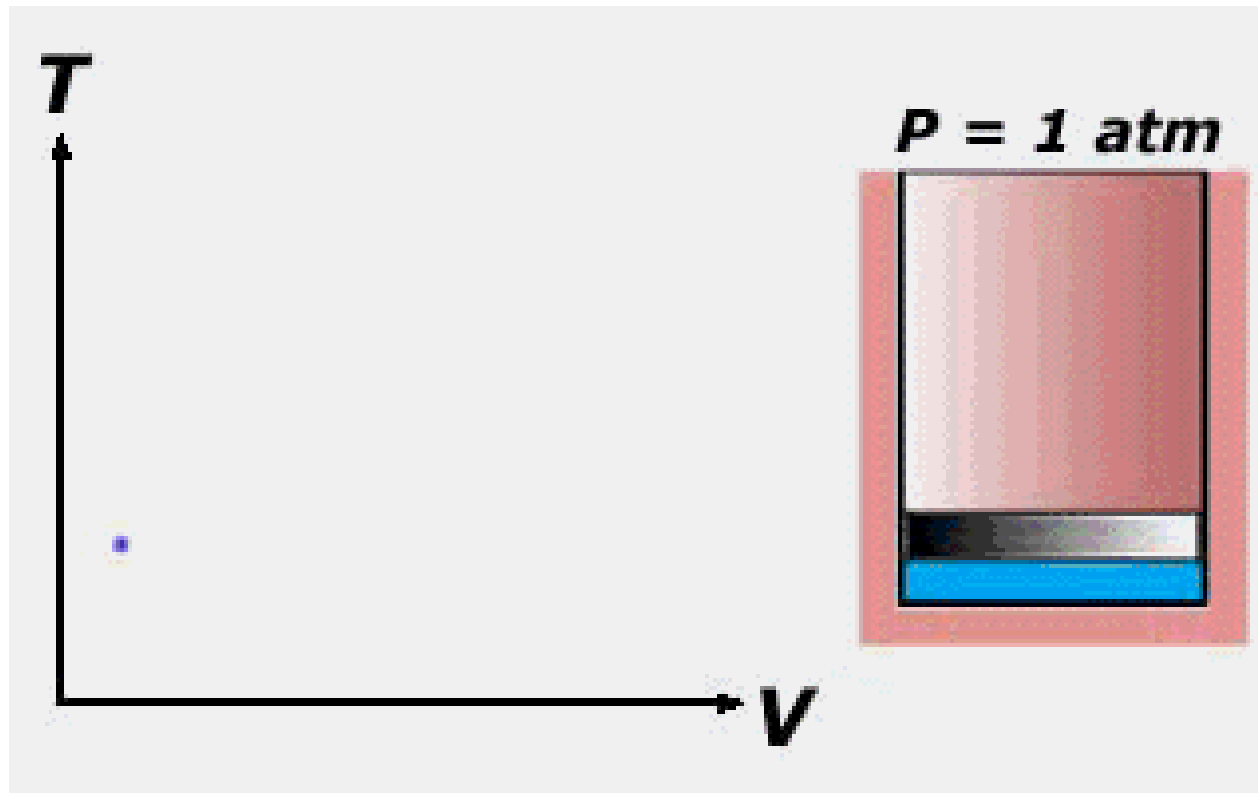
- Are composed of a single chemical species (e.g., either O_2 or CO_2 but not a mixture of O_2 and CO_2).
- May exist in more than one phase (e.g., solid and liquid)

A mixture of snow, ice, liquid water and water vapor is a pure substance.



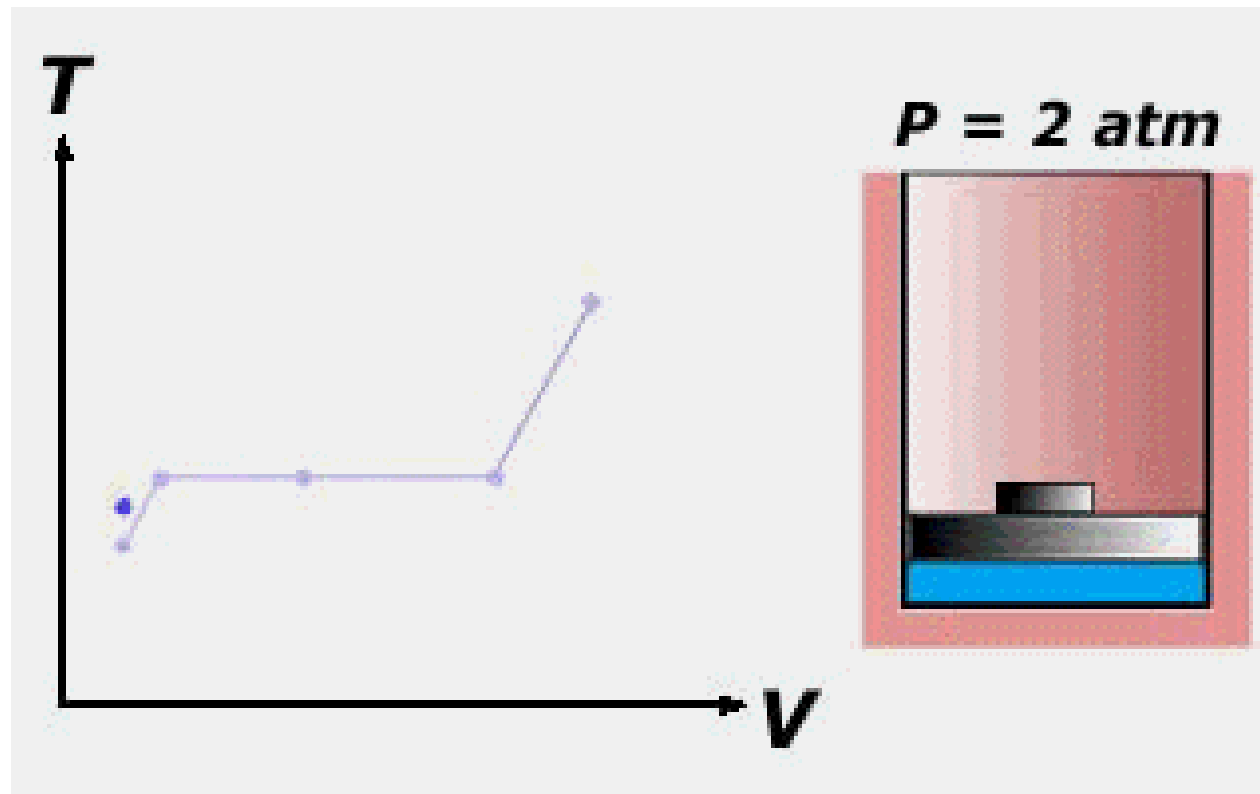
phase Change and P-v-T Surface

- **Constant Pressure Heating** in Piston-Cylinder at **$P = 1 \text{ atm}$**



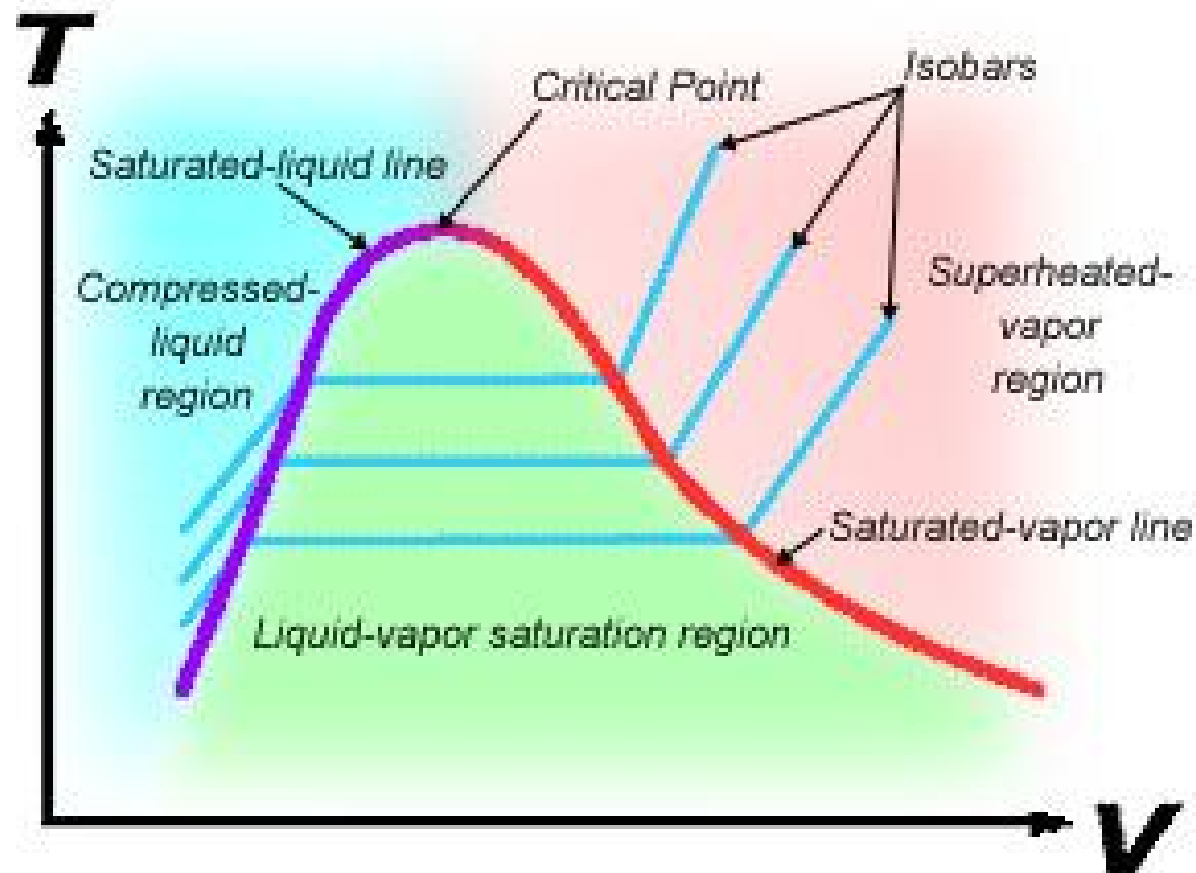
3.3.1 Phase Change and P-v-T Surface

- **Constant Pressure Heating** in Piston-Cylinder at $P = 2 \text{ atm}$



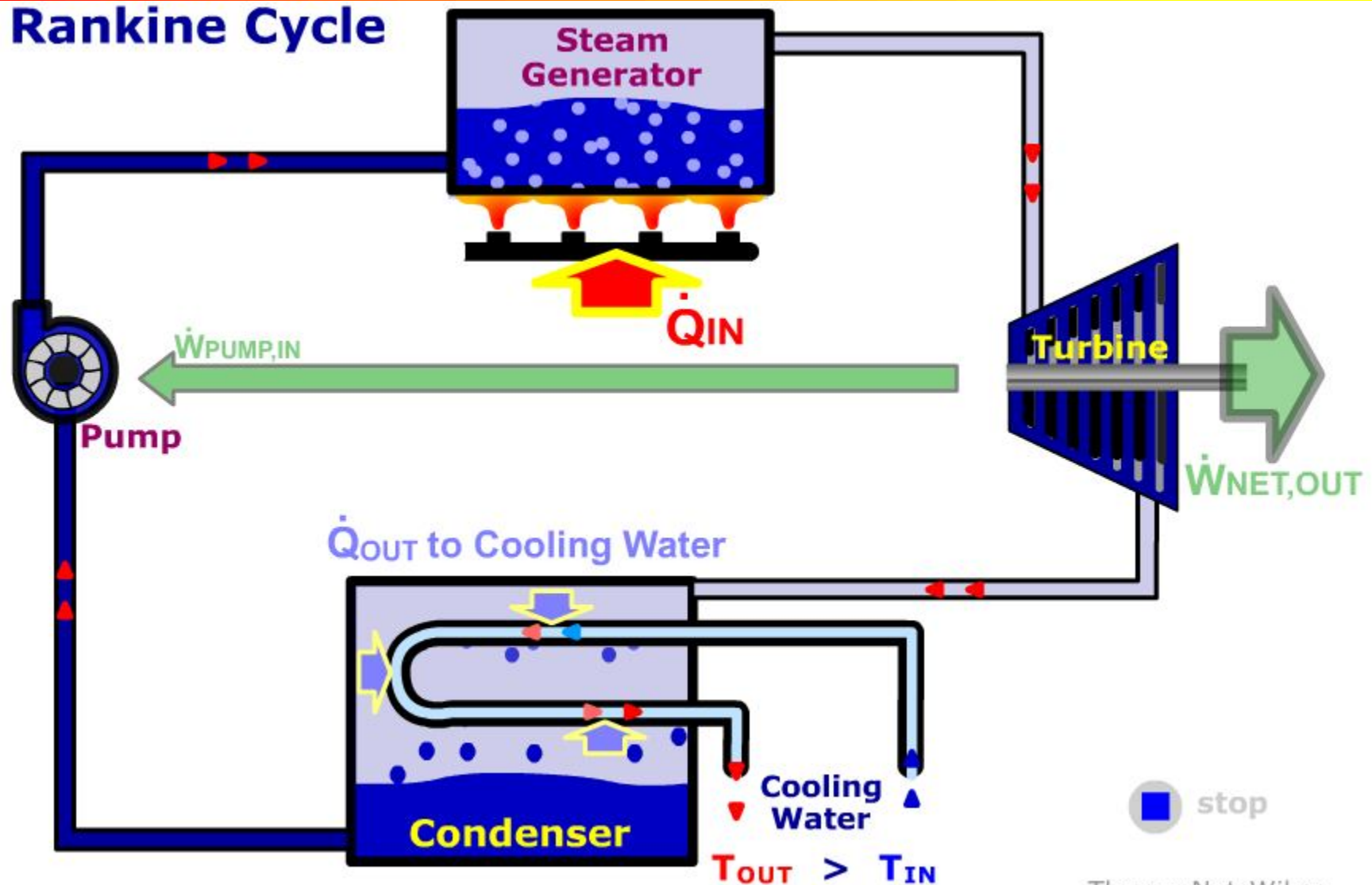
3.3.1 Phase Change and P-v-T Surface

- Regions on **T-v** Diagram
- Note directions of **Isobars**



3.3.1 Phase Change and P-v-T Surface

Rankine Cycle

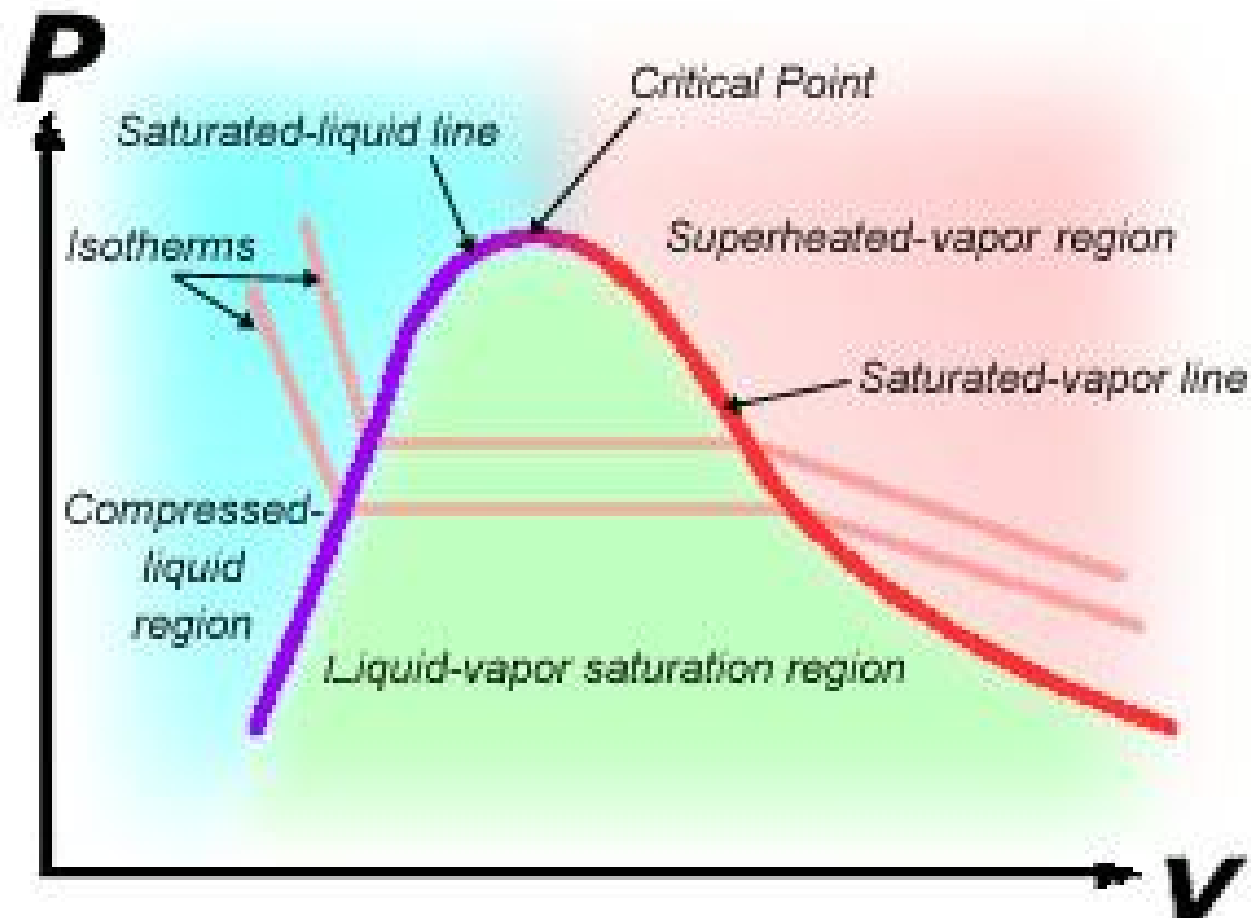


TN ANIMATION

ThermoNet: Wiley

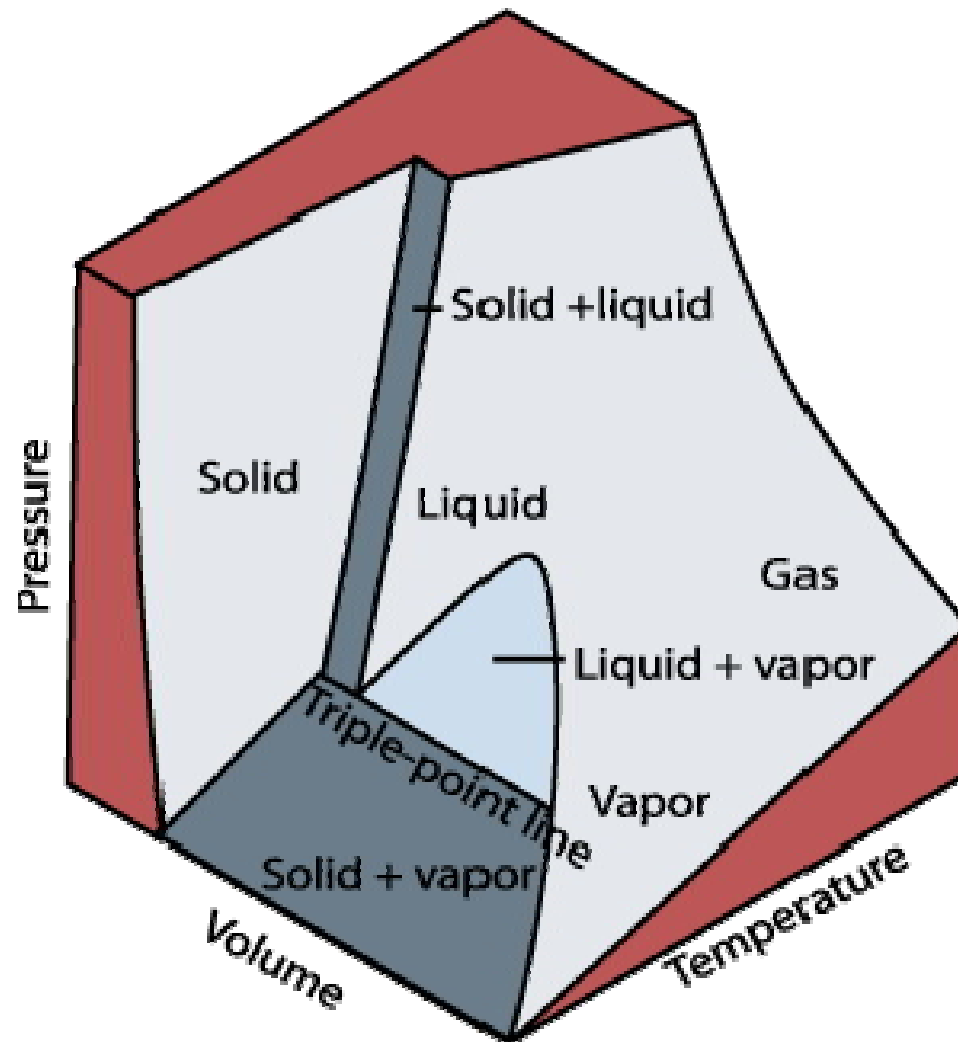
3.3.1 Phase Change and P-v-T Surface

- Regions on **P-v** Diagram
- Note directions of **Isotherms**



3.3.1 Phase Change and P-v-T Surface

- Three-Dimensional P-v-T Surface

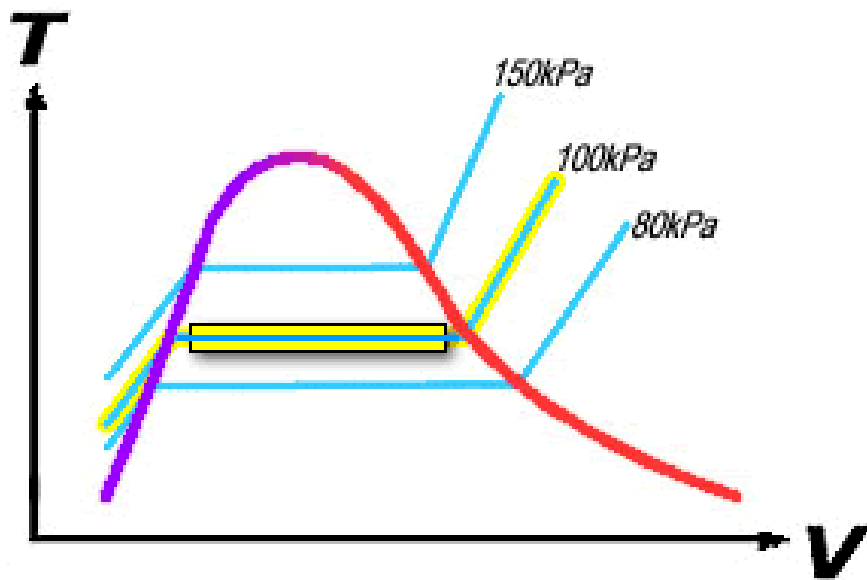


3.4 Liquid-Vapor Tables

- **For Ideal Gases (treated later):**
 - $Pv = RT$
 - Very simple and accurate relation
- **No similar relation exists for liquids, saturated liquid vapor mixtures or superheated vapors**
- **Typically superheated vapors do not obey the ideal gas law.**
- **Use data tabulated based on T and P**
 - Compressed Liquid Tables
 - Saturated Liquid-Vapor Tables
 - Superheated Vapor Tables

3.5 Saturation and Quality

- Property Notation (Subscripts):
 - **L = Saturated Liquid** (e.g., v_L and u_L)
 - **V = Saturated Vapor** (e.g., v_V and u_V)
 - **LV = Difference between saturated vapor and liquid values** (e.g., $v_{LV} = v_V - v_L$)
 - **SAT = Saturated Mixture** (T_{SAT} and P_{SAT})



Properties of Saturated Water - Press. Table (SI)

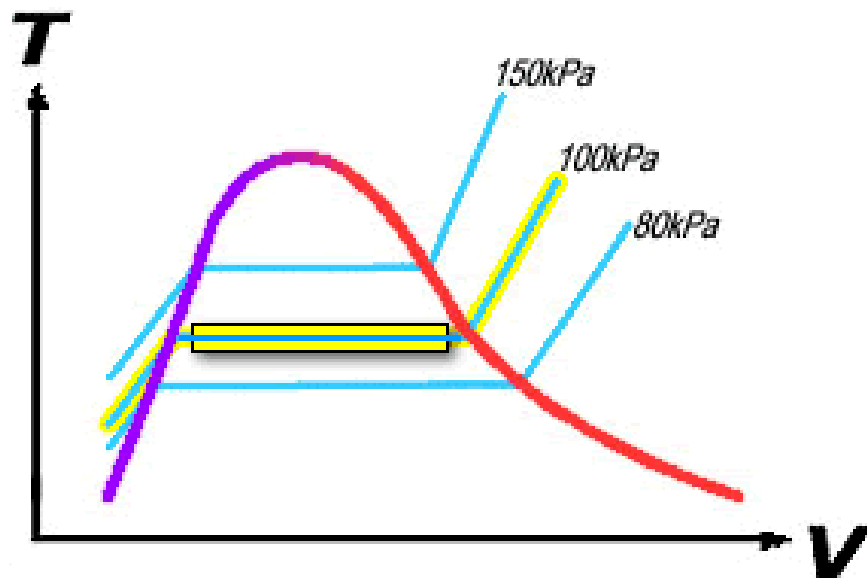
P kPa	T °C	Specific Volume, m ³ /kg		
		v_L	v_{LV}	v_V
80	93.511	0.001038	2.0866	2.0876
100	99.632	0.001043	1.6933	1.6943
150	111.38	0.001053	1.1584	1.1595

3.5 Saturation and Quality

- Quality (x):** Mass Fraction of Saturated Vapor

$$x = \frac{\text{mass of vapor}}{\text{total mass of mixture}} = \left(\begin{array}{c} \text{mass fraction} \\ \text{of vapor} \end{array} \right)$$

$$1 - x = \frac{\text{mass of liquid}}{\text{total mass of mixture}} = \left(\begin{array}{c} \text{mass fraction} \\ \text{of liquid} \end{array} \right)$$



Properties of Saturated Water - Press. Table (SI)

P kPa	T °C	Specific Volume, m ³ /kg		
		v _L	v _{LV}	v _V
80	93.511	0.001038	2.0866	2.0876
100	99.632	0.001043	1.6933	1.6943
150	111.38	0.001053	1.1584	1.1595

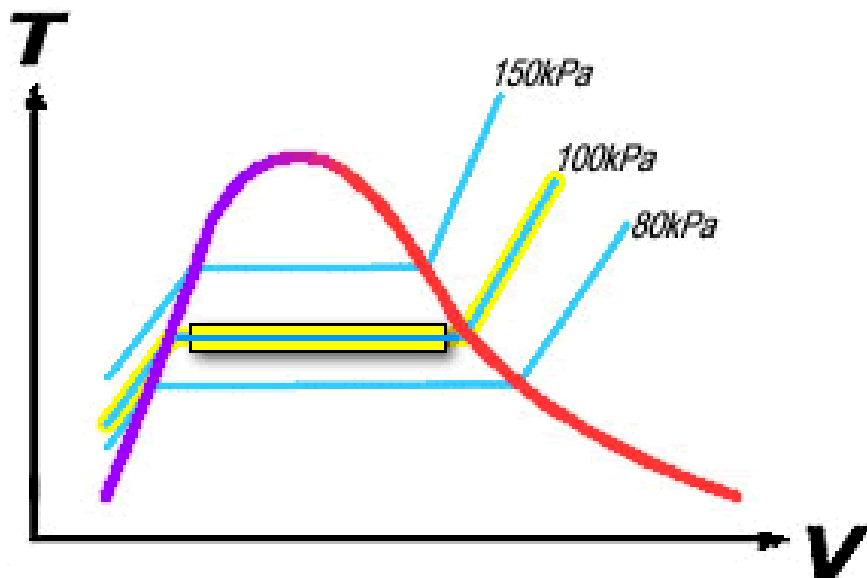
3.5 Saturation and Quality

- Specific Volume (v) of Saturated Liquid Vapor Mixture with quality x

$$v = v_L + xv_V$$

- Quality of Saturated Liquid Vapor Mixture with Specific Volume (v)

$$x = \frac{v - v_L}{v_V - v_L} = \frac{v - v_L}{v_{LV}}$$



Properties of Saturated Water - Press. Table (SI)

P kPa	T °C	Specific Volume, m ³ /kg		
		v_L	v_{LV}	v_V
80	93.511	0.001038	2.0866	2.0876
100	99.632	0.001043	1.6933	1.6943
150	111.38	0.001053	1.1584	1.1595

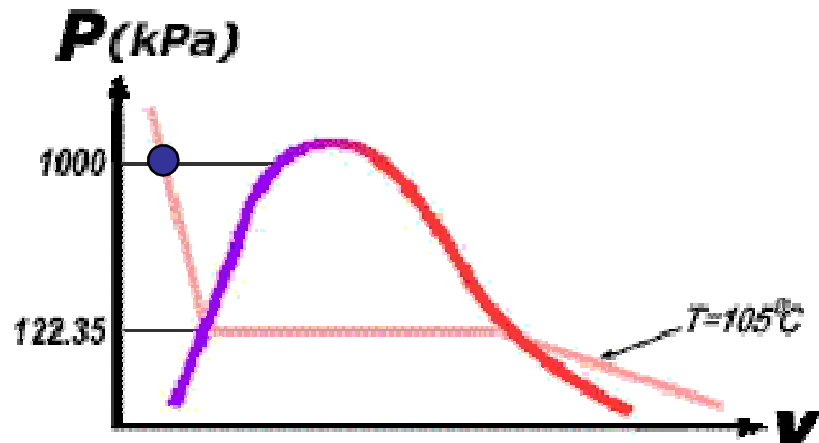
3.5 Saturation and Quality

- Determine Phase if:
 - $P = 100 \text{ kPa}$ and $v = 0.001000 \text{ m}^3/\text{kg}$
 - $P = 100 \text{ kPa}$ and $T = 100^\circ\text{C}$
 - $P = 100 \text{ kPa}$ and $v = 1.0000 \text{ m}^3/\text{kg}$

Properties of Saturated Water - Press. Table (SI)

P kPa	T $^\circ\text{C}$	Specific Volume, m^3/kg		
		v_L	v_{LV}	v_V
80	93.511	0.001038	2.0866	2.0876
100	99.632	0.001043	1.6933	1.6943
150	111.38	0.001053	1.1584	1.1595

3.6 Compressed (Subcooled) Liquids

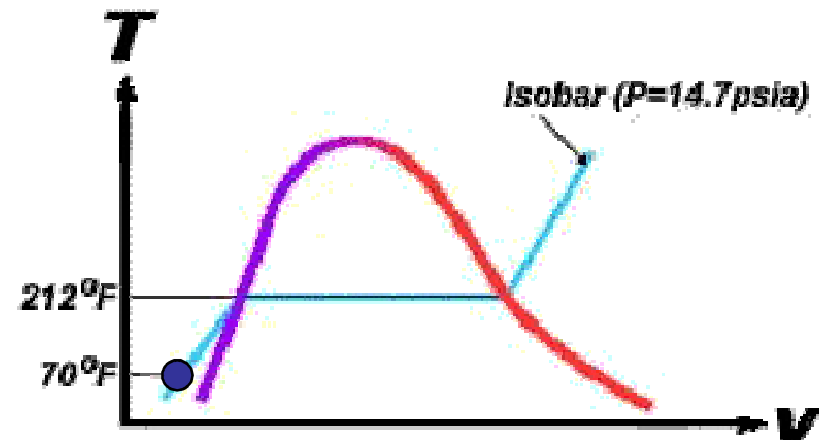


$P = 1000 \text{ kPa} \ \& \ T = 105^\circ\text{C}$

$P_{SAT}(105^\circ\text{C}) = 122.35 \text{ kPa}$

Since $P > P_{SAT}(T)$

→ **Compressed Liquid**



$T = 70^\circ\text{F} \ \& \ P = 14.7 \text{ psia}$

$T_{SAT}(14.7 \text{ psia}) = 212^\circ\text{F}$

Since $T < T_{SAT}(P)$

→ **Subcooled Liquid**

- Subscript **CL** = **Compressed Liquid**: e.g., v_{CL}

3.6 Incompressible Liquid Approx (ICL)

- $v_{CL}(70^{\circ}\text{C}, 5000 \text{ kPa}) = 0.001020 \text{ m}^3/\text{kg}$
- $v_L(70^{\circ}\text{C}) = 0.00102 \text{ m}^3/\text{kg}$
- $v_L(5000 \text{ kPa}) = 0.00129 \text{ m}^3/\text{kg}$
- $v_{CL}(T,P) \cong v_L(T) \rightarrow \text{ICL}$

Properties of Water in the **Compressed Liquid State (SI)**

P	T	v	u	h	s
kPa	$^{\circ}\text{C}$	m^3/kg	kJ/kg	kJ/kg	$\text{kJ}/(\text{kg}\cdot\text{K})$
5,000					
	50	0.001010	208.58	213.63	0.7014
	70	0.001020	291.97	297.07	0.9520

ThermoNet: Wiley

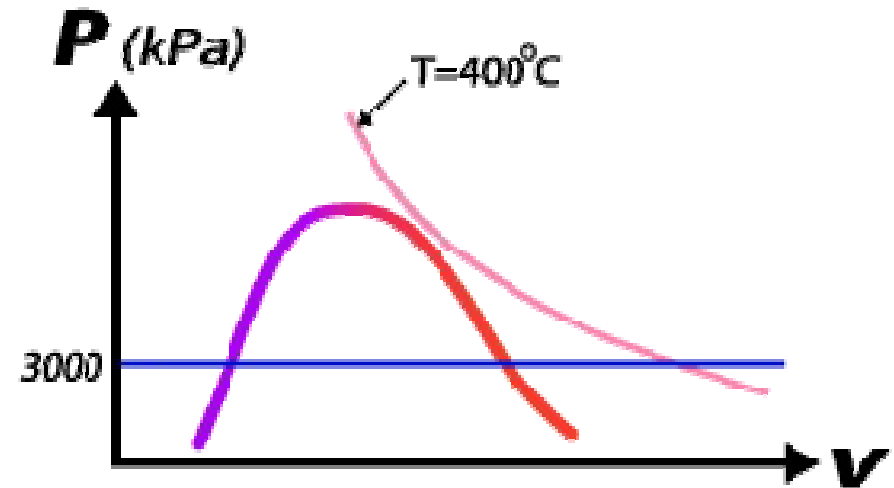
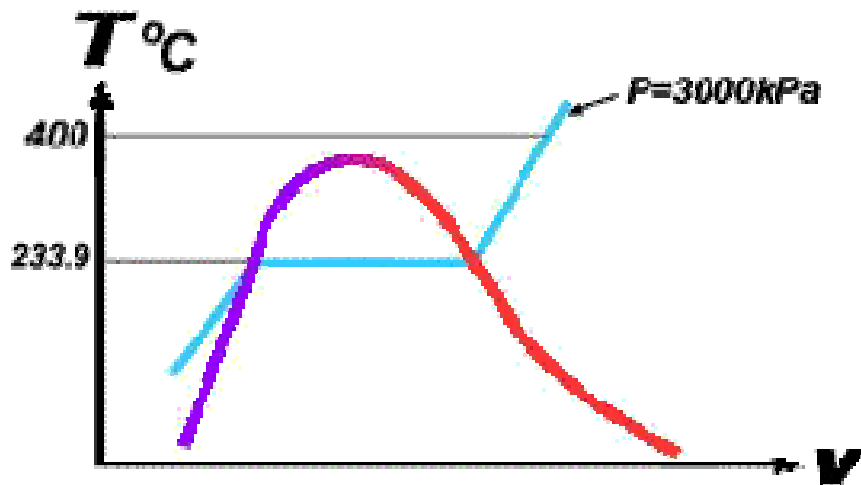
Properties of **Saturated Water (SI)**

T $^{\circ}\text{C}$	P kPa	Specific Volume, m^3/kg			Internal Energy, kJ/kg		
		v_L	v_{LV}	v_V	u_L	u_{LV}	u_V
70	31.18	0.00102	5.0437	5.045	292.98	2175.8	2468.8
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
264	5000	0.00129	0.03815	0.039	1147.8	1448.7	2596.5

3.6 Incompressible Liquid Approx (ICL)

- $v_{CL}(T,P) \cong v_L(T)$
- $u_{CL}(T,P) \cong u_L(T)$
- $h_{CL}(T,P) \cong h_L(T) + v_L(T) [P - P_{SAT}(T)]$
 - Recall $h = u + Pv \rightarrow h$ sensitive to P
 - If $P \cong P_{SAT}(T)$
 - $\rightarrow h_L(T) \gg v_L(T) [P - P_{SAT}(T)]$
 - $\rightarrow h_{CL}(T,P) \cong h_L(T)$

3.7 Superheated Vapor



$T = 400^{\circ}\text{C}$ & $P = 3000\text{ kPa}$

$T_{\text{SAT}}(3000\text{ kPa}) = 233.9^{\circ}\text{C}$

Since $T > T_{\text{SAT}}(P) \rightarrow$ **Superheated Vapor**

3.7 Superheated Vapor

Properties of Water in the Superheated Vapor State (SI)

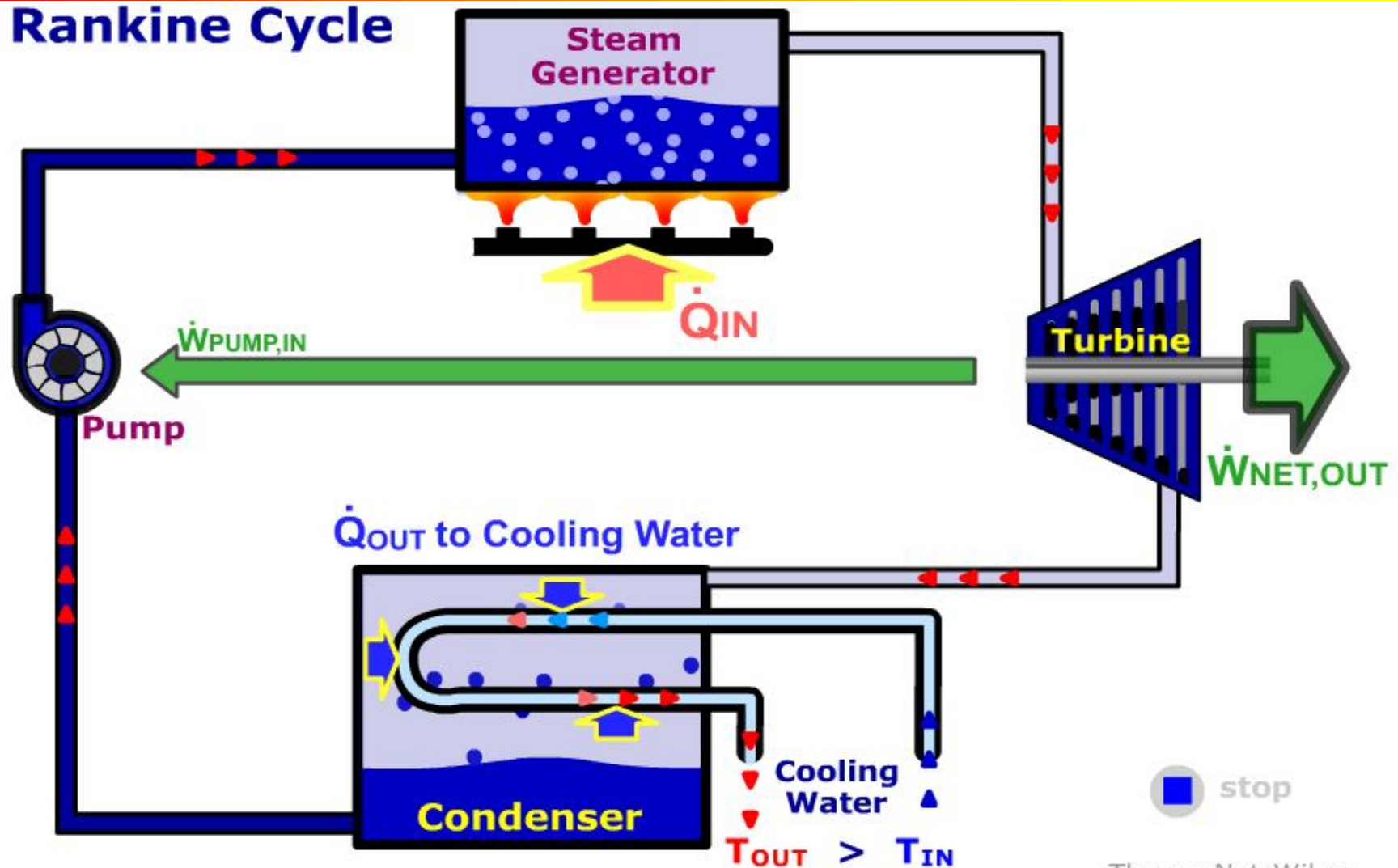
P	T	v	u	h	s
kPa	°C	m³/kg	kJ/kg	kJ/kg	kJ/(kg·K)
200	(120.24)	(0.8859)	(2529.4)	(2706.5)	(7.1272)
	150	0.9597	2576.7	2768.6	7.2793
	200	1.0803	2653.9	2870.0	7.5059
	250	1.1988	2730.8	2970.5	7.7078
300	(133.56)	(0.6059)	(2543.5)	(2725.3)	(6.9921)
	150	0.6339	2570.7	2760.9	7.0779
	200	0.7163	2650.2	2865.1	7.3108
	250	0.7963	2728.2	2967.1	7.5157

3.8 Gases

- Molecules are relatively far apart
- Do not feel one another's presence except during collisions
- Have a low density
- Are highly compressible
- In next two slides, compare
 - Liquid-Vapor working fluid in steam engine
 - Gas working fluid in gas turbine

3.8 Gases

Rankine Cycle

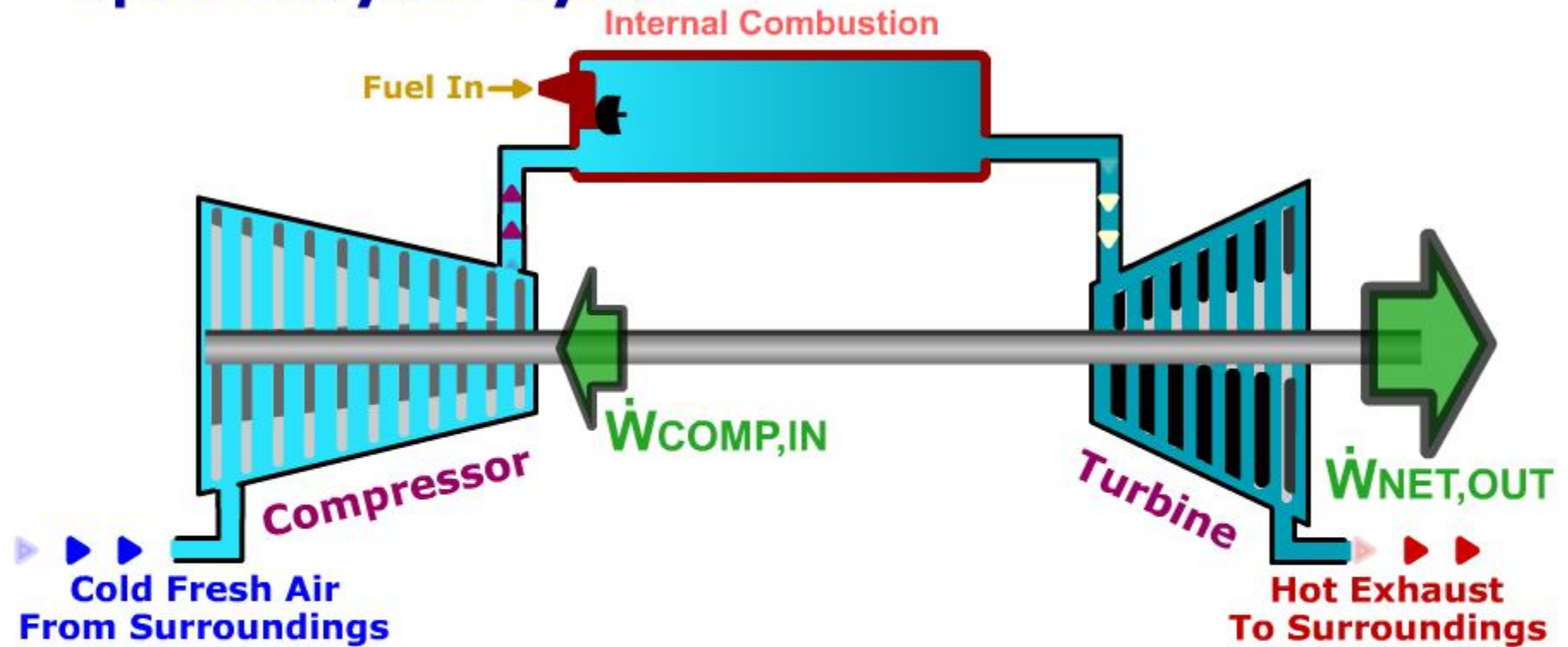


TN ANIMATION

ThermoNet:Wiley

3.8 Gases

Open Brayton Cycle



Open Brayton

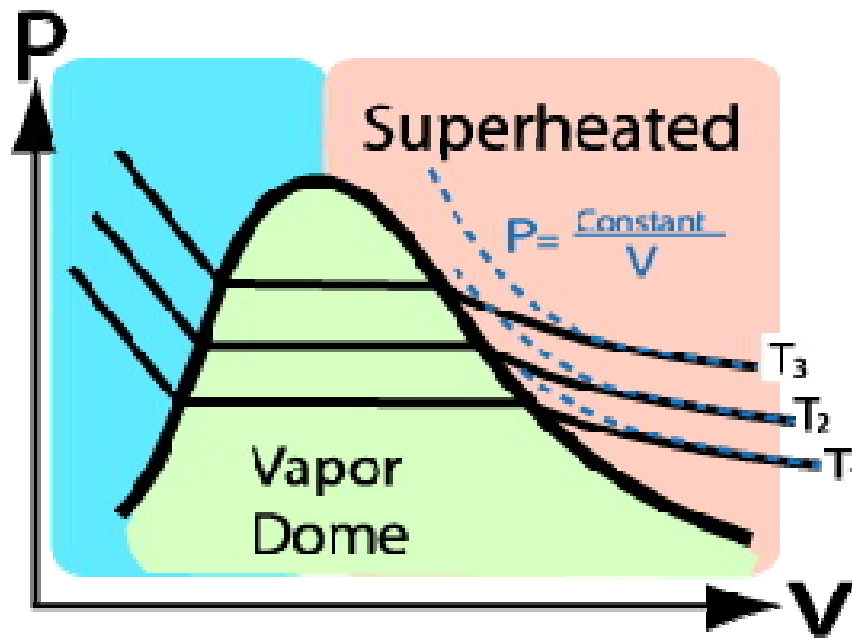
Closed Brayton



TN INTERACTIVE

ThermoNet: Wiley

3.9 Ideal Gas Law



$$PV = n\bar{R}T \quad \Leftrightarrow \quad n = \frac{m}{M}$$

$$PV = \frac{m}{M}\bar{R}T \quad \Leftrightarrow \quad \bar{R} = RM$$

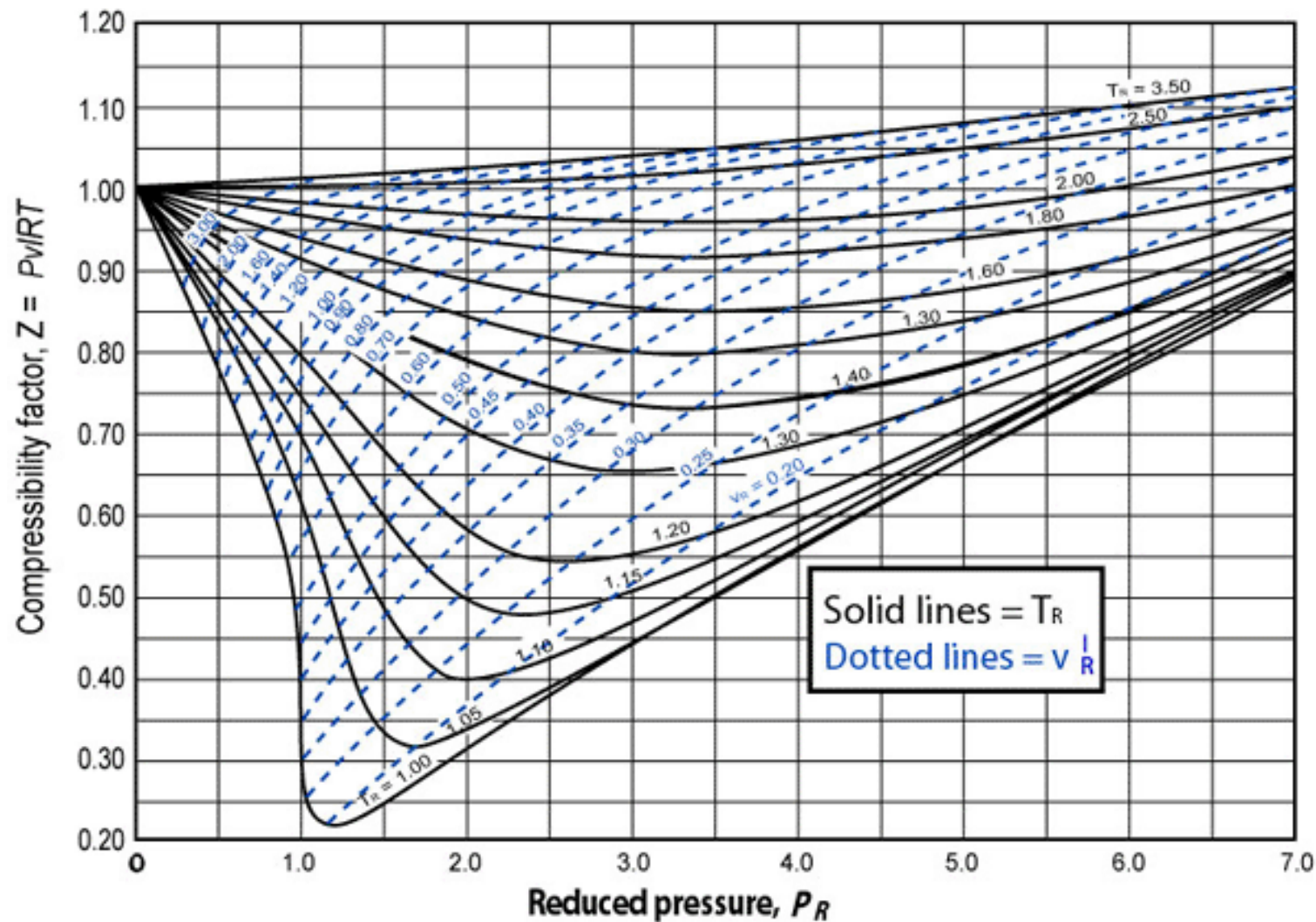
$$PV = mRT \quad \Leftrightarrow \quad v = \frac{V}{m}$$

$$Pv = RT$$

- **Universal Gas Constant (\bar{R}):** All gases have same value.
- **Particular Gas Constant (R):** Each gas has a unique value.

3.10 Compressibility Factor

- Use if not IGL and vapor tables not available



$$Z = \frac{Pv}{RT}$$
$$P_R = \frac{P}{P_{CR}}$$
$$T_R = \frac{T}{T_{CR}}$$

3.11 Other Equations of State

- **Van der Waals' equation**

$$P = \frac{RT}{v-b} - \frac{a}{v^2}$$

- **Redlich-Kwong Equation**

$$P = \frac{RT}{v - b_{RK}} - \frac{a_{RK}}{v(v + b_{RK}) T^{1/2}}$$

- **Benedict-Webb-Rubin Equation of State**

$$P = \frac{RT}{v} + (B_0 RT - A_0 - \frac{C_0}{T^2}) \left(\frac{1}{v^2} \right) + \frac{(bRT - a)}{v^3} + \frac{\alpha a}{v^6} + c \frac{1 + \gamma / v^2}{v^3 T^2} \exp \left(\frac{-\gamma}{v^2} \right)$$

- **Virial Equation of State**

$$P = \frac{RT}{v} \left(1 + \frac{B}{v} + \frac{C}{v^2} + \dots \right)$$

3.12 Internal Energy and Enthalpy

- Internal Energy
 - If not an ideal gas, $u = u(T, P)$
 - If **ideal gas**, $u = u(T) \neq u(P)$
- Enthalpy
 - Recall $h = u + Pv$
 - For an **Ideal Gas**, $Pv = RT \rightarrow h = u(T) + RT$
 - Therefore for **ideal gas**, $h = h(T) \neq h(P)$
- T, u and h are dependent properties for ideal gases

3.13 Heat Capacities and Specific Heats

- Approximately,

$$C = \frac{\Delta \text{Energy}}{\Delta T}$$

- Heat capacity (C_V) and specific heat capacity (c_V) for constant volume process**

$$C_V = \left(\frac{\partial U}{\partial T} \right)_V \quad \text{and} \quad c_V = \left(\frac{\partial u}{\partial T} \right)_V$$

- Heat capacity (C_P) and specific heat capacity (c_P) for constant pressure process**

$$C_P = \left(\frac{\partial H}{\partial T} \right)_P \quad \text{and} \quad c_P = \left(\frac{\partial h}{\partial T} \right)_P$$

3.13 Specific Heats for Ideal Gases

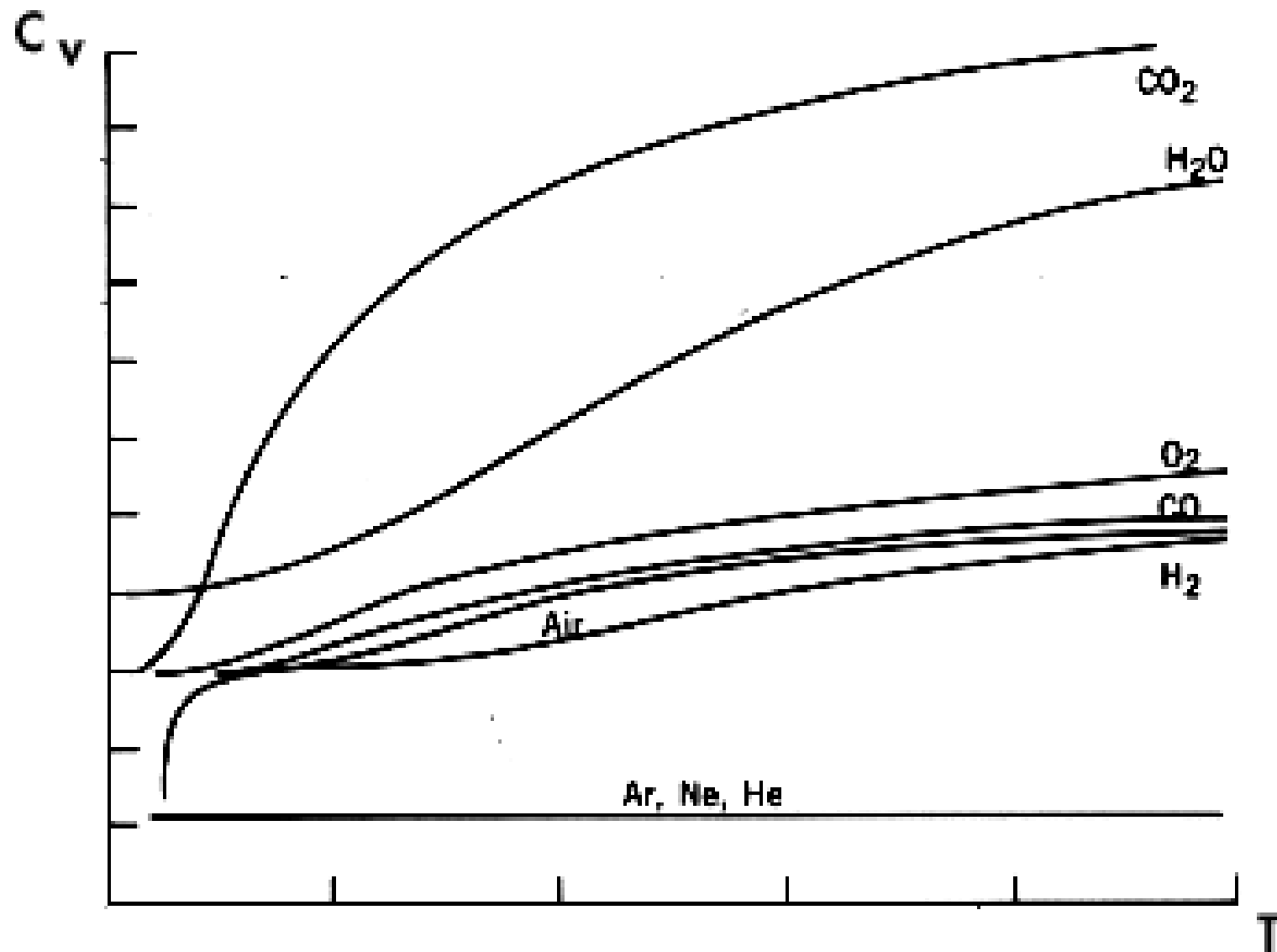
- For an **ideal gas**, $h = h(T) \neq h(P)$ and

$$c_P = \left(\frac{\partial h}{\partial T} \right)_P = \frac{dh}{dT} \quad \Rightarrow \quad \Delta h = \int_{T_1}^{T_2} c_P dT \quad \underline{\underline{\text{Always}}}$$

- Similarly, for **ideal gas** $u = u(T) \neq u(V)$ and

$$c_V = \left(\frac{\partial u}{\partial T} \right)_V = \frac{du}{dT} \quad \Rightarrow \quad \Delta u = \int_{T_1}^{T_2} c_V dT \quad \underline{\underline{\text{Always}}}$$

3.13 Specific Heats for Ideal Gases



3.13 Specific Heats for Ideal Gases

$$\Delta u = \int_{T_1}^{T_2} c_v dT \qquad \Delta h = \int_{T_1}^{T_2} c_p dT$$

- $R = c_p - c_v$
- For monatomic gases (e.g., He, Ar, Ne)
 - $c_v = 3R/2 = \text{Constant}$
 - $c_p = 5R/2 = \text{Constant}$
- $\Delta u = c_v \Delta T$ **only if $c_v = \text{constant}$**
- $\Delta h = c_p \Delta T$ **only if $c_p = \text{constant}$**

3.13 Specific Heats for Solids and Liquids

- For **incompressible solids and liquids**,
 - $C_P = C_V$
 - Sometimes denoted as c

$$\Delta u = \Delta h = \int_{T_1}^{T_2} c dT$$

3.14 Ideal Gas Tables

- Unlike steam tables, pressure not tabulated
- Use $Pv = RT$ to relate P , v and T
- Use tables to relate T , u and h

3.15 Some Other Thermodynamic Properties

- **Isothermal Compressibility (κ)**

$$\kappa = -\frac{1}{V} \left(\frac{\partial V}{\partial P} \right)_T$$

- **Coefficient of Thermal Expansion (β)**

$$\beta = \frac{1}{V} \left(\frac{\partial V}{\partial T} \right)_P$$

$$\frac{dV}{V} = \beta dT - \kappa dP$$

- **Joule Thompson Coefficient (μ)**

$$\mu = \left(\frac{\partial T}{\partial P} \right)_h$$