Thermodynamics
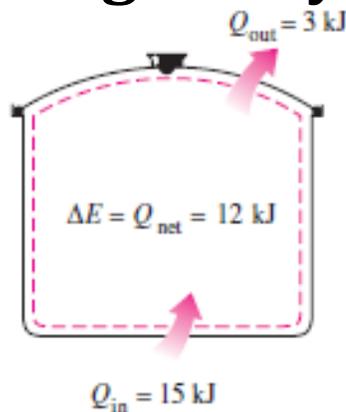## ENGR360-MEP112

LECTURE 4

Objectives:

1. **Introduce the first law of thermodynamics (energy balance).**

2. **Mechanisms of energy transfer in open and closed systems.**

3. **Energy conversion efficiency.**

4. **The concept of a pure substance.**

5. **The physics of phase-change processes.**

6. **p-*v*, T-*v*, and p-T property diagrams.**

THE FIRST LAW OF THERMODYNAMICS

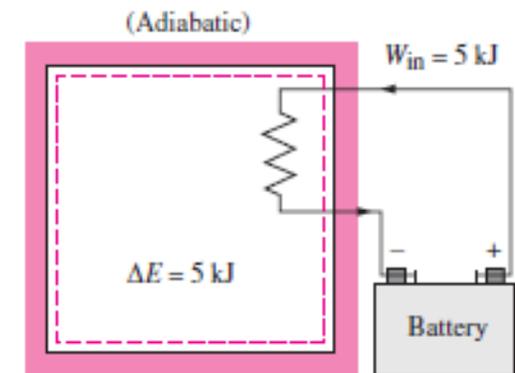❑ **The first law of thermodynamics, also known as the conservation of energy principle.**

❑ **Energy Balance**

$$\left(\begin{array}{c} \text{Total energy} \\ \text{entering the system} \end{array}\right) - \left(\begin{array}{c} \text{Total energy} \\ \text{leaving the system} \end{array}\right) = \left(\begin{array}{c} \text{Change in the total} \\ \text{energy of the system} \end{array}\right)$$

$Q_{out} = 3 \text{ kJ}$

$\Delta E = Q_{net} = 12 \text{ kJ}$

$$\boxed{E_{in} - E_{out} = \Delta E_{system}}$$

$Q_{in} = 15 \text{ kJ}$

In the absence of any work interactions, the energy change of a system is equal to the net heat transfer.

(Adiabatic)

$W_{in} = 5 \text{ kJ}$

$\Delta E = 5 \text{ kJ}$

Battery

The work (electrical) done on an adiabatic system is equal to the increase in the energy of the system.

THE FIRST LAW OF THERMODYNAMICS

❑ **Energy Change of a System, ΔE_{system}**

Energy change = Energy at final state - Energy at initial state

$$\Delta E_{system} = E_{final} - E_{initial} = E_2 - E_1$$

$$\Delta E_{system} = \Delta U + \Delta KE + \Delta PE$$

$$\Delta U = m(u_2 - u_1)$$

$$\Delta KE = \frac{1}{2}m(v_2^2 - v_1^2)$$

$$\Delta PE = mg(z_2 - z_1)$$

THE FIRST LAW OF THERMODYNAMICS

❑ **Mechanisms of Energy Transfer, E_{in} and E_{out}**

Energy can only transfer through the system _boundary_ in the form of:

Heat Transfer	• Heat gain (Q_{in}) • Heat loss (Q_{out})
Work Transfer	• Work done on the system (W_{in}) • Work done by the system (W_{out})
Mass Transfer	• Mass enters the system ($E_{mass,in}$) • Mass leaves the system ($E_{mass,out}$)

THE FIRST LAW OF THERMODYNAMICS

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out})$$

where the subscripts "**in**" and "**out**" denote quantities that **enter** and **leave** the system, respectively. All six quantities on the right side of the equation represent "**amounts**," *and thus they are positive quantities*. *The direction of any energy transfer is described by the subscripts "in" and "out"*.

THE FIRST LAW OF THERMODYNAMICS

❑ Energy Balance for closed system

$$\left(\begin{array}{c}\textbf{Total energy} \\ \textbf{entering the system}\end{array}\right) - \left(\begin{array}{c}\textbf{Total energy} \\ \textbf{leaving the system}\end{array}\right) = \left(\begin{array}{c}\textbf{Change in the total} \\ \textbf{energy of the system}\end{array}\right)$$

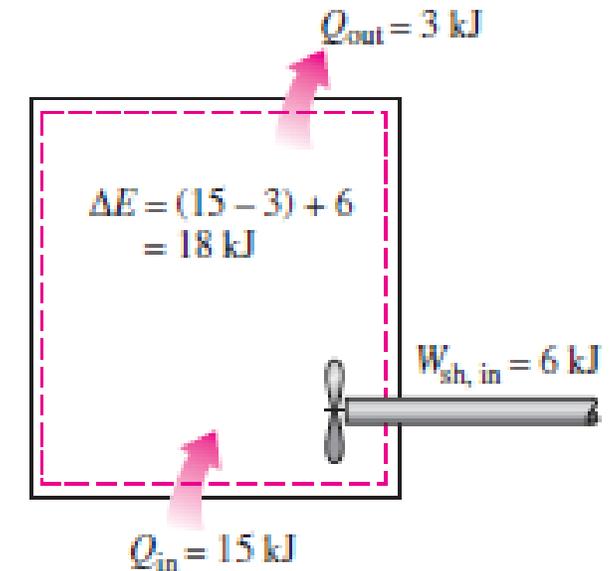$$\boxed{E_{in} - E_{out} = \Delta E_{system}}$$

$$\boxed{\left(Q_{in} - Q_{out}\right) + \left(W_{in} - W_{out}\right) = \Delta U + \Delta KE + \Delta PE}$$

For stationary systems:

$$\boxed{(Q_{in} - Q_{out}) + (W_{in} - W_{out}) = \Delta U}$$

For stationary and adiabatic systems:

$$\boxed{(W_{in} - W_{out}) = \Delta U}$$

$Q_{out} = 3\ \text{kJ}$

$\Delta E = (15-3)+6$
$= 18\ \text{kJ}$

$W_{sh,\ in} = 6\ \text{kJ}$

$Q_{in} = 15\ \text{kJ}$

The energy change of a system during a process is equal to the *net* work and heat transfer between the system and its surroundings.
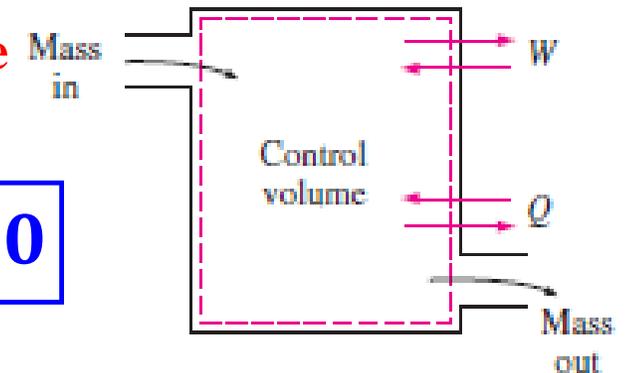
THE FIRST LAW OF THERMODYNAMICS

❏ Energy Balance for open system

$$\begin{pmatrix} \text{Total rate of energy} \\ \text{entering the system} \end{pmatrix} - \begin{pmatrix} \text{Total rate of energy} \\ \text{leaving the system} \end{pmatrix} = \begin{pmatrix} \text{Change in the total} \\ \text{rate of energy of the system} \end{pmatrix}$$

$$\dot{E}_{in} - \dot{E}_{out} = \frac{dE_{system}}{dt}$$

Zero, for steady-state steady-flow process

Mass in — W

Control volume

Q

Mass out

$$\left(\dot{Q}_{in} - \dot{Q}_{out}\right) + \left(\dot{W}_{in} - \dot{W}_{out}\right) + \left(\dot{E}_{mass,in} - \dot{E}_{mass,out}\right) = 0$$

Or

$$\dot{Q}_{in} + \dot{W}_{in} + \dot{E}_{mass,in} = \dot{Q}_{out} + \dot{W}_{out} + \dot{E}_{mass,out}$$

The energy content of a control volume can be changed by mass flow as well as heat and work interactions.

THE FIRST LAW OF THERMODYNAMICS

Example:

A fan that consumes **9 W** of electric power when operating. It is claimed to discharge air at a rate of **0.5 kg/s** at a discharge velocity of **8 m/s**. Determine if this claim is reasonable.

$$\dot{Q}_{in} + \dot{W}_{in} + \dot{E}_{mass,in} = \dot{Q}_{out} + \dot{W}_{out} + \dot{E}_{mass,out}$$

$$0 + 9 + 0 = 0 + 0 + \dot{m}\frac{v^2}{2}$$

$$9 = 0.5\frac{v^2}{2} \qquad\qquad \therefore v = 6 \text{ m/s}$$

Therefore, the claim is <u>false</u>.

THE FIRST LAW OF THERMODYNAMICS

For a **closed system** undergoing a **cycle**, the initial and final states are identical, and thus, $\Delta E_{system} = E_2 - E_1 = 0$
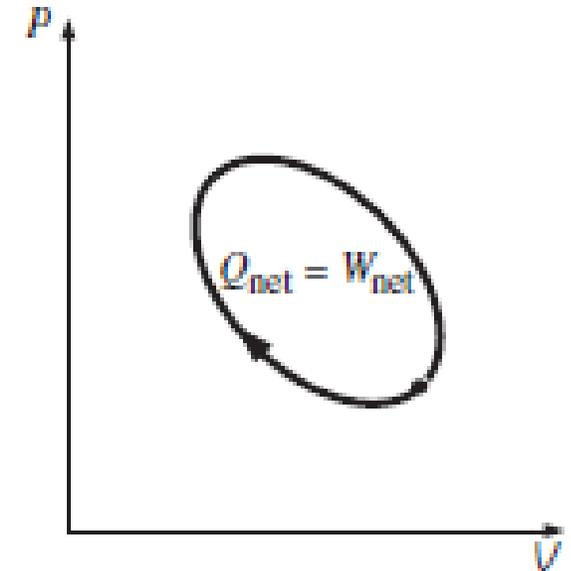
Then the energy balance for a cycle simplifies to:

$$E_{in} = E_{out} = 0 \quad \text{Or} \quad E_{in} = E_{out}$$

$$(Q_{in} - Q_{out}) = (W_{in} - W_{out})$$

$$\boxed{Q_{net} = W_{net}}$$

Similarly, for a **open system** undergoing a **cycle**:

$$\boxed{\dot{Q}_{net} = \dot{W}_{net}}$$

ENERGY CONVERSION EFFICIENCY

$$\text{Efficiency } (\eta) = \frac{\text{Useful output}}{\text{Total input}}$$

❑ **Pump efficiency:**

$$\eta_p = \frac{\text{Net change in power potential of the fluid}}{\text{Mechanical power input}}$$

$$\eta_p = \frac{\Delta \dot{E}_{mech}}{\dot{W}_{shaft}} = \frac{\dot{m}\left[\dfrac{p_2 - p_1}{\rho} + \dfrac{v_2^2 - v_1^2}{2} + g(z_2 - z_1)\right]}{\text{Mechanical power input}}$$

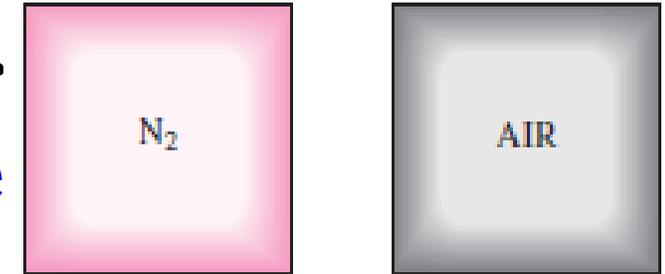# THE FIRST LAW OF THERMODYNAMICS

❑ **Turbine efficiency:**

$$\eta_t = \frac{\text{Mechanical power output}}{\text{Net change in power potential of the fluid}}$$

$$\boxed{\eta_t = \frac{\dot{W}_{shaft}}{\Delta \dot{E}_{mech}} = \frac{\text{Mechanical power output}}{\dot{m}\left[\dfrac{p_1 - p_2}{\rho} + \dfrac{v_1^2 - v_2^2}{2} + g(z_1 - z_2)\right]}}$$

1. PURE SUBSTANCE

❑ **A substance that has a fixed chemical composition is called a pure substance. Water is a pure substance.**

❑ **A mixture of various chemical elements or compounds also qualifies as a pure substance as long as the mixture is homogeneous.**

Nitrogen and gaseous air are pure substances.

❑ **Air gas, for example, is a mixture of several gases, but it is often considered to be a pure substance because it has a uniform chemical composition.**

2. PHASES OF A PURE SUBSTANCE

❑ **There are three principal phases: solid, liquid, and gas.**

❑ **Intermolecular bonds are strongest in solids and weakest in gases.**

❑ **The molecules in a solid are arranged in a three-dimensional pattern (lattice). The mutual attractive forces of molecules are large enough to keep the molecules at fixed positions.**

❑ **The molecules in the liquid phase are no longer at fixed positions relative to each other and they can rotate and translate freely. In a liquid, the intermolecular forces are weaker relative to solids.**

2. PHASES OF A PURE SUBSTANCE

❑ **In the gas phase, the molecules are far apart from each other. Gas molecules move randomly and continuously colliding with each other and the walls of the container. The intermolecular forces are very small, and collisions are the only mode of interaction between the molecules.** *Molecules in the gas phase are at a considerably higher energy level than they are in the liquid or solid phases. Therefore, the gas must release a large amount of its energy before it can condense or freeze.*

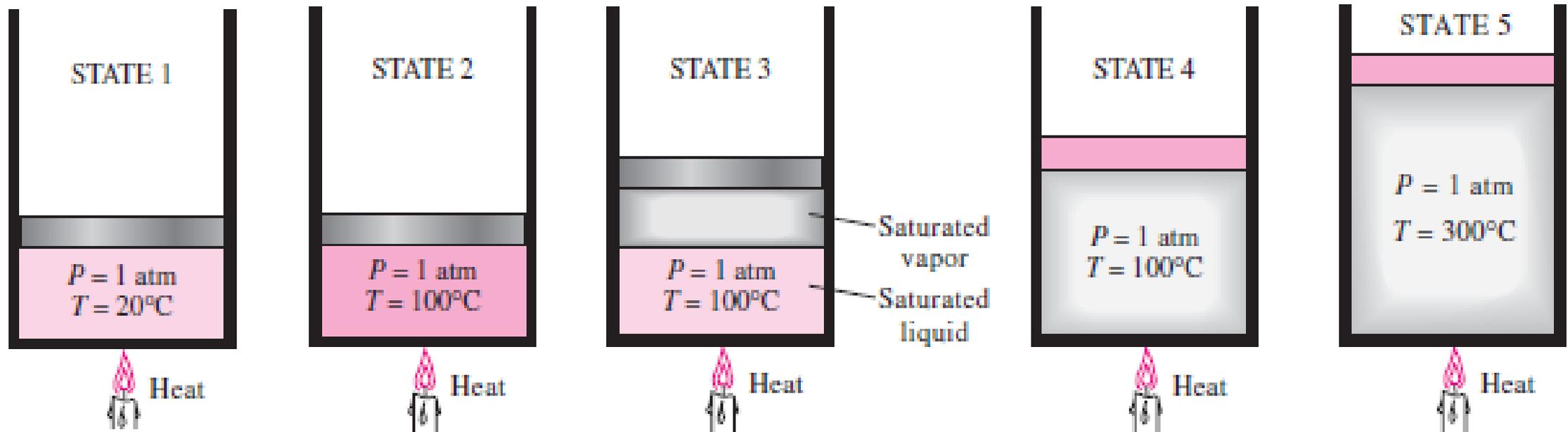
(a)   (b)   (c)
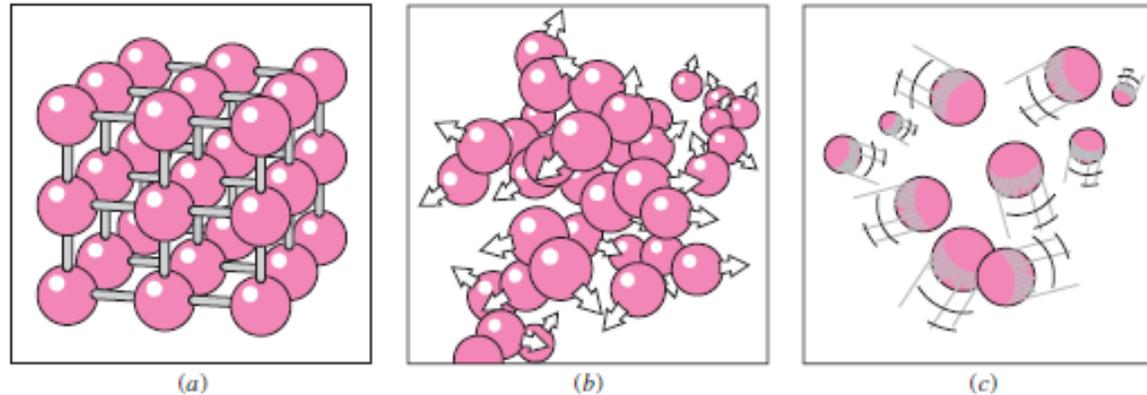
The arrangement of atoms in different phases: (a) molecules are at relatively fixed positions in a solid,
(b) groups of molecules move about each other in the liquid phase, and (c) molecules move randomly in the
gas phase.

3. PHASE-CHANGE PROCESSES OF A PURE SUBSTANCE

❑ **When two phases of a pure substance coexist in equilibrium, phase-change process occurs.**

❑ **Example: Water-boiling process at the atmospheric pressure:**

Consider a weightless piston–cylinder device containing liquid water at 20°C and 1 atm pressure which is continuously heated to 300°C.

STATE 1

$P = 1$ atm
$T = 20°C$

Heat

STATE 2

$P = 1$ atm
$T = 100°C$

Heat

STATE 3

$P = 1$ atm
$T = 100°C$

Saturated vapor

Saturated liquid

Heat

STATE 4

$P = 1$ atm
$T = 100°C$

Heat

STATE 5

$P = 1$ atm
$T = 300°C$

Heat

3. PHASE-CHANGE PROCESSES OF A PURE SUBSTANCE

o **State 1**

Water exists in the liquid phase, and it is called a compressed liquid, or a subcooled liquid. Water is not about to vaporize.

o **State 2**

Water is about to vaporize at 100ºC. A liquid that is about to vaporize is called a saturated liquid.

o **State 3**

The temperature stops rising. Saturated liquid and saturated vapor coexist in equilibrium in the form of saturated mixture.

3. PHASE-CHANGE PROCESSES OF A PURE SUBSTANCE

o **State 4**

All the liquid vaporizes and the entire cylinder is filled with saturated vapor that is on the borderline of the liquid phase. The vapor is about to condense.
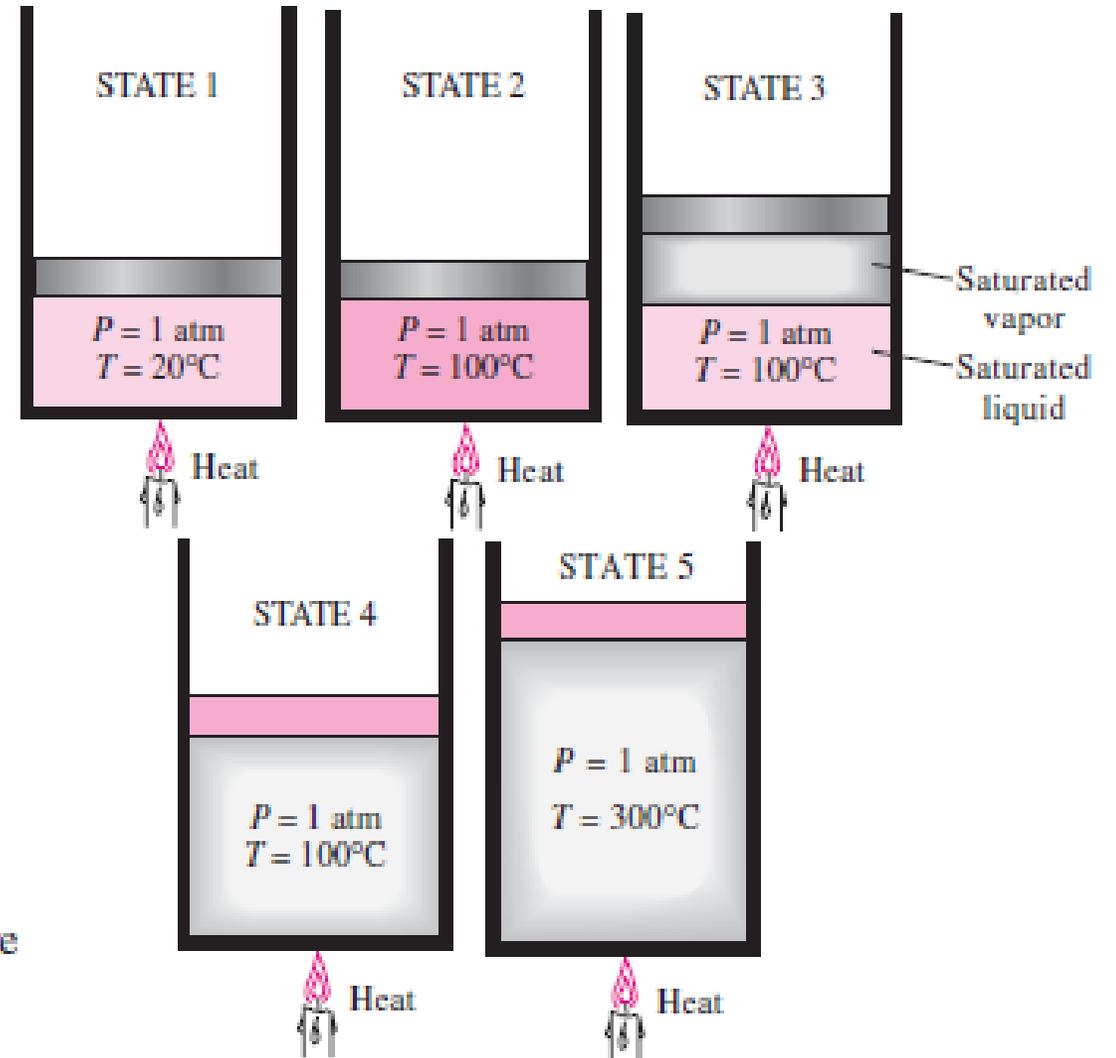
o **State 5**

Back to a single-phase region again (this time vapor). Further transfer of heat results in an increase in temperature to 300ºC. The vapor that is not about to condense is called superheated vapor.

3. PHASE-CHANGE PROCESSES OF A PURE SUBSTANCE
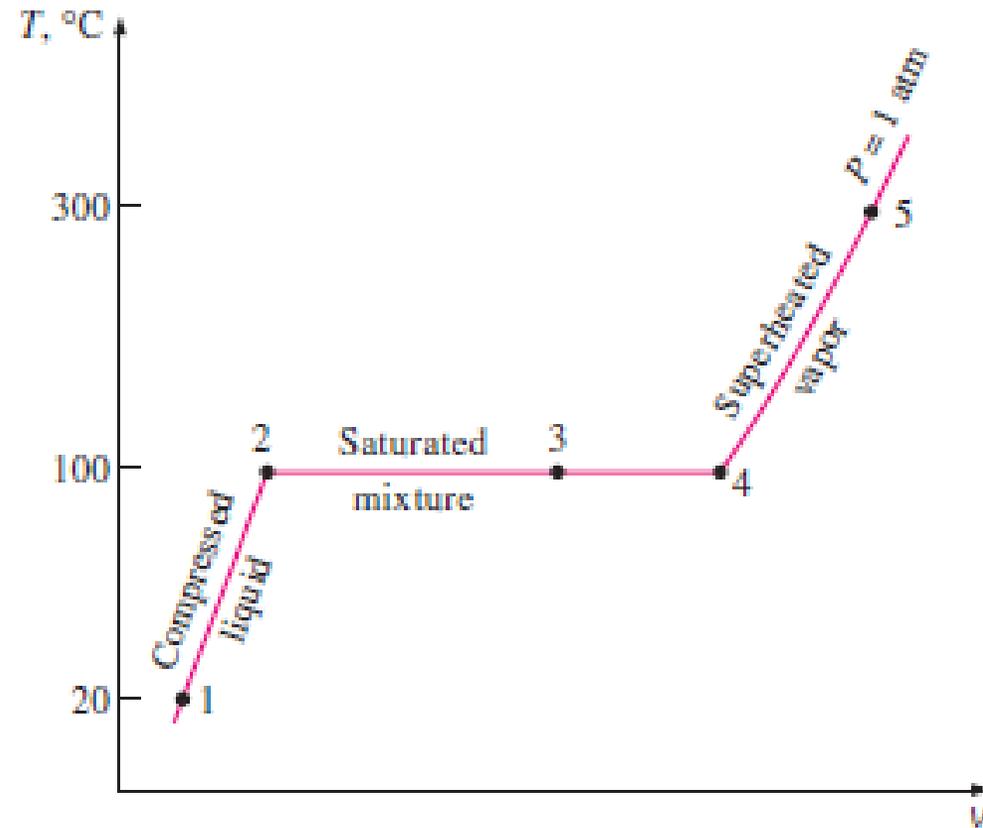
T-v diagram for the heating process of water at constant pressure
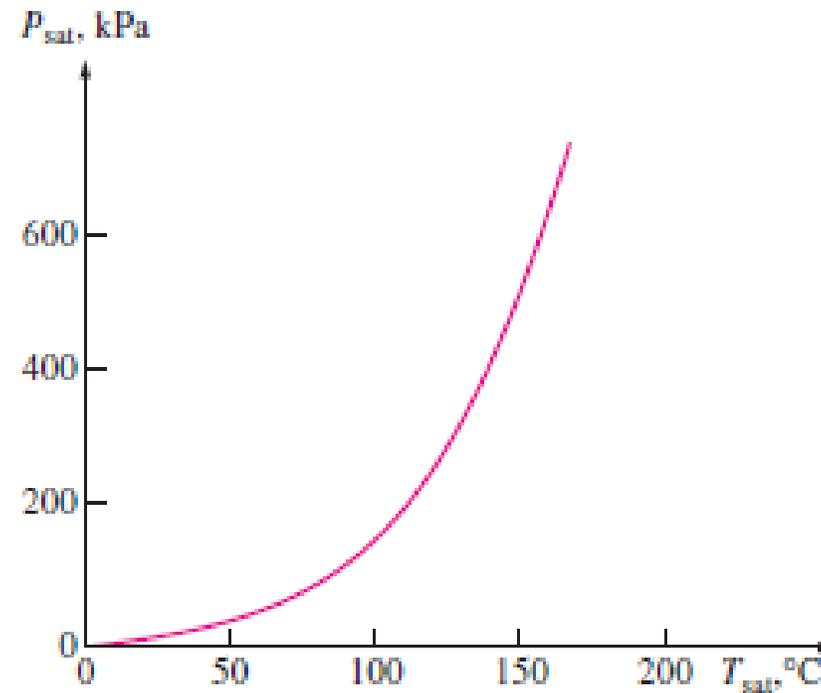
3. PHASE-CHANGE PROCESSES OF A PURE SUBSTANCE

❑ **Saturation temperature**: is the temperature at which a pure substance changes phase.

❑ **Saturation pressure**: is the pressure at which a pure substance changes phase.

❑ **Latent heat**: is the amount of energy absorbed or released during a phase-change process.

❑ **Latent heat of vaporization**: is the energy absorbed during vaporization process and it is equal to the energy released during condensation process.

❑ **Latent heat of fusion**: is the energy absorbed during melting process and it is equal to the energy released during freezing process.

3. PHASE-CHANGE PROCESSES OF A PURE SUBSTANCE

Saturation (boiling) pressure of water at various temperatures

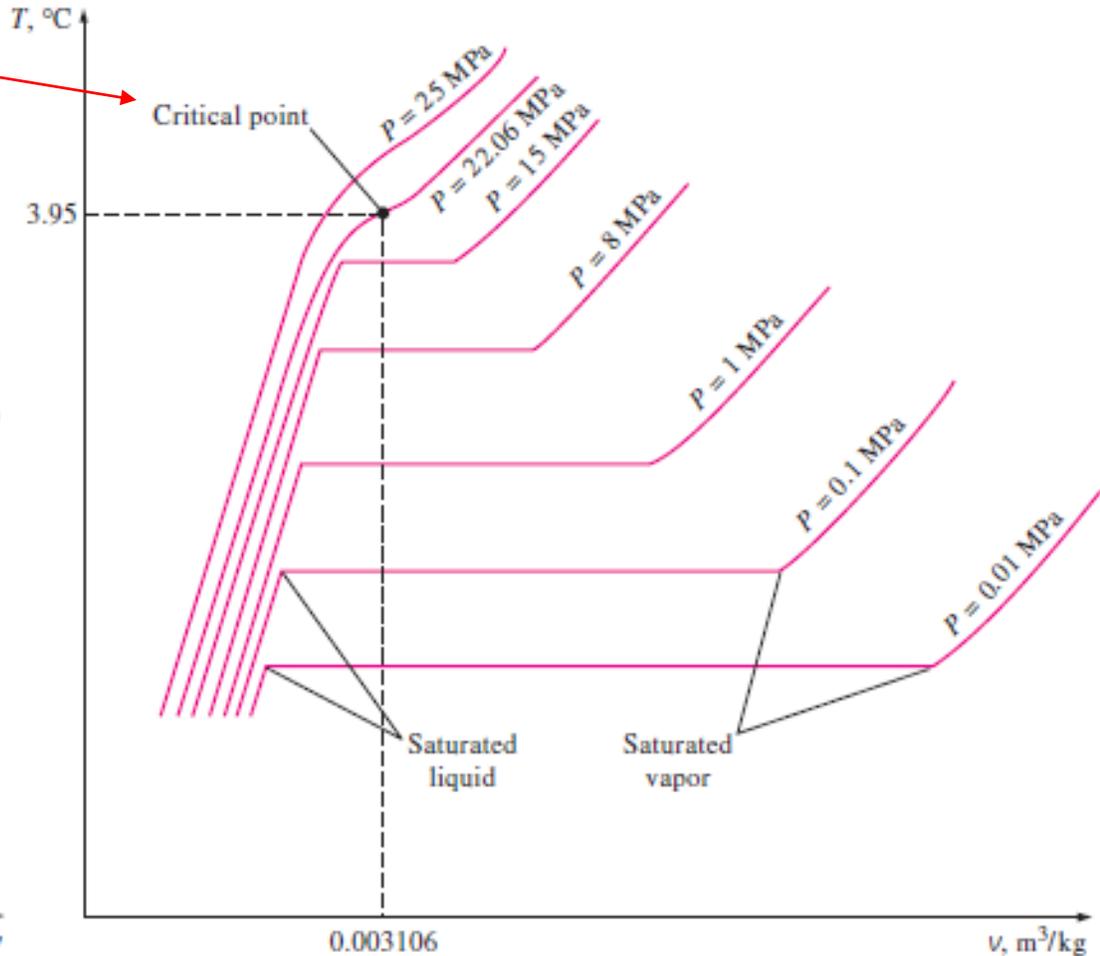| Temperature, T, °C	Saturation pressure, P_{sat}, kPa
−10	0.26
−5	0.40
0	0.61
5	0.87
10	1.23
15	1.71
20	2.34
25	3.17
30	4.25
40	7.39
50	12.35
100	101.4
150	476.2
200	1555
250	3976
300	8588

The liquid–vapor saturation curve of water.

4. PROPERTY DIAGRAMS FOR PHASE-CHANGE PROCESSES

A. T-*v* diagram

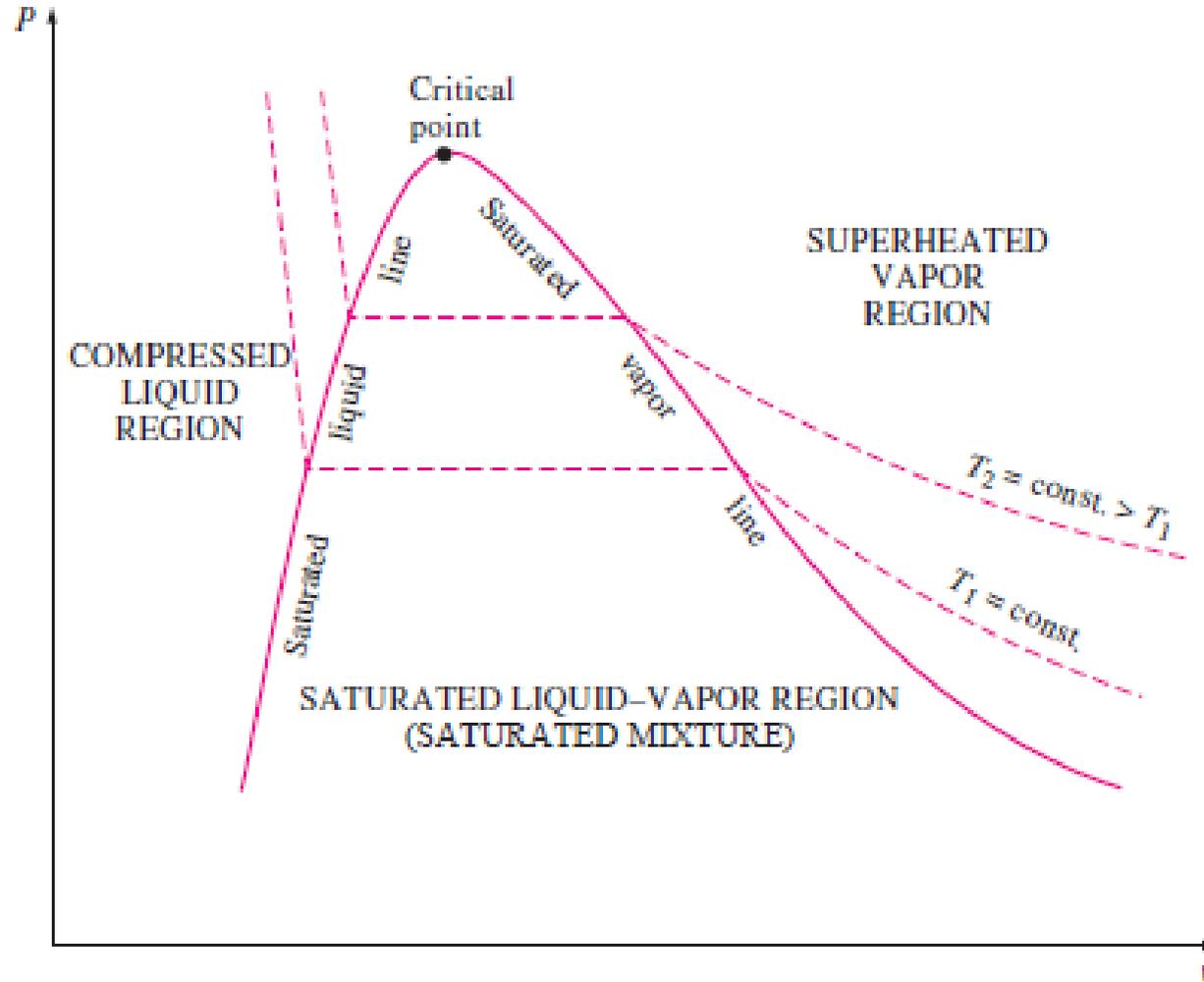The point at which the saturated liquid and saturated vapor states are identical
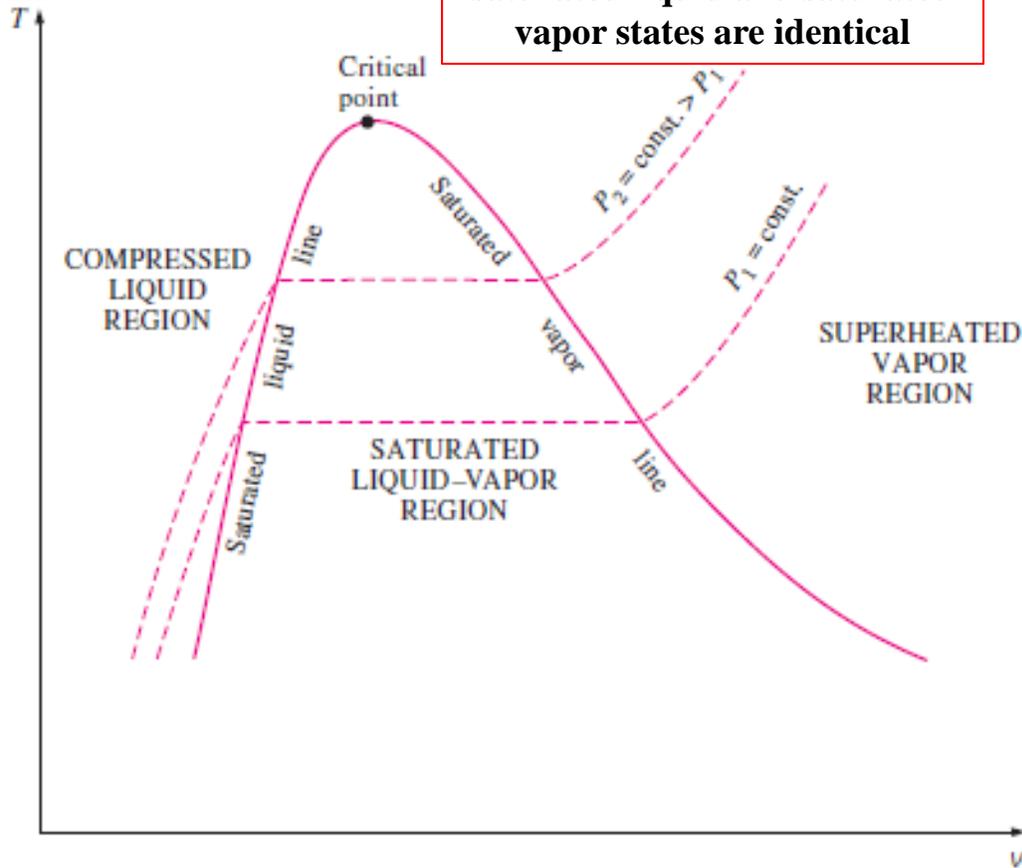
T-*v* diagram of water.

T-*v* diagram of constant-pressure phase-change processes of a pure substance at various pressures (for water).
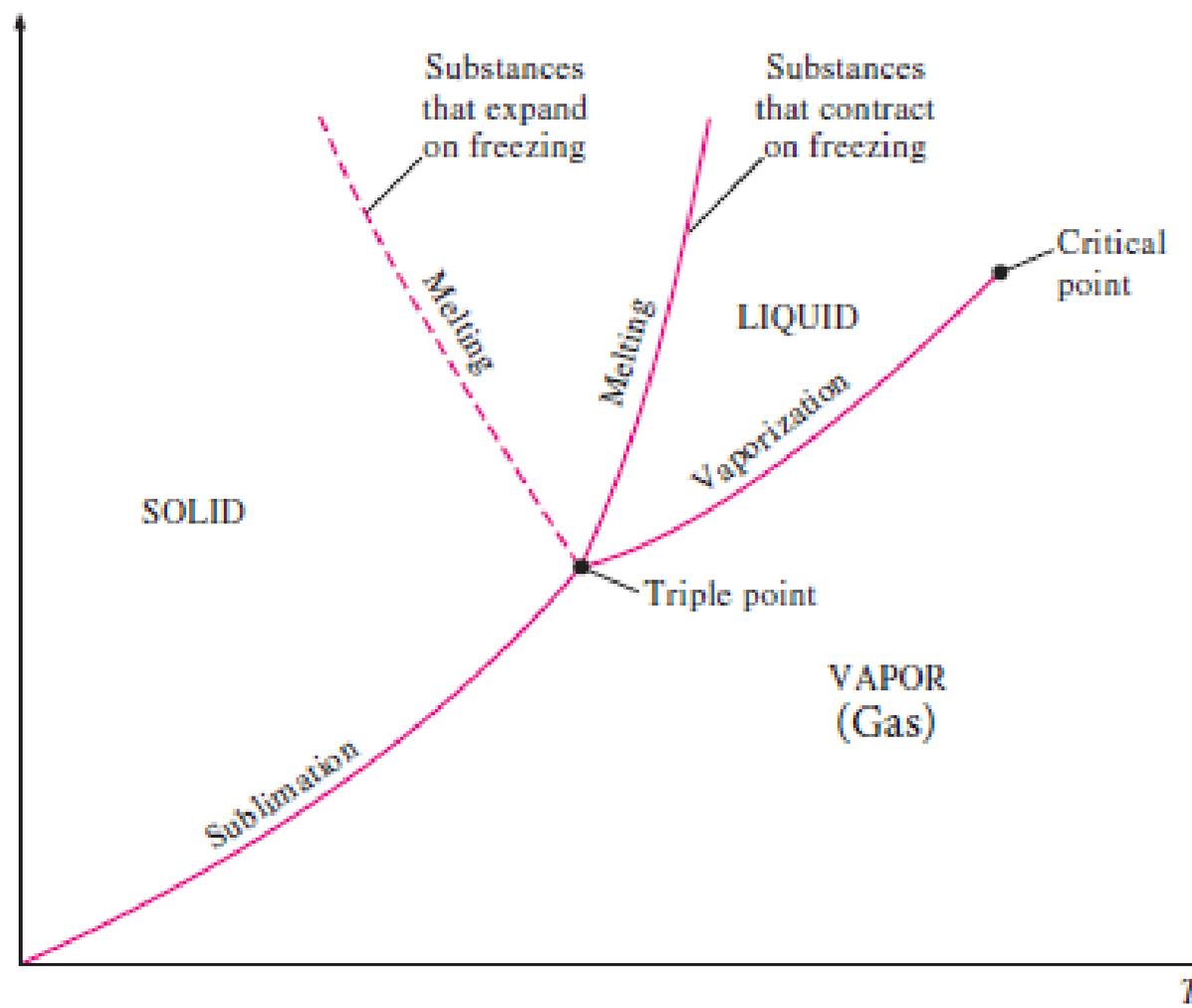
4. PROPERTY DIAGRAMS FOR PHASE-CHANGE PROCESSES

B. p-*v* diagram

P-v diagram of water.

4. PROPERTY DIAGRAMS FOR PHASE-CHANGE PROCESSES
C. p-T diagram

P-T diagram of pure substances.