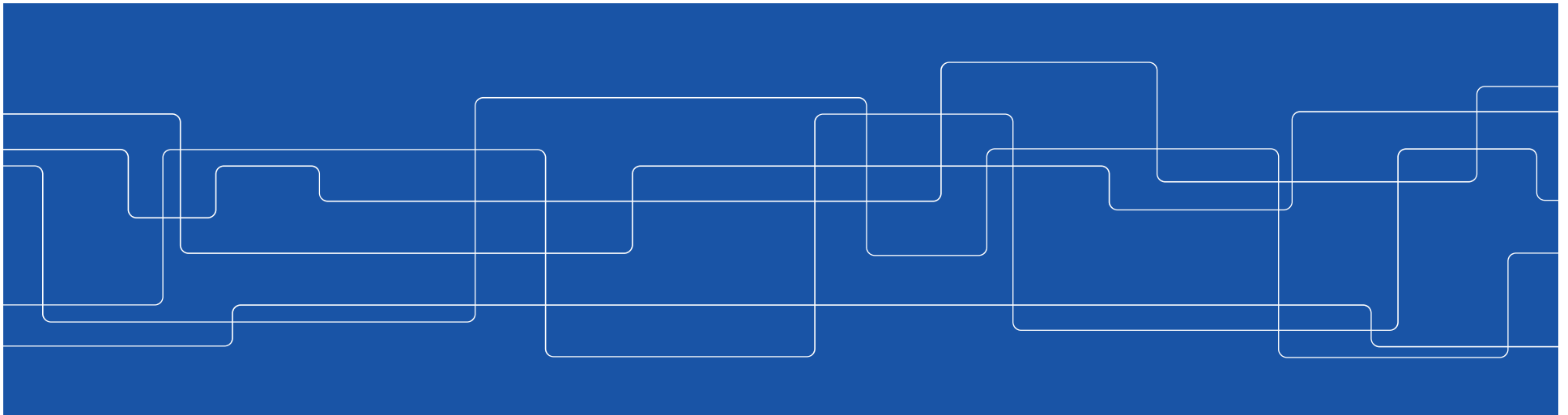




# **ME-238 Applied Thermodynamics**

## **Electrical Engineering, 1<sup>ST</sup> Semester**

Course Instructor: Engr. Ayman Shabbir





## Course Details

Basic Concepts, the system, Open and close system, properties of a system, control volume, working substance, heat and work, state and properties, thermodynamic process and cycle, forms of energy, first law of thermodynamics, first law of thermodynamics for a cycle, first law of thermodynamics for state change, Internal energy, enthalpy, specific heats, ideal gas laws, equations of state, properties of pure substances, phase diagram, use of steam tables, Phased change process of pure substances, thermodynamic processes relationship, constant volume, constant pressure, temperature, enthalpy and general law processes, steady state and steady flow process, uniform state and uniform flow processes. second law of thermodynamics, definitions, and its applications, reversible and irreversible processes, Carnot cycle and thermodynamic temperature scale, concept of entropy, enthalpy-entropy diagrams of working fluids, thermodynamic cycles, efficiencies, and their applications, idealized P-V and T – S diagrams, Carnot cycle, Rankine cycle and its applications, concept of open and closed cycles.



## Books

1. Thermodynamics An Engineering Approach, Y. A Cengel, and M. A. Boles, 10<sup>th</sup> Edition.
2. Applied Thermodynamics for Engineering Technologists By T. D. Eastop and A. McConkey, 5<sup>th</sup> Edition
3. Basic Engineering Thermodynamics By Rayner Joel, 5<sup>th</sup> Edition
4. Fundamentals of Thermodynamics by Sonntag, Borgnakke, Van Wylen



# Teaching methodology

- Class lectures
- Course works
- Assignments



## Assessment/Evaluation

Mid term exam 30%

Final term exam 40%

Course work, course assignments and class participation and other related activities 30%



# Introduction

Thermodynamics is science of energy

*Measure of the ability of a body or system to do work or produce a change.*

*Energy is the capacity of a physical system to perform work*

*The capacity for vigorous activity; available power*

Therme (heat) dynamics (power)---heat into work  
power generation, refrigeration, properties of matter



## **Introduction-What is thermodynamics**

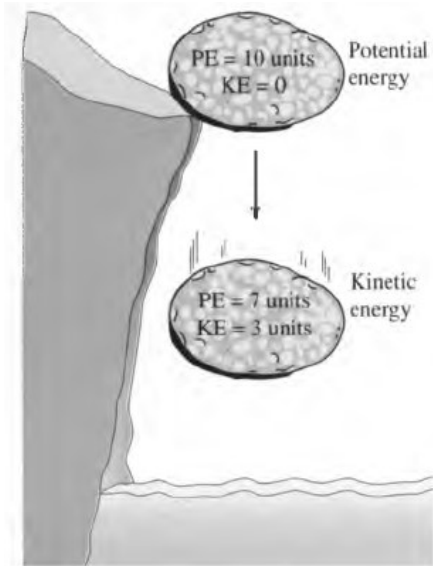
The science concerned with the relations between heat and mechanical energy or work, and the conversion of one into the other

Physics that deals with the relationships and conversions between heat and other forms of energy.

Thermodynamics is the branch of physics that studies how heat changes to and from other energy forms.

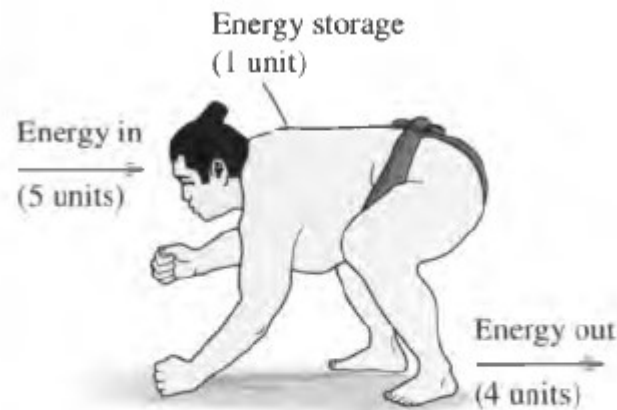


# Introduction-Laws of thermodynamics



**FIGURE 1-1**

Energy cannot be created or destroyed; it can only change forms (the first law).



**FIGURE 1-2**

Conservation of energy principle for the human body.





# Introduction-Laws of thermodynamics

Energy has a quality and quantity

actual processes occur in a direction of decreasing quality of energy



**FIGURE 1-3**

Heat flows in the direction of decreasing temperature.



# Introduction-classification

Classical (macroscopic) and Statistical (microscopic) thermodynamics



## Introduction-Application areas

Automotive engines

Refrigeration and air conditioning

Rockets

Conventional power plants

Design of vehicles

Solar collectors

Cooling of electronics

Electric and gas range

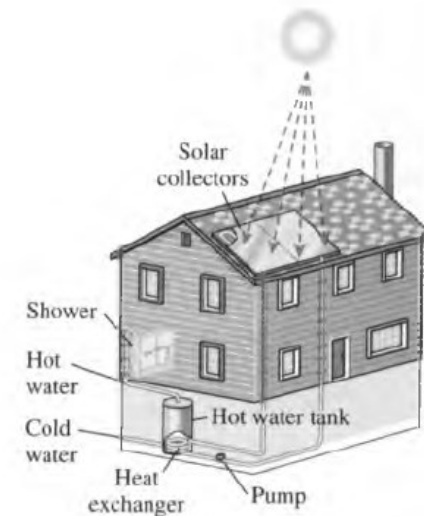
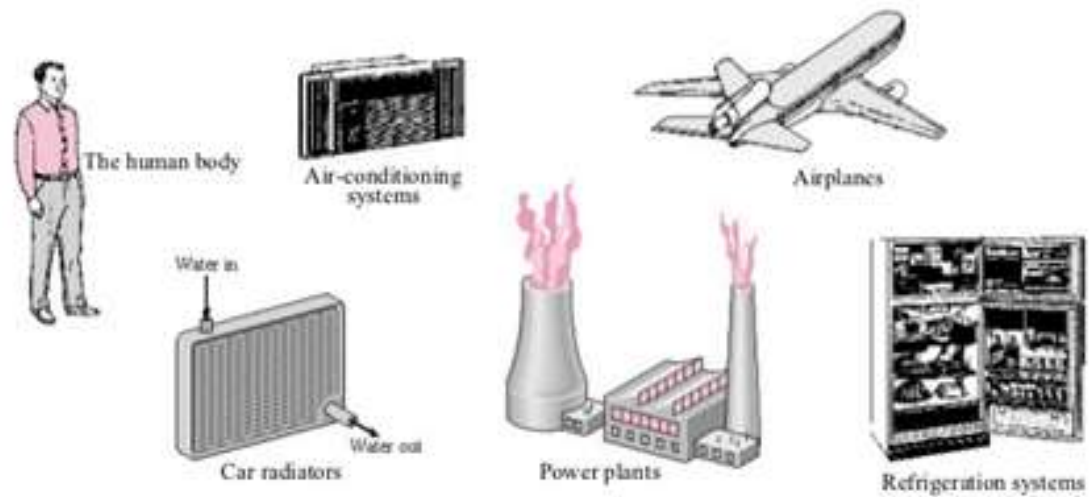


FIGURE 1-4

The design of many engineering systems, such as this solar hot water system, involves thermodynamics.



# Introduction-Application areas





## Dimensions and Units

Any physical quantity can be characterized by **dimensions**. **The magnitudes** assigned to the dimensions are called **units**.

two sets of units are in common use today: the **English system**, which is also known as the United States Customary System (USCS), and the metric **SI** (from *Le Système International d'Unités*), which is also known as the International System.



## Dimensions and Units

SI unit of force, which is named after Sir Isaac Newton (1647–1723), is *newton (not Newton), and it is abbreviated as **N***.

The length of an object can be 5 **m** or 5 **meters**, *not 5 **ms** or 5 **meter***

The proper abbreviation of meter is **m** (not **m.**).

**TABLE 1–1**

The seven fundamental (or primary) dimensions and their units in SI

Dimension	Unit
Length	meter (m)
Mass	kilogram (kg)
Time	second (s)
Temperature	kelvin (K)
Electric current	ampere (A)
Amount of light	candela (cd)
Amount of matter	mole (mol)



# Dimensions and Units

The **SI** is based on a decimal relationship between units.

**TABLE 1-2**

Standard prefixes in SI units

Multiple	Prefix
$10^{12}$	tera, T
$10^9$	giga, G
$10^6$	mega, M
$10^3$	kilo, k
$10^2$	hecto, h
$10^1$	deka, da
$10^{-1}$	deci, d
$10^{-2}$	centi, c
$10^{-3}$	milli, m
$10^{-6}$	micro, $\mu$
$10^{-9}$	nano, n
$10^{-12}$	pico, p

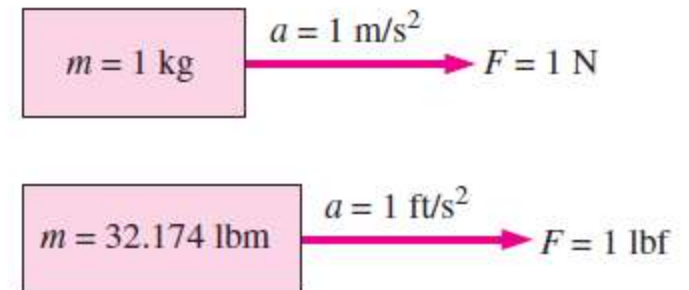


## Dimensions and Units

In the English system, the energy unit is the **Btu (British thermal unit)**, which is defined as the energy required to raise the temperature of 1 lbm of water at 68°F by 1°F. In the metric system, the amount of energy needed to raise the temperature of 1 g of water at 14.5°C by 1°C is defined as 1 **calorie (cal)**, and 1 cal = 4.1868 J. (1 Btu = 1.0551 kJ).

$$1 \text{ lbm} = 0.45359 \text{ kg}$$

$$1 \text{ ft} = 0.3048 \text{ m}$$







# Dimensions and Units

## **EXAMPLE 1–1** Spotting Errors from Unit Inconsistencies

While solving a problem, a person ended up with the following equation at some stage:

$$E = 25 \text{ kJ} + 7 \text{ kJ/kg}$$

where  $E$  is the total energy and has the unit of kilojoules. Determine how to correct the error and discuss what may have caused it.

## **EXAMPLE 1–2** Obtaining Formulas from Unit Considerations

A tank is filled with oil whose density is  $\rho = 850 \text{ kg/m}^3$ . If the volume of the tank is  $V = 2 \text{ m}^3$ , determine the amount of mass  $m$  in the tank.



# Dimensions and Units

## LENGTH

1 in = 2.54 cm  
1 ft = 12 in = 30.48 cm  
1 yd = 3 ft  
1 mi = 5280 ft  
1 nautical mile = 6080 ft  
1 mi = 1.609344 km

## AREA

1 mi<sup>2</sup> = 640 acres  
1 hectare = 10000 m<sup>2</sup> = (100 m)<sup>2</sup>

## VOLUME

1 imp. gal = 4.546090 litres = 4 quarts  
1 imp. quart = 40 fluid ounces  
1 bushel = 8 gallons  
1 litre = 1000 cm<sup>3</sup>  
1 U. S. gal (liq) = 3.785306 litres  
1 Hogshead = 238.47427 litres  
1 Noggin = 142.0652 cm<sup>3</sup>

## WEIGHT/MASS

1 lb = 16 oz  
1 lb = 453.59237 g  
1 ton = 2000 lb  
1 metric ton = 1000 kg  
1 carat = 200 mg  
1 slug = 14.5939 kg

## ENERGY

1 Btu = 1055.6 J (N m = kg m<sup>2</sup>/s<sup>2</sup>)  
1 calorie = 4.1868 J  
1 Joule = 10<sup>7</sup> ergs (g cm<sup>2</sup>/s<sup>2</sup>)

## FORCE

1 Newton = 0.22480894 lb  
1 Newton = 10<sup>5</sup> dynes (g cm/s<sup>2</sup>)

## POWER

1 horsepower (mechanical)  
= 550 ft lb/s = 745.700 watts



## Dimensions and Units

**Example 1:** Convert the length 56.43 ft to its equivalent in units of meters.

**Example 2:** Highway regulations in a certain jurisdiction state that a truck with two axles may have a maximum weight of 16000 pounds on the front axle and 20000 pounds on the rear axle. Convert these weights to their equivalents in kilograms, rounded to the nearest ten kilograms.



## Dimensions and Units

**Example 3:** According to one internet site, the distance from Vancouver, B. C. to Hong Kong is 5550 nautical miles, as the crow flies. Ignoring the question of whether any crow really could fly that far, determine what this distance is in units of kilometers.

**Example 4:** The speed limit on the Coquihalla Highway in British Columbia is 110 km/h. What is the equivalent speed in units of mi/h, rounded down to the nearest multiple of 5?



## Dimensions and Units

**Example 5:** According to the U. S. Department of Energy, the 2003 model of the Chevrolet Malibu has a highway fuel economy rating of 29 mi/gal. Assuming this is a reference to the U. S. gallon, compute the equivalent value of this fuel consumption rate in units of km/L. Round the answer to one decimal place.

**Example 6:** A particularly fine variety of cheese is sold for \$1.47 per ounce. What is this price in dollars per kilogram?



## Dimensions and Units

**Example 7:** Horse race lengths are often measured in furlongs, where 8 furlongs is equivalent to one mile. A fairly fast horse can run a 9 furlong race in about 1 minute and 45 seconds. Compute the speed of this horse in km/h.

**Example 8:** A rectangular region of forest measuring 5.6 mi by 9.2 mi was destroyed by fire. Compute the area of this region and express your final answer in units of hectares.

**Example 9:** Typical barometric pressure as reported in Canada is  $101 \text{ kPa} = 101,000 \text{ N/m}^2$ . Convert this value to its equivalent in pounds per square inch, the units used for barometric pressure in the United States.



# Introduction-System, boundary and surroundings

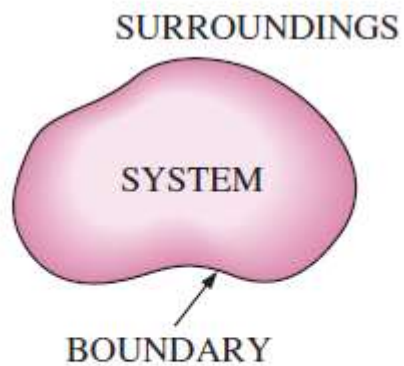
**System** Quantity of matter or a region in space under consideration

**Surroundings** mass or region outside the system

**Boundary** surface that separates system and surroundings

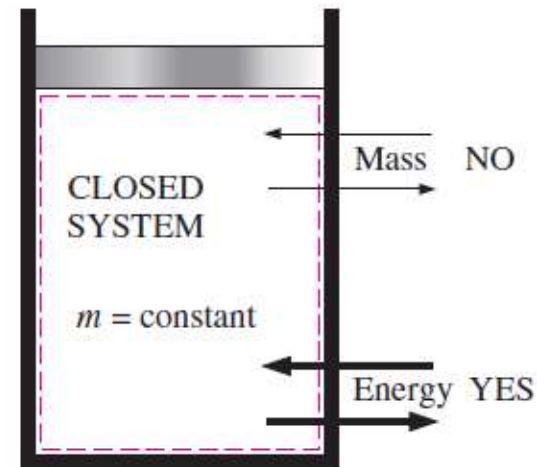


# Introduction-Systems



**FIGURE 1-15**

System, surroundings, and boundary.



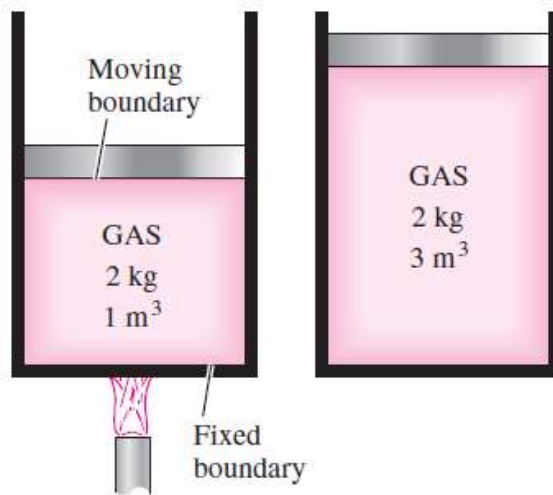
**FIGURE 1-16**

Mass cannot cross the boundaries of a closed system, but energy can.



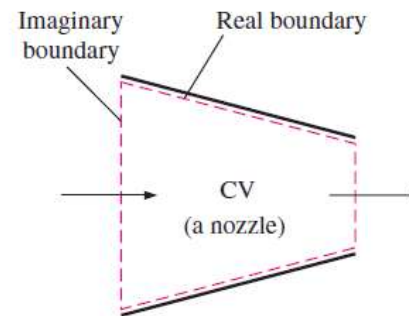


# Introduction-Systems

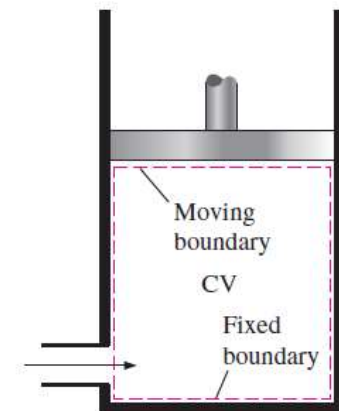


**FIGURE 1-17**

A closed system with a moving boundary.



(a) A control volume with real and imaginary boundaries



(b) A control volume with fixed and moving boundaries

**FIGURE 1-18**

A control volume can involve fixed, moving, real, and imaginary boundaries.



## Introduction-Systems

A **control volume** can be fixed in size and shape, as in the case of a nozzle, or it may involve a moving boundary. Most control volumes, **however, have fixed boundaries and thus do not involve any moving boundaries**. A control volume can also involve heat and work interactions just as a closed system, in addition to mass interaction.



# Introduction-Systems

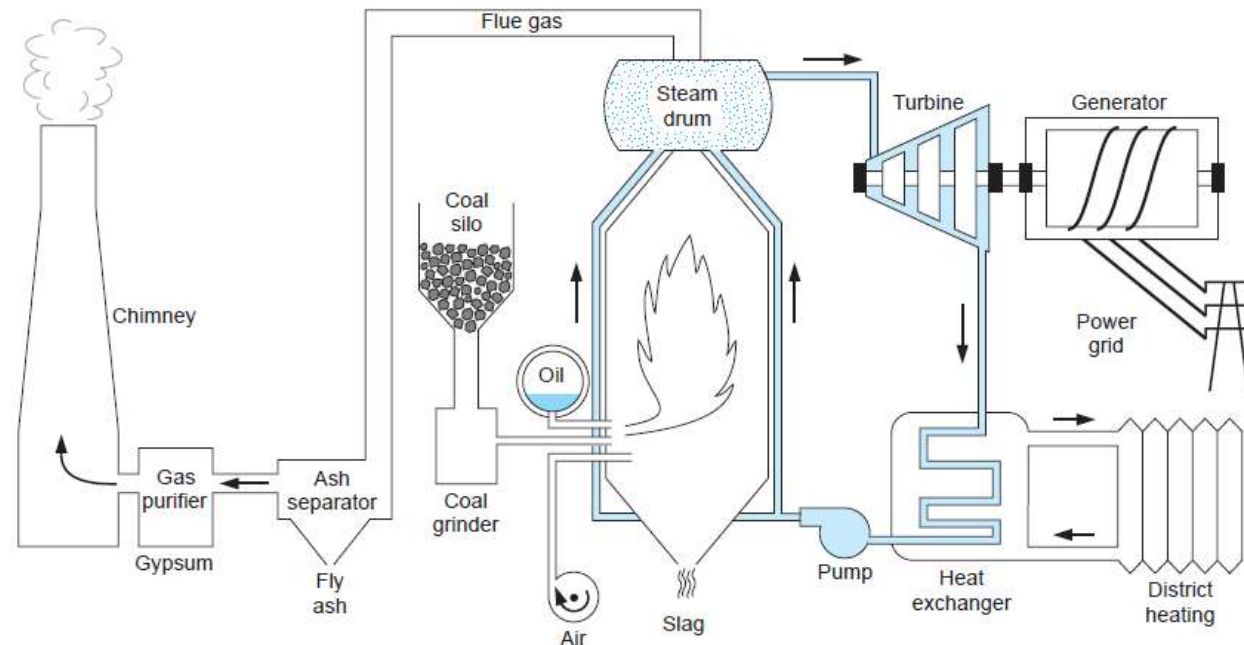
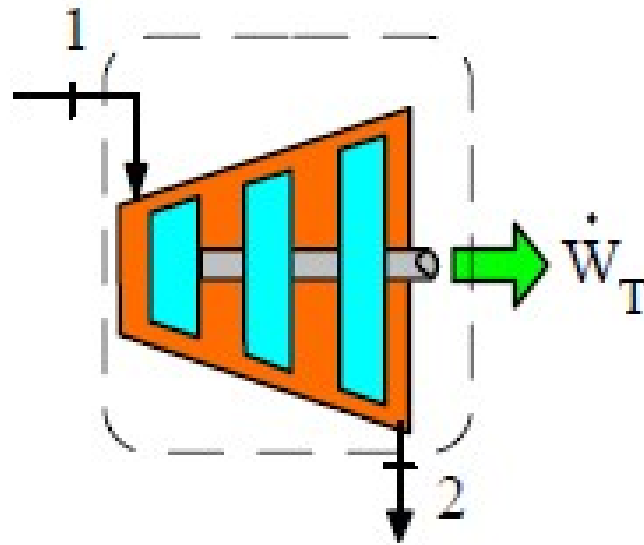


FIGURE 1.1 Schematic diagram of a steam power plant.

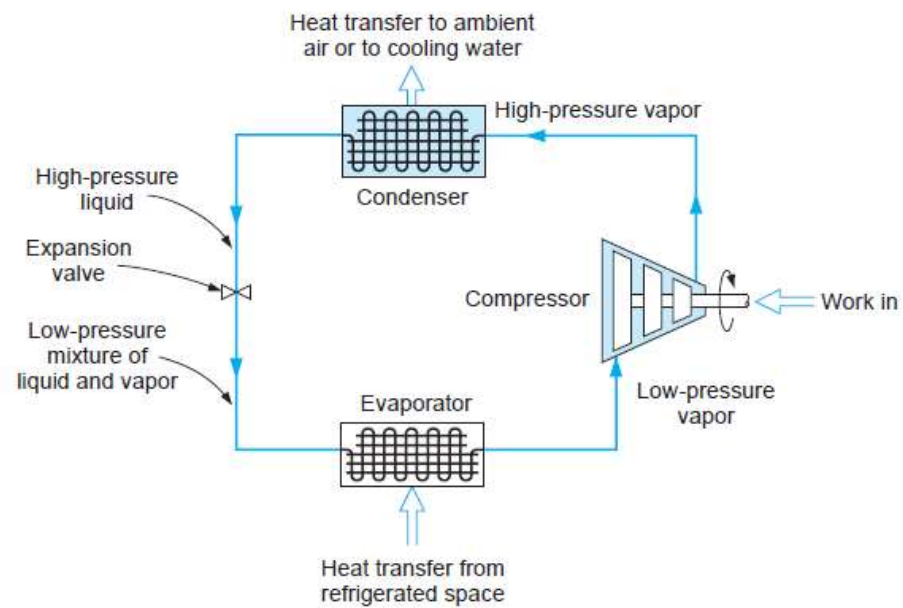


# Introduction-Systems





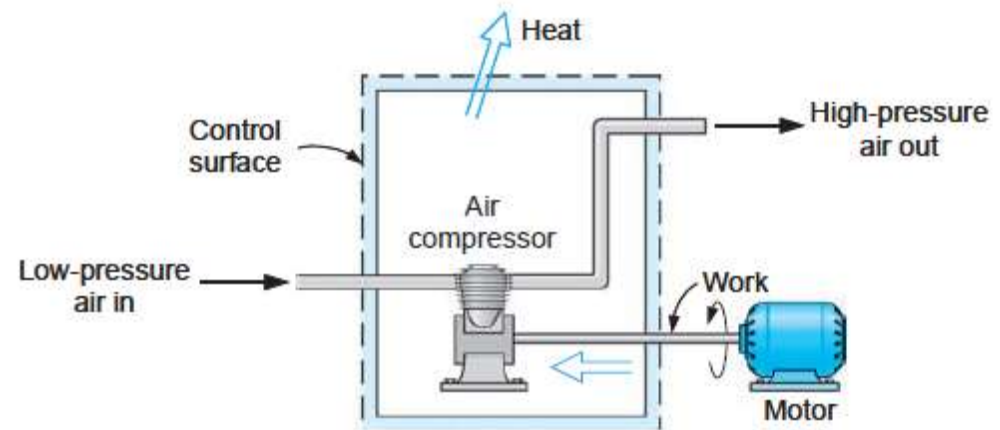
# Introduction-Systems



**FIGURE 1.6**  
Schematic diagram of a  
simple refrigeration  
cycle.



# Introduction-Systems



**FIGURE 2.2** Example of a control volume.

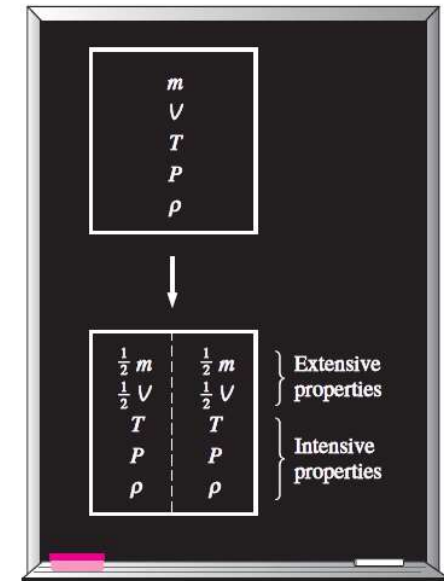


# Introduction-Properties of a system

Characteristics of a system are called its ***properties***

Intensive and extensive properties

Upper case letters for extensive and  
lower case letters for intensive properties



**FIGURE 2-6**

Criteria to differentiate intensive and extensive properties.



# Introduction-Properties

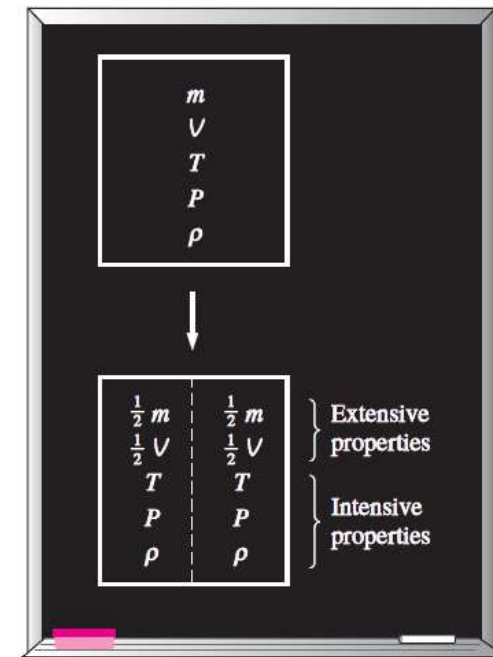
Characteristics of system are called System properties.

Density

$$\rho = \frac{m}{V} \quad \frac{\text{kg}}{\text{m}^3}$$

Depends on operating conditions  
(temperature and pressure)

Density of most gases is proportional to pressure and inversely proportional to temperature



**FIGURE 2-6**

Criteria to differentiate intensive and extensive properties.





# Introduction-Properties

## Density

pressure is usually negligible. At 20°C, for example, the density of water changes from 998 kg/m<sup>3</sup> at 1 atm to 1003 kg/m<sup>3</sup> at 100 atm, a change of just 0.5 percent. The density of liquids and solids depends more strongly on temperature than it does on pressure. At 1 atm, for example, the density of water changes from 998 kg/m<sup>3</sup> at 20°C to 975 kg/m<sup>3</sup> at 75°C, a change of 2.3 percent, which can still be neglected in many engineering analyses.



# Introduction-Properties

## Specific gravity

$$SG = \frac{\rho_{\text{Substance}}}{\rho_{\text{Water}}}$$

## Specific weight

$$\gamma_s = \frac{\text{Weight}}{V} \quad \left[ \frac{\text{N}}{\text{m}^3} \right]$$

**TABLE 2–1**

The specific gravity of some substances at 20°C and 1 atm unless stated otherwise

Substance	SG
Water	1.0
Blood (at 37°C)	1.06
Seawater	1.025
Gasoline	0.68
Ethyl alcohol	0.790
Mercury	13.6
Balsa wood	0.17
Dense oak wood	0.93
Gold	19.3
Bones	1.7–2.0
Ice (at 0° C)	0.916
Air	0.001204



# Introduction-Properties

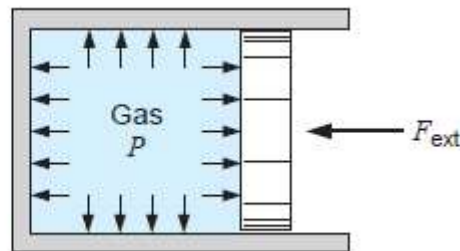
**Pressure**: We define pressure as the normal component of force per unit area.

$$1 \text{ Pa} = 1 \text{ N/m}^2$$

$$1 \text{ bar} = 10^5 \text{ Pa} = 0.1 \text{ MPa}$$

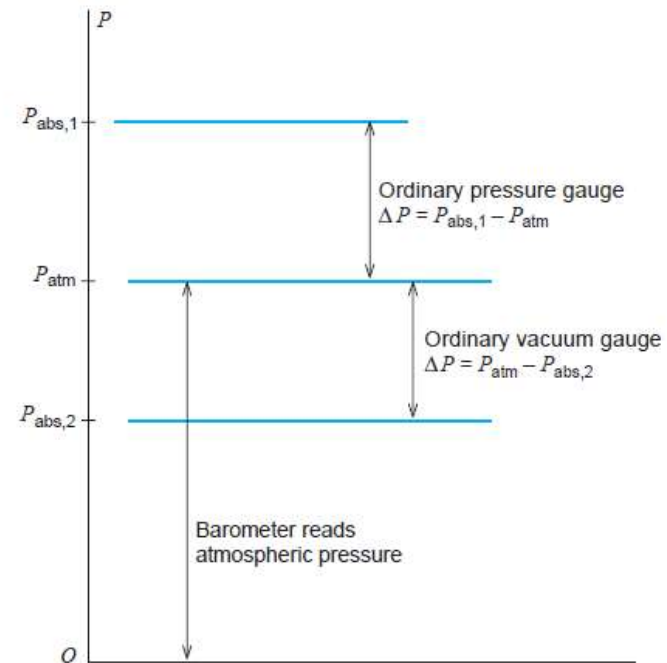
$$1 \text{ atm} = 101\,325 \text{ Pa} = 14.696 \text{ lbf/in.}^2$$

**FIGURE 2.10** The balance of forces on a movable boundary relates to inside gas pressure.





# Introduction-Properties



**FIGURE 2.12**  
Illustration of terms  
used in pressure  
measurement.



# Introduction-Properties





# Introduction-Properties

**Temperature**: Sense of hotness or coldness when we touch an object

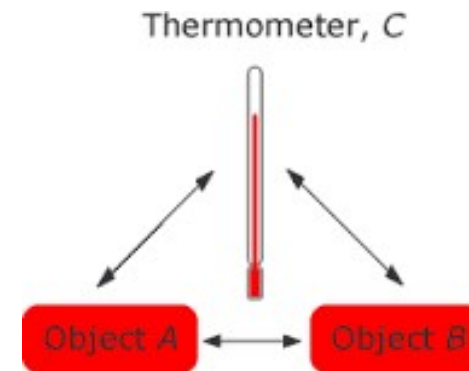
$$K = ^\circ C + 273.15$$

$$R = F + 459.67$$



# Introduction-Properties

## Zeroth law of thermodynamics



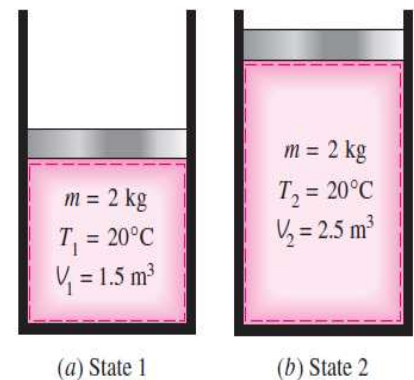
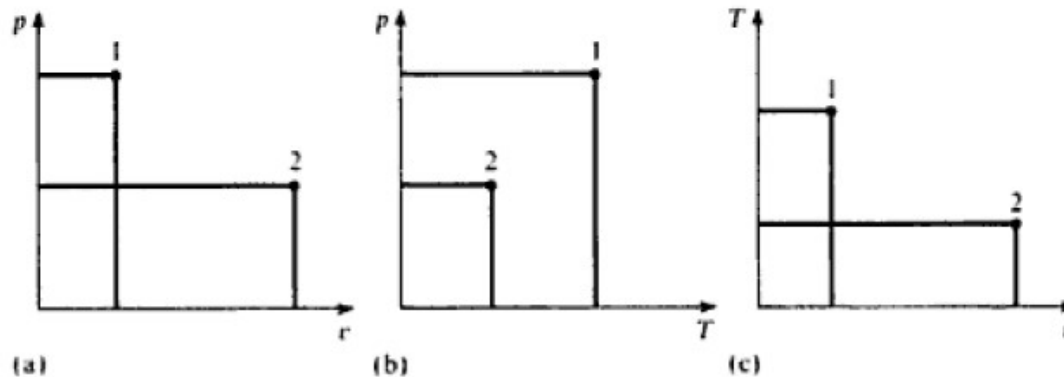
*Because the principle is not derivable from other laws, and because it precedes the first and second laws of thermodynamics in the logical presentation of thermodynamics, it is called the zeroth law of thermodynamics. This law is really the basis of temperature measurement.*



## Introduction-State and equilibrium

At a given state, all the properties of a system have fixed values. If the value of even one property changes, the state will change to a different one.

**Fig. 1.11** State of a working fluid on a property diagram



**FIGURE 2-10**

A system at two different states.

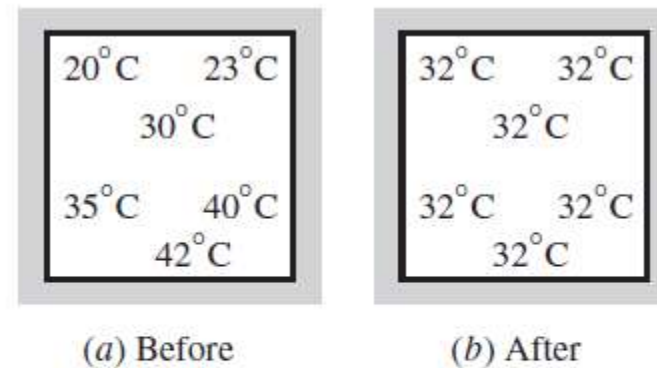




## Introduction-State and equilibrium

Thermodynamics deals with *equilibrium states*. The word **equilibrium** implies a state of balance.

- No unbalanced potentials within the system



**FIGURE 2-11**

A closed system reaching thermal equilibrium.



## Introduction-State postulate

The number of properties required to fix the *state* of a system is given by ***state postulate***.

Simple compressible system

Systems where electrical, gravitational, magnetic, motion and surface tension effects are absent.

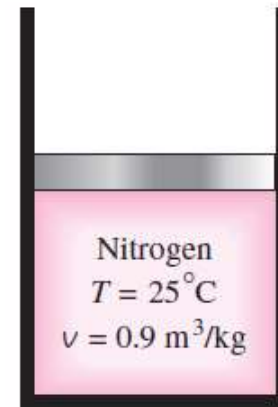
State of a simple compressible system is completely described by two independent intensive properties.



## Introduction-State postulate

Two properties should be independent

Temperature and specific volume, for example, are always independent properties, and together they can fix the state of a simple compressible system. Temperature and pressure, however, are independent properties for single-phase systems, but are dependent properties for multiphase systems.



**FIGURE 2–12**

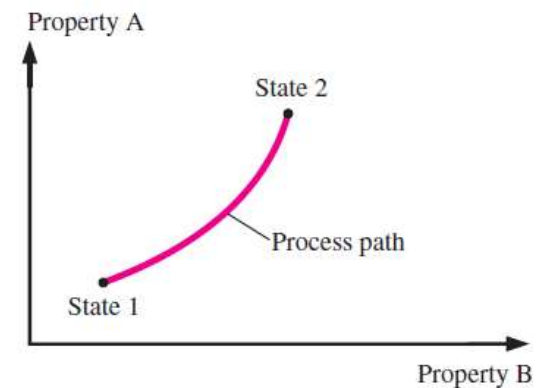
The state of nitrogen is fixed by two independent, intensive properties.



## Introduction-Processes and cycles

Path followed by a system to undergo a change from one equilibrium state to another is called Thermodynamical process.

Iso prefix, Isothermal, Isobaric etc



**FIGURE 2-13**

A process between states 1 and 2 and the process path.



# Introduction-Steady flow process

Steady flow

Properties are not going to vary with time

Uniform flow

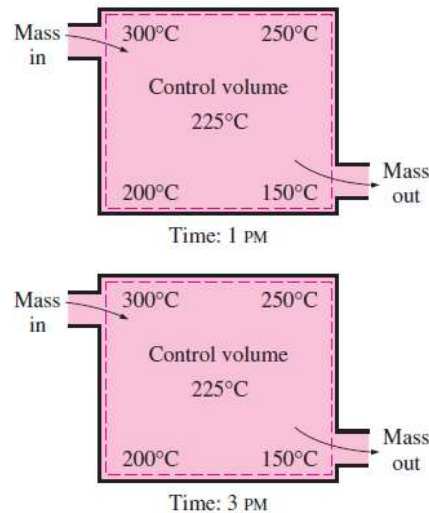
Properties are not going to vary at different locations over a specific region

Steady flow devices can be represented by steady flow processes

Turbines, pumps, boilers, condensers, heat exchangers etc.

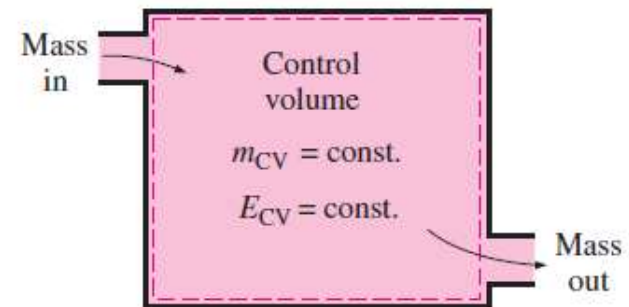


## Introduction-Steady flow processes



**FIGURE 2-16**

During a steady-flow process, fluid properties within the control volume may change with position but not with time.



**FIGURE 2-17**

Under steady-flow conditions, the mass and energy contents of a control volume remain constant.



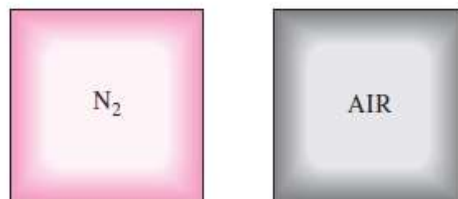
# **Phase change of pure substances**

Chapter 3 from Yunus Cengel



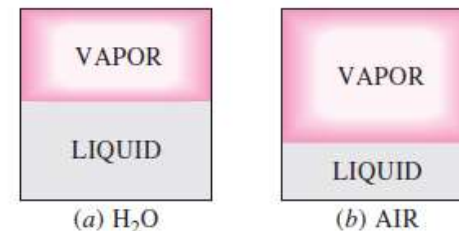
## Pure Substance

A substance that has a fixed chemical composition throughout is called a **pure substance**. Water, nitrogen, helium, and carbon dioxide, for example are all pure substances.



**FIGURE 4-1**

Nitrogen and gaseous air are pure substances.



**FIGURE 4-2**

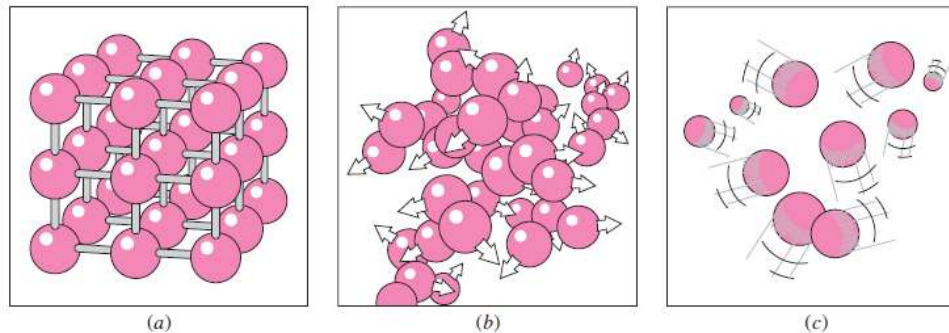
A mixture of liquid and gaseous water is a pure substance, but a mixture of liquid and gaseous air is not.





## Phases of pure substance

Substances exist in different **phases**. *At room temperature and pressure, copper is a solid, mercury is a liquid, and nitrogen is a gas.*



**FIGURE 4-5**

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 about at random in the gas phase.



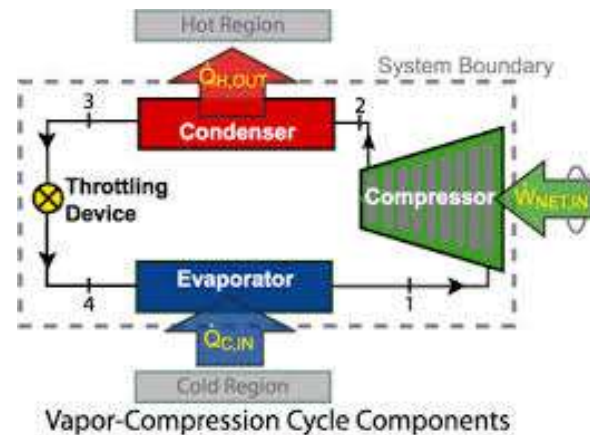
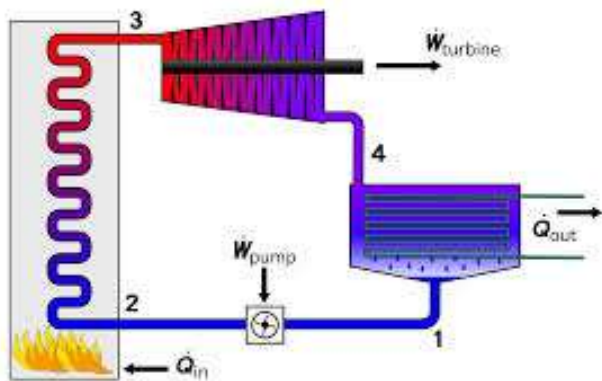
## Phases of pure substances

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



## Phase-change processes of pure substances

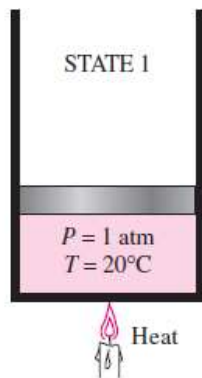
Water exists as a mixture of liquid and vapor in the boiler and the condenser of a steam power plant. The refrigerant turns from liquid to vapor in the freezer of a refrigerator.





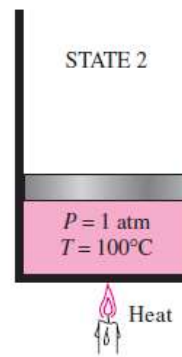
## Compressed and saturated liquid

**Compressed liquid, or a subcooled liquid**, meaning that it is not about to vaporize.



**FIGURE 4-6**

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



**FIGURE 4-7**

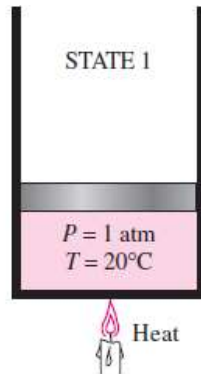
At 1 atm pressure and 100°C, water exists as a liquid that is ready to vaporize (*saturated liquid*).

A liquid that is *about to* vaporize is called a **saturated liquid**



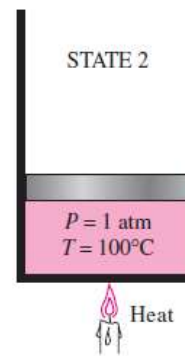
## Saturated and superheated vapor

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



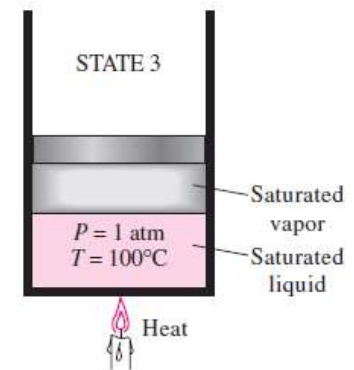
**FIGURE 4-6**

At 1 atm and  $20^\circ\text{C}$ , water exists in the liquid phase (*compressed liquid*).



**FIGURE 4-7**

At 1 atm pressure and  $100^\circ\text{C}$ , water exists as a liquid that is ready to vaporize (*saturated liquid*).

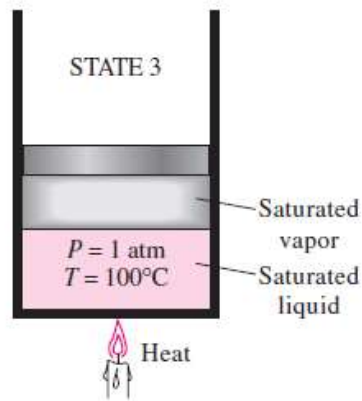


**FIGURE 4-8**

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

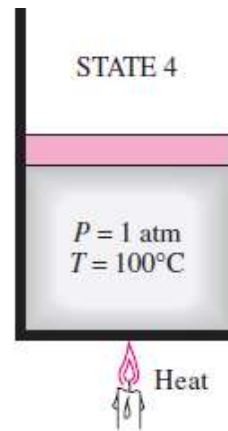


## Saturated and superheated vapor



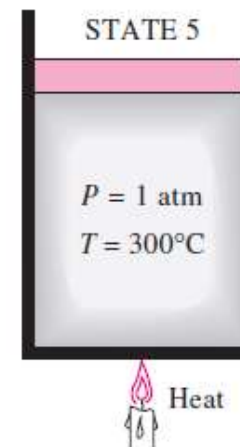
**FIGURE 4-8**

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



**FIGURE 4-9**

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



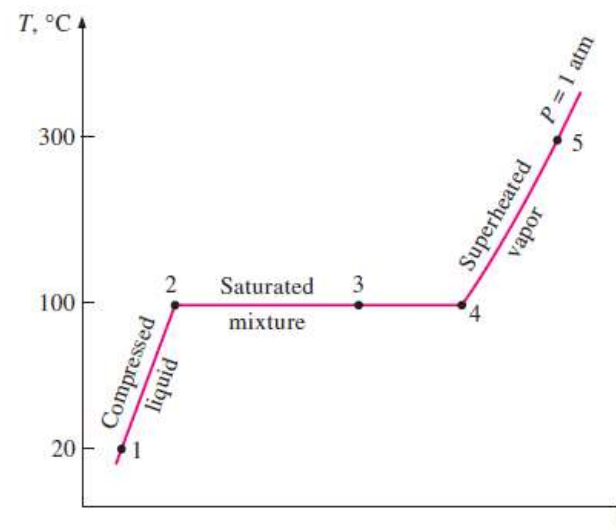
**FIGURE 4-10**

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

A vapor that is not about to condense is called a **superheated vapor**



## Saturation temperature and pressure



**FIGURE 4-11**

*T-v* diagram for the heating process of water at constant pressure.



## Saturation temperature and pressure

The statement “water boils at 100°C” is incorrect. The correct statement is “**water boils at 100°C at 1 atm pressure.**”

*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 the **saturation temperature  $T_{sat}$** . ***Likewise, at a given temperature,*** the pressure at which a pure substance changes phase is called the **saturation pressure  $P_{sat}$** .





## Saturation temperature and pressure

The amount of energy absorbed or released during a phase-change process is called the **latent heat**. More specifically, the amount of energy absorbed during melting is called the **latent heat of fusion** and is equivalent to the amount of energy released during freezing. Similarly, the amount of energy absorbed during vaporization is called the **latent heat of vaporization** and is equivalent to the energy released during condensation.



## Saturation temperature and pressure

The magnitudes of the latent heats depend on the temperature or pressure at which the phase change occurs. At 1 atm pressure, the latent heat of fusion of water is 333.7 kJ/kg and the latent heat of vaporization is 2256.5 kJ/kg.



# Saturation temperature and pressure

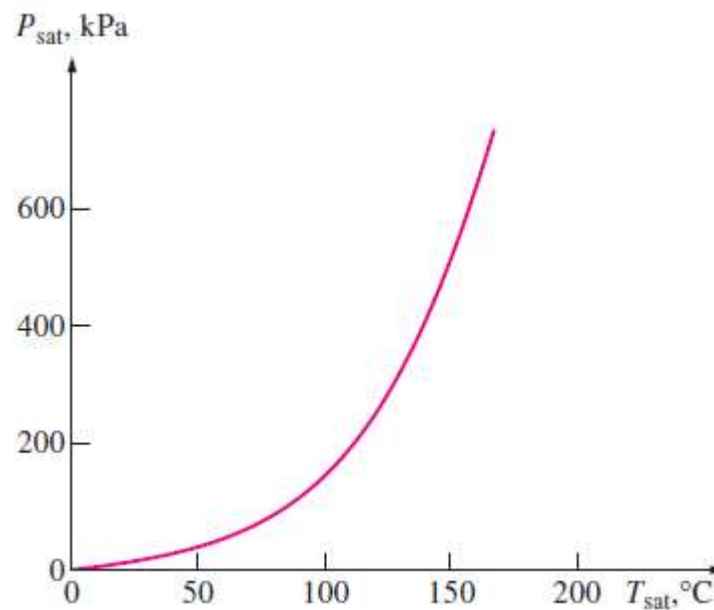
**TABLE 4-1**

Saturation (boiling) pressure of water at various temperatures

Temperature, $T$ , °C	Saturation pressure, $P_{\text{sat}}$ , 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

**FIGURE 4-12**

The liquid–vapor saturation curve of a pure substance (numerical values are for water).



**TABLE 4-2**

Variation of the standard atmospheric pressure and the boiling (saturation) temperature of water with altitude

Elevation, m	Atmospheric pressure, kPa	Boiling temperature, °C
0	101.33	100.0
1,000	89.55	96.5
2,000	79.50	93.3
5,000	54.05	83.3
10,000	26.50	66.3
20,000	5.53	34.7



## Property diagram for phase change process

**Critical Point** is defined as the point at which the saturated liquid and saturated vapor states are identical.

The temperature, pressure, and specific volume of a substance at the critical point are called, respectively, the *critical temperature*  $T_{cr}$ , *critical pressure*  $P_{cr}$ , and *critical specific volume*  $v_{cr}$ .

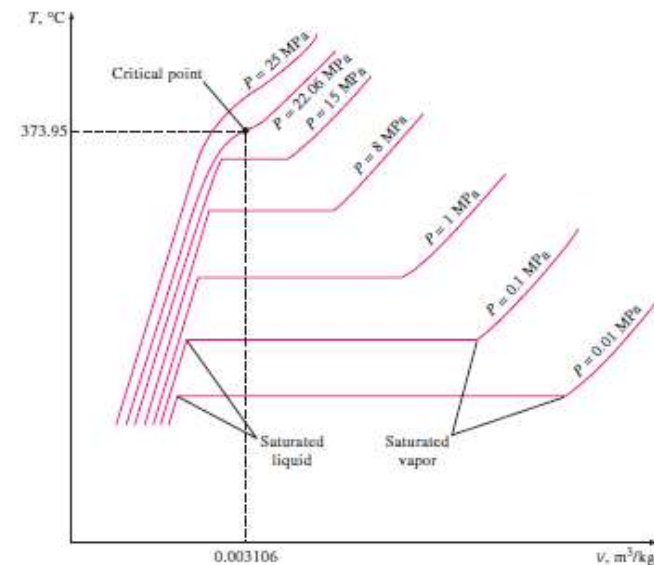
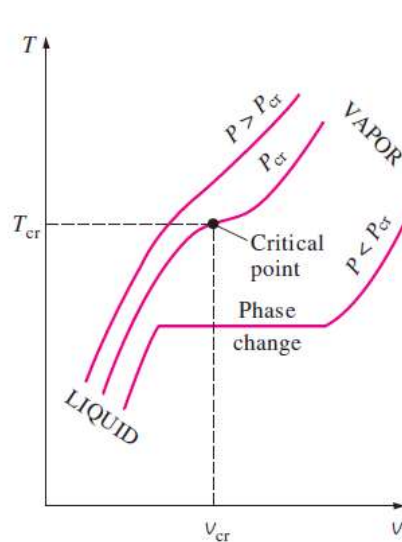


FIGURE 4-16

$T$ - $v$  diagram of constant-pressure phase-change processes of a pure substance at various pressures (numerical values are for water).

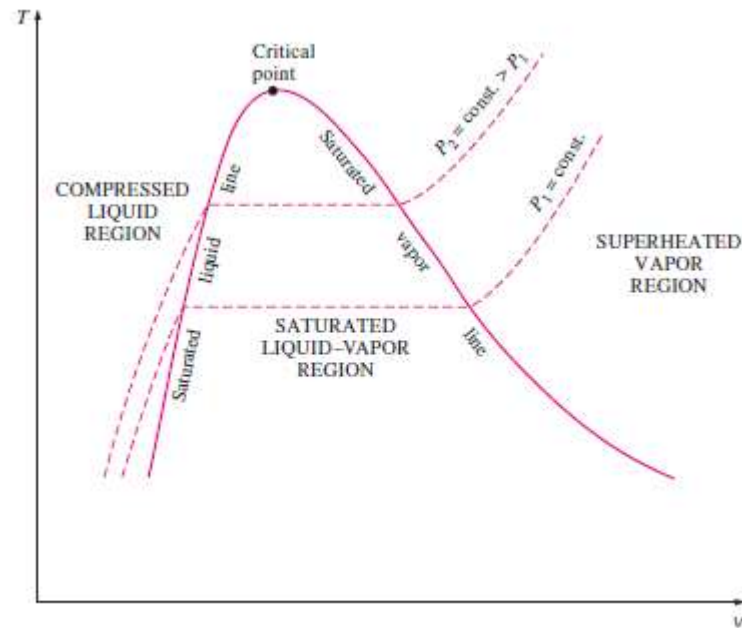


# Property diagram for phase change process



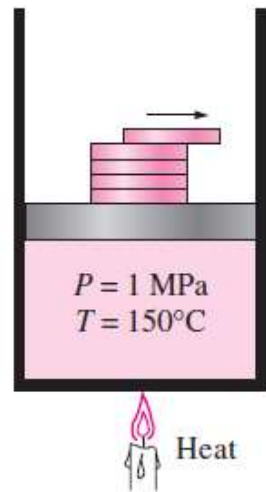
**FIGURE 4-17**

At supercritical pressures ( $P > P_{cr}$ ), there is no distinct phase-change (boiling) process.



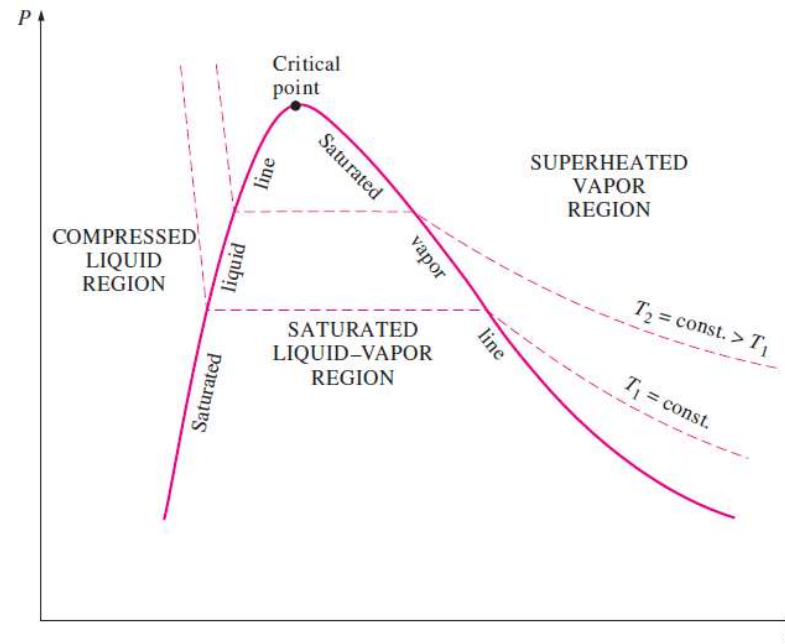


## Property diagram for phase change process



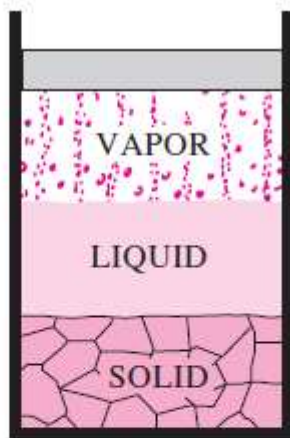
**FIGURE 4-20**

The pressure in a piston–cylinder device can be reduced by reducing the weight of the piston.



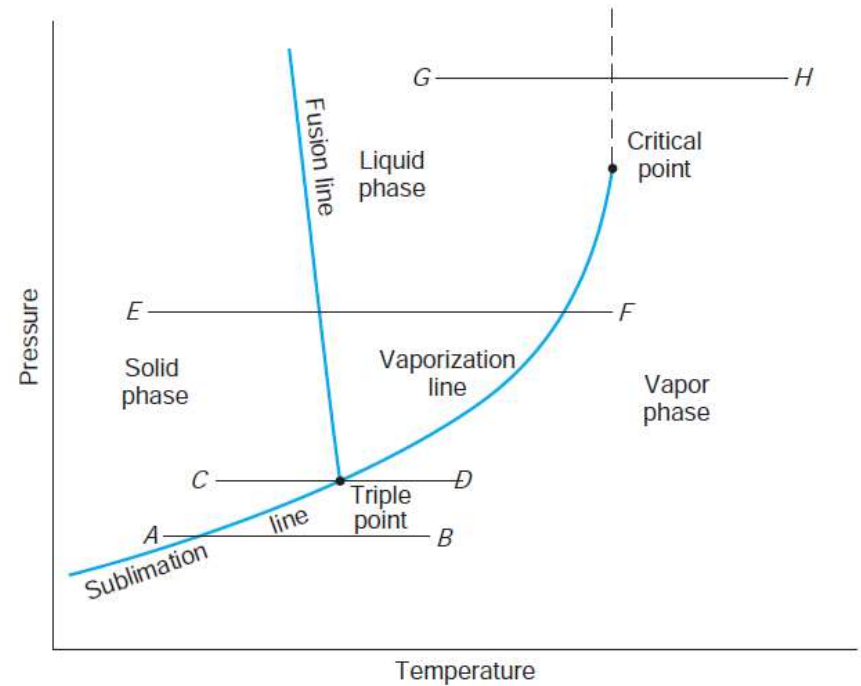


# Phase change of a pure substance



**FIGURE 3-23**

At triple-point pressure and temperature, a substance exists in three phases in equilibrium.

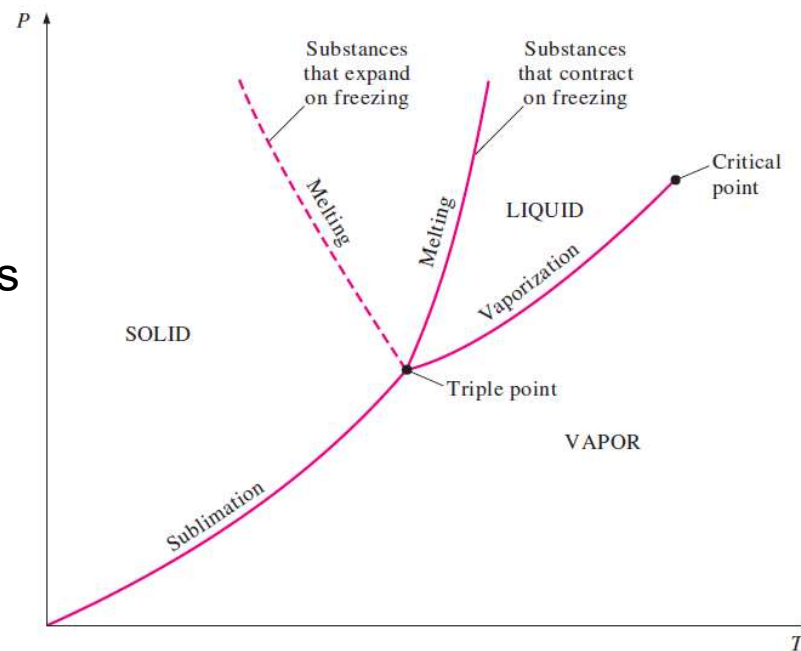


**FIGURE 3.5**  $P$ - $T$  diagram for a substance such as water.



# Property diagram for phase change process

This diagram is often called the **phase diagram** since all three phases are separated from each other by three lines







# Phase change of a pure substance

TABLE 3.2

*Some Solid-Liquid-Vapor Triple-Point Data*

	Temperature, °C	Pressure, kPa
Hydrogen (normal)	−259	7.194
Oxygen	−219	0.15
Nitrogen	−210	12.53
Carbon dioxide	−56.4	520.8
Mercury	−39	0.000 000 13
Water	0.01	0.6113
Zinc	419	5.066
Silver	961	0.01
Copper	1083	0.000 079

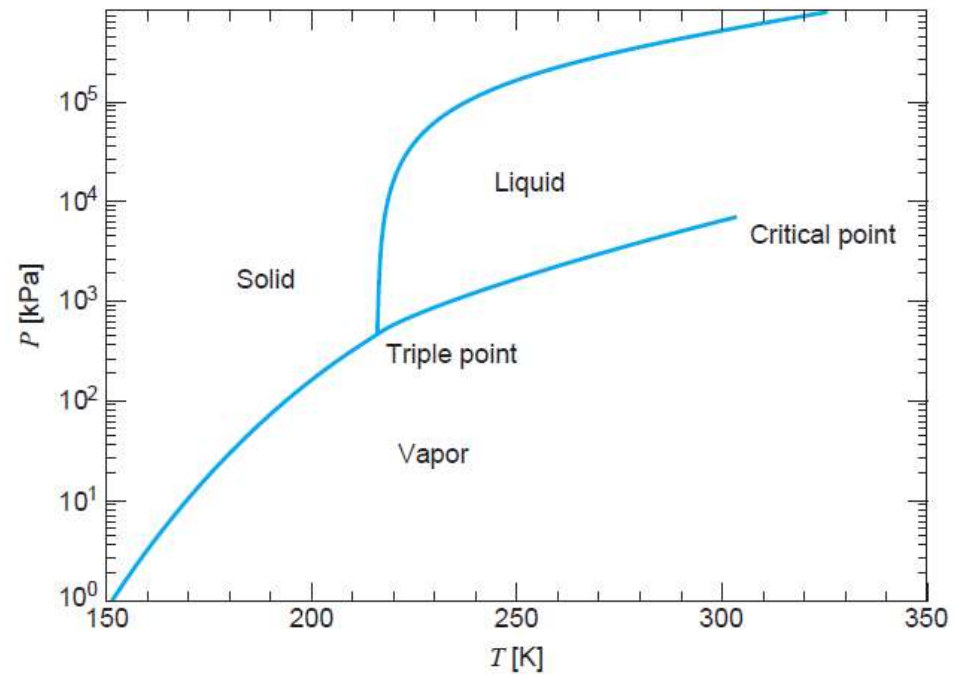


## Property diagram for phase change process

There are two ways a substance can pass from the solid to vapor phase: either it melts first into a liquid and subsequently evaporates, or it evaporates directly without melting first. The latter occurs at pressures below the triple-point value. Passing from the solid phase directly into the vapor phase is called **sublimation**.



## Phase change of a pure substance



**FIGURE 3.6** Carbon dioxide phase diagram.



## Phase change of a pure substance

Although we have made these comments with specific reference to water (only because of our familiarity with water), all pure substances exhibit the same general behavior.



## Property tables

Some thermodynamic properties can be measured easily, but others cannot and are calculated by using the relations between them and measurable properties.

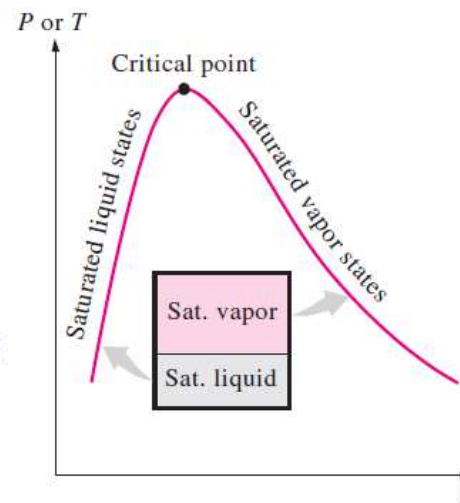


# Saturated liquid and saturated vapor state

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

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

**Quality**  $x$  as the ratio of the mass of vapor to the total mass of the mixture:



**FIGURE 4-34**

The relative amounts of liquid and vapor phases in a saturated mixture are specified by the *quality*  $x$ .

Temp. °C $T$	Sat. press. kPa $P_{\text{sat}}$	Specific volume m <sup>3</sup> /kg	
		Sat. liquid $v_f$	Sat. vapor $v_g$
85	57.868	0.001032	2.8261
90	70.183	0.001036	2.3593
95	84.609	0.001040	1.9808

**FIGURE 4-30**

A partial list of Table A-4.



## Ideal gas equation of state

The vapor phase of a substance is customarily called a gas when it is above the critical temperature.

Any equation that relates the pressure, temperature, and specific volume of a substance is called an **equation of state**.

The simplest and best-known equation of state for substances in the gas phase is the ideal-gas equation of state. This equation predicts the P-v-T behavior of a gas quite accurately within some properly selected region.



## Ideal equation of state

In 1662, Robert Boyle, an Englishman, observed during his experiments with a vacuum chamber **the pressure of gases is inversely proportional to their volume.** In 1802, Frenchmen J. Charles and J. Gay-Lussac experimentally determined that **at low pressures the volume of a gas is proportional to its temperature**

$$P = R \left( \frac{T}{v} \right)$$

$$Pv = RT$$

*P is the absolute pressure, T is the absolute temperature, and v is the specific volume*





# Ideal gas equation of state

## Boyle's Law

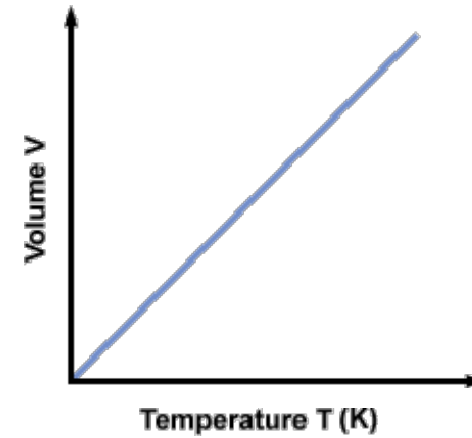
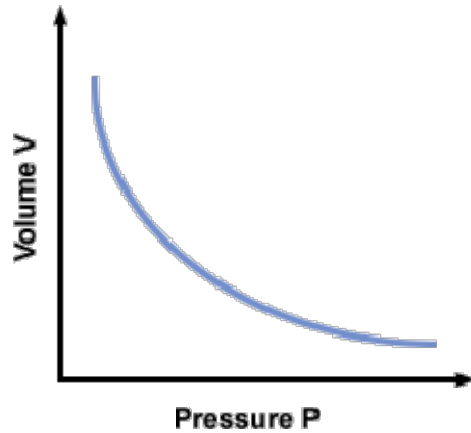
The absolute pressure exerted by a given mass of an ideal gas is inversely proportional to the volume it occupies if the temperature and amount of gas remain unchanged within a closed system.

## Charles Law

When the pressure on a sample of a dry gas is held constant, the absolute temperature and the volume will be directly related.



## Ideal gas equation of state



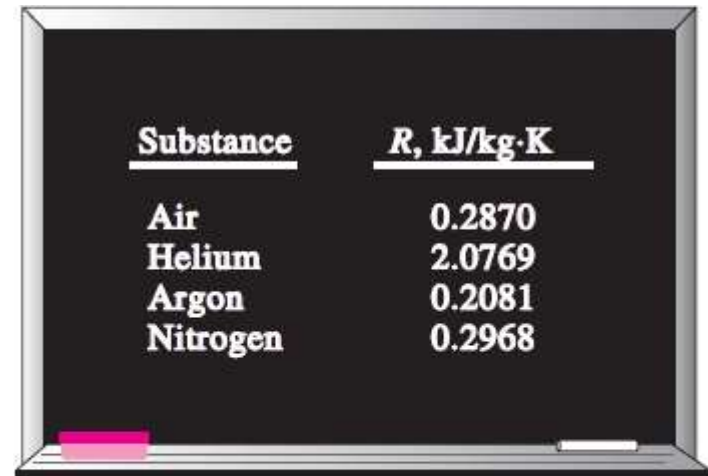


## Ideal gas equation of state

$$R = \frac{R_u}{M} \quad (\text{kJ/kg} \cdot \text{K} \text{ or } \text{kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})$$

$$R_u = \begin{cases} 8.31447 \text{ kJ/kmol} \cdot \text{K} \\ 8.31447 \text{ kPa} \cdot \text{m}^3/\text{kmol} \cdot \text{K} \\ 0.0831447 \text{ bar} \cdot \text{m}^3/\text{kmol} \cdot \text{K} \\ 1.98588 \text{ Btu/lbmol} \cdot \text{R} \\ 10.7316 \text{ psia} \cdot \text{ft}^3/\text{lbmol} \cdot \text{R} \\ 1545.37 \text{ ft} \cdot \text{lbf/lbmol} \cdot \text{R} \end{cases}$$

$$m = MN \quad (\text{kg})$$



<u>Substance</u>	<u>R, kJ/kg·K</u>
Air	0.2870
Helium	2.0769
Argon	0.2081
Nitrogen	0.2968

**FIGURE 4-45**

Different substances have different gas constants.



## Ideal gas equation of state

$$V = m\bar{v} \longrightarrow P\bar{v} = mRT$$

$$mR = (MN)R = NR_u \longrightarrow P\bar{v} = NR_uT$$

$$V = N\bar{V} \longrightarrow P\bar{V} = R_uT$$

where  $\bar{v}$  is the molar specific volume, that is, the volume per unit mole (in  $\text{m}^3/\text{kmol}$  or  $\text{ft}^3/\text{lbmol}$ ).

$$\frac{P_1\bar{V}_1}{T_1} = \frac{P_2\bar{V}_2}{T_2}$$

For a fixed mass at two different states



## Ideal gas equation of state



FIGURE 4-47

The ideal-gas relation often is not applicable to real gases; thus, care should be exercised when using it.

An ideal gas is an *imaginary substance that obeys the ideal gas equation of state*. It has been experimentally observed that the ideal-gas relation given closely approximates the  $P$ - $v$ - $T$  **behavior of real gases at low densities**. At low pressures and high temperatures, the density of a gas decreases, and the gas behaves as an ideal gas under these conditions

In the range of practical interest, many familiar gases such as air, nitrogen, oxygen, hydrogen, helium, argon, neon, krypton, and even heavier gases such as  $\text{CO}_2$  can be treated as ideal gases with negligible error (**often less than 1 percent**).



## Ideal gas equation of state

### **Example**

What is the mass of air contained in a room 6 m × 10 m × 4 m if the pressure is 100 kPa and the temperature is 25°C?

$$m = \frac{PV}{RT} = \frac{100 \text{ kN/m}^2 \times 240 \text{ m}^3}{0.287 \text{ kN m/kg K} \times 298.2 \text{ K}} = 280.5 \text{ kg}$$



## Ideal gas equation of state

### Example

A tank has a volume of  $0.5 \text{ m}^3$  and contains  $10 \text{ kg}$  of an ideal gas having a molecular mass of  $24$ . The temperature is  $25^\circ\text{C}$ . What is the pressure?

$$R = \frac{\bar{R}}{M} = \frac{8.3145 \text{ kN m/kmol K}}{24 \text{ kg/kmol}} \\ = 0.34644 \text{ kN m/kg K}$$

$$P = \frac{mRT}{V} = \frac{10 \text{ kg} \times 0.34644 \text{ kN m/kg K} \times 298.2 \text{ K}}{0.5 \text{ m}^3} \\ = 2066 \text{ kPa}$$



## Ideal gas equation of state

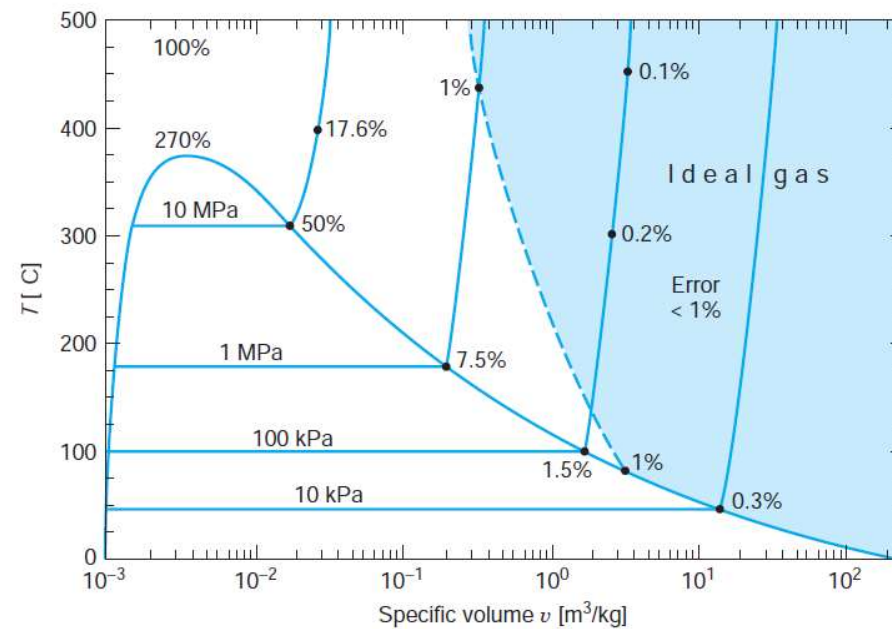
The ideal-gas equation of state is a good approximation at low density. **But what constitutes low density?** In other words, over what range of density will the ideal-gas equation of state hold with accuracy? The second question is, how much does an actual gas at a given pressure and temperature deviate from ideal-gas behavior?





# Ideal gas equation of state

**FIGURE 3.21**  
Temperature-specific  
volume diagram for  
water.



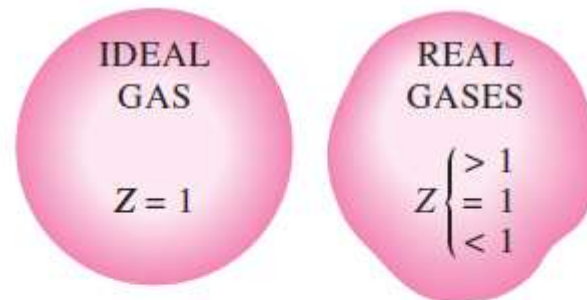


## Compressibility factor

$$Z = \frac{PV}{RT}$$

$$PV = ZRT$$

$$Z = \frac{V_{\text{actual}}}{V_{\text{ideal}}}$$



$$P_R = \frac{P}{P_{\text{cr}}} \quad \text{and} \quad T_R = \frac{T}{T_{\text{cr}}}$$

**FIGURE 4-50**

The compressibility factor is unity for ideal gases.

For real gases Z can be greater than or less than unity



## Compressibility factor

At very low pressures, a gas behaves as an ideal gas regardless of temperature.

At high temperatures ideal-gas behavior can be approximated with good accuracy regardless of pressure

The deviation of a gas from ideal-gas behavior is greatest in the vicinity of the critical point

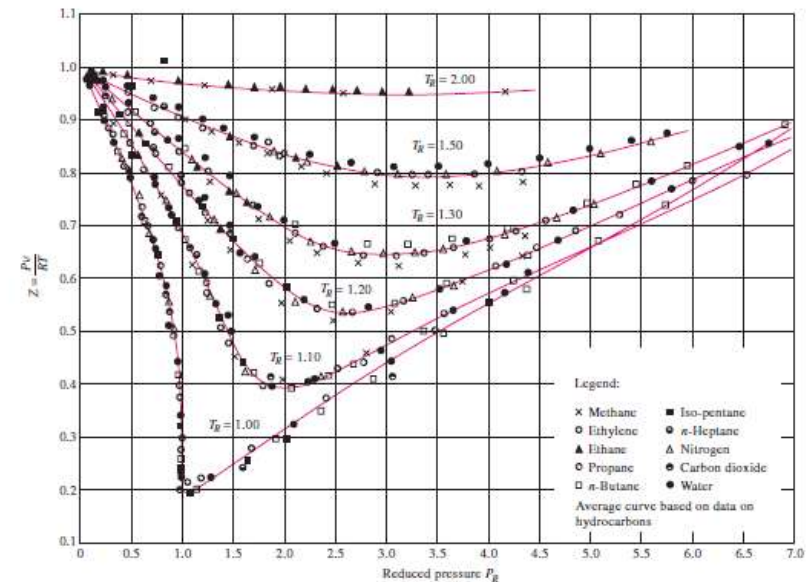
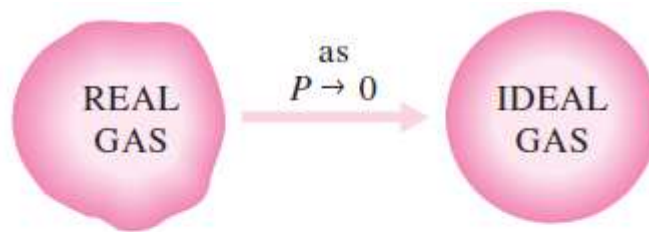


FIGURE 4-51

Comparison of Z factors for various gases.

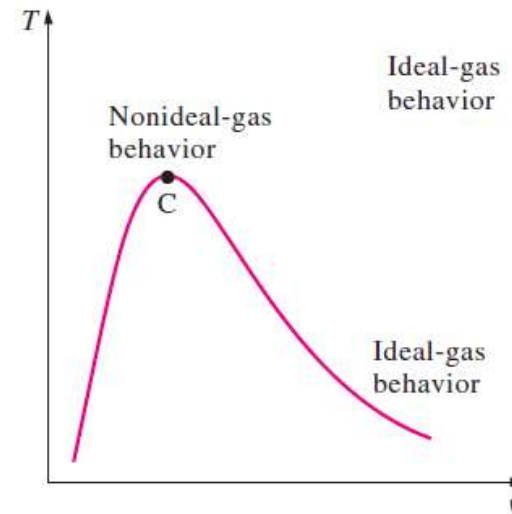


## Compressibility factor



**FIGURE 4-52**

At very low pressures, all gases approach ideal-gas behavior (regardless of their temperature).



**FIGURE 4-53**

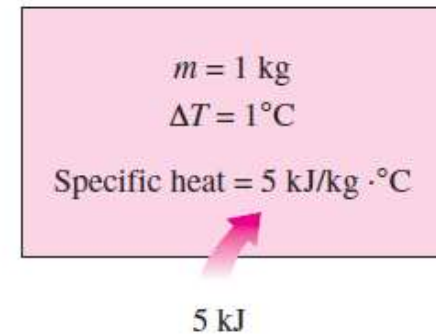
Gases deviate from the ideal-gas behavior the most in the neighborhood of the critical point.



# Energy analysis of closed system

## Specific Heats

The specific heat is defined as the energy required to raise the temperature of a unit mass of a substance by one degree



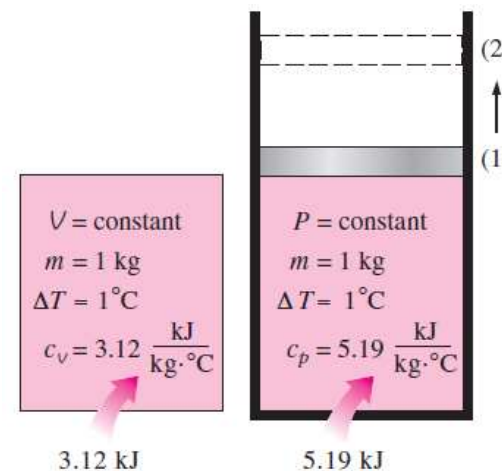
**FIGURE 4–18**

Specific heat is the energy required to raise the temperature of a unit mass of a substance by one degree in a specified way.



## Energy analysis of closed system

The specific heat at constant pressure  $c_p$  is always greater than  $c_v$  because at constant pressure the system is allowed to expand and the energy for this expansion work must also be supplied to the system.



**FIGURE 4-19**

Constant-volume and constant-pressure specific heats  $c_v$  and  $c_p$  (values given are for helium gas).



# Energy analysis of closed system

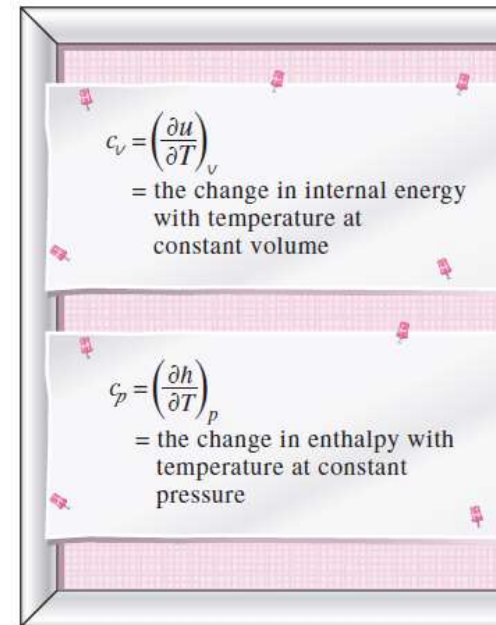
$$e_{\text{in}} - e_{\text{out}} = \Delta e_{\text{system}}$$

$$\delta e_{\text{in}} - \delta e_{\text{out}} = du$$

$$c_v dT = du \quad \text{at constant volume}$$

$$c_v = \left( \frac{\partial u}{\partial T} \right)_v$$

$$c_p = \left( \frac{\partial h}{\partial T} \right)_p$$

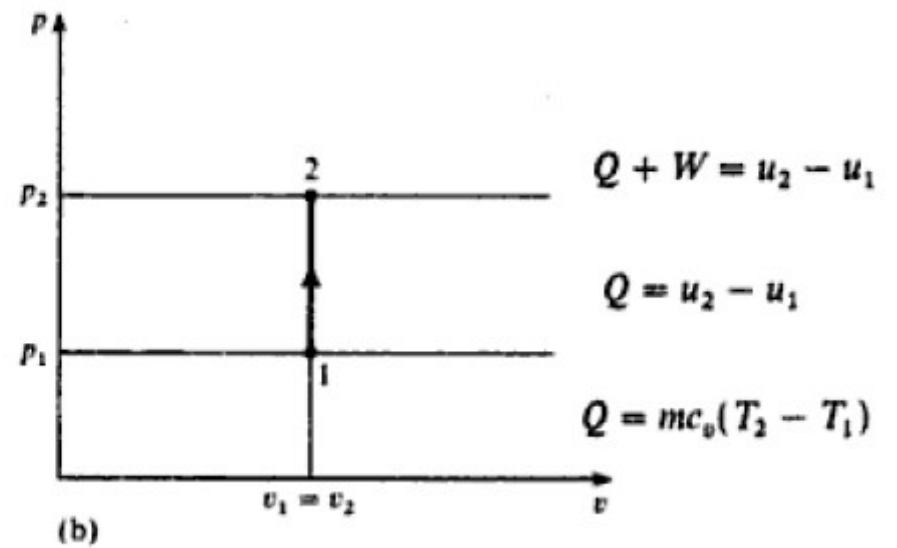
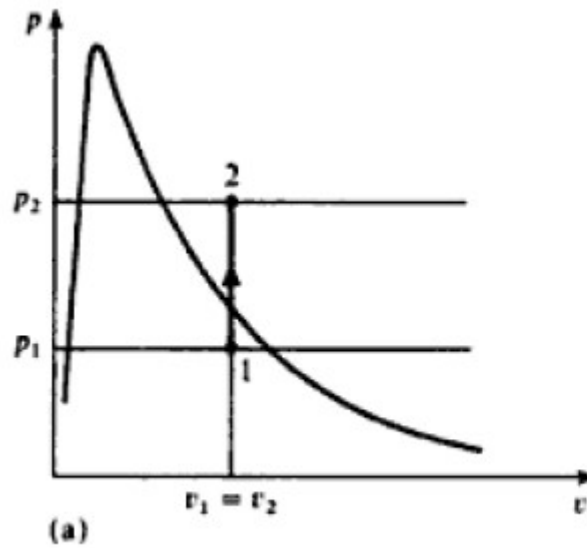


**FIGURE 4-20**

Formal definitions of  $c_v$  and  $c_p$ .



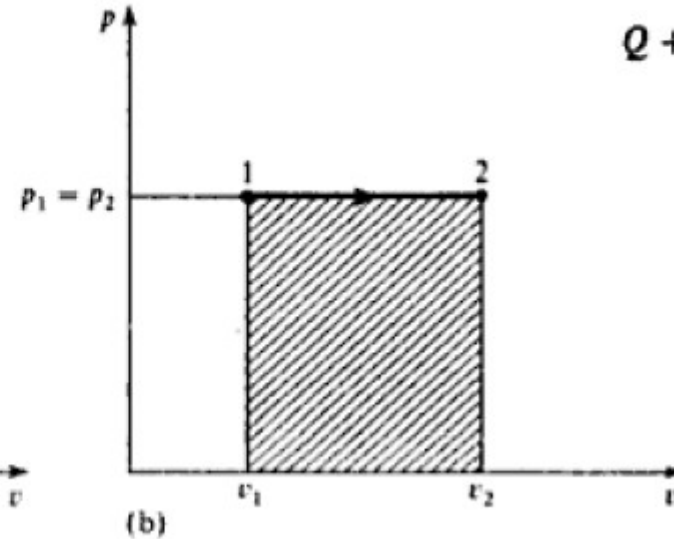
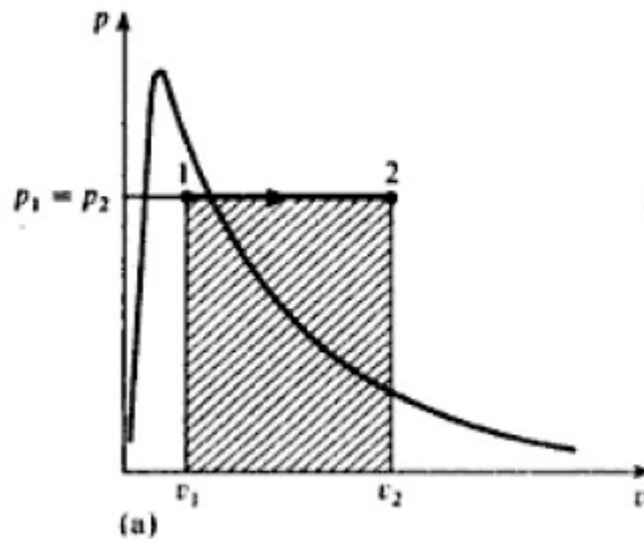
# Thermodynamical Processes







# Thermodynamical Processes



$$Q + W = u_2 - u_1$$

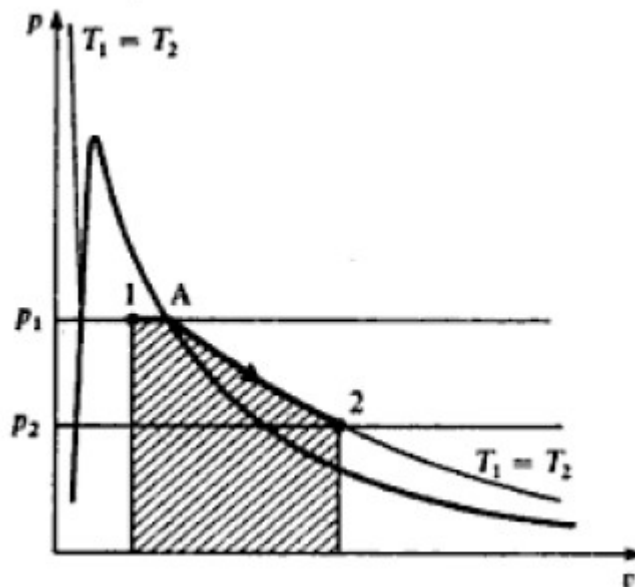
$$Q = (u_2 - u_1) + p(v_2 - v_1) = (u_2 + pv_2) - (u_1 + pv_1)$$

$$Q = h_2 - h_1$$

$$Q = mc_p(T_2 - T_1)$$



# Thermodynamical Processes



$$Q + W = u_2 - u_1$$

$$W = p_1 V_1 \ln\left(\frac{p_2}{p_1}\right)$$

$$W = mRT \ln\left(\frac{p_2}{p_1}\right)$$



## Thermodynamical Processes

For a perfect gas from Joule's law, equation (2.14), we have

$$U_2 - U_1 = mc_v(T_2 - T_1)$$

Hence for an isothermal process for a perfect gas, since  $T_2 = T_1$ , then

$$U_2 - U_1 = 0$$

i.e. the internal energy remains constant in an isothermal process for a perfect gas.

From the non-flow energy equation (1.4) for unit mass

$$Q + W = u_2 - u_1$$

Therefore, since  $u_2 = u_1$ , then

$$Q + W = 0 \quad (3.12)$$

Note that the heat flow plus the work input is zero in an isothermal process *for a perfect gas only*. From Example 3.2 for steam it is seen that, although the process is isothermal, the change in internal energy is 217.5 kJ/kg, and therefore the heat supplied plus the work done is not zero.



# Thermodynamical Processes

From the non-flow equation (1.4),

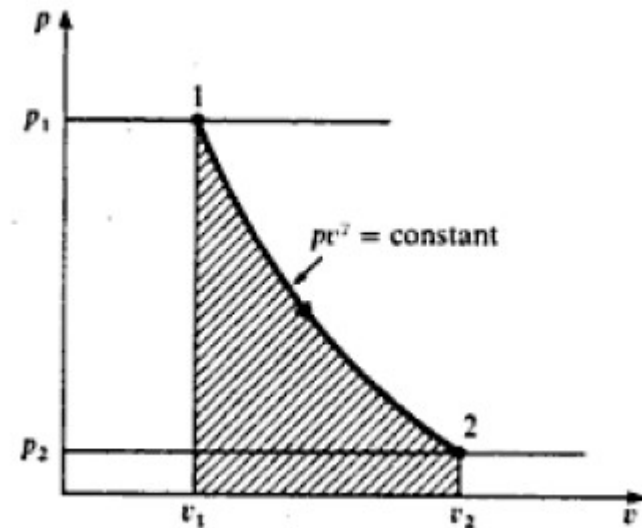
$$Q + W = u_2 - u_1$$

and for an adiabatic process

$$Q = 0$$

Therefore we have

$$W = u_2 - u_1 \quad \text{for any adiabatic non-flow process}$$





## Thermodynamical Processes

i.e.  $p v = R T$

therefore

$$p = \frac{R T}{v}$$

Substituting in equation (3.16)

$$\frac{R T}{v} v^{\gamma} = \text{constant}$$

i.e.  $T v^{\gamma-1} = \text{constant}$

Also,  $v = (R T)/p$ ; hence substituting in equation (3.16)

$$p \left( \frac{R T}{p} \right)^{\gamma} = \text{constant}$$

therefore

$$\frac{T^{\gamma}}{p^{\gamma-1}} = \text{constant}$$

or  $\frac{T}{p^{(\gamma-1)/\gamma}} = \text{constant}$



# Thermodynamical Processes

$$p_1 v_1^\gamma = p_2 v_2^\gamma \quad \text{or} \quad \frac{p_1}{p_2} = \left( \frac{v_2}{v_1} \right)^\gamma$$

From equation (3.17)

$$T_1 v_1^{\gamma-1} = T_2 v_2^{\gamma-1} \quad \text{or} \quad \frac{T_1}{T_2} = \left( \frac{v_2}{v_1} \right)^{\gamma-1}$$

From equation (3.18)

$$\frac{T_1}{p_1^{(\gamma-1)/\gamma}} = \frac{T_2}{p_2^{(\gamma-1)/\gamma}} \quad \text{or} \quad \frac{T_1}{T_2} = \left( \frac{p_1}{p_2} \right)^{(\gamma-1)/\gamma}$$



# Thermodynamical Processes

i.e. for unit mass  $u_2 - u_1 = c_v(T_2 - T_1)$

therefore

$$W = c_v(T_2 - T_1)$$

Also, from equation (2.21),

$$c_v = \frac{R}{(\gamma - 1)}$$

Hence substituting

$$W = \frac{R(T_2 - T_1)}{(\gamma - 1)}$$

Using equation (2.5),  $pv = RT$ ,

$$W = \frac{p_2 v_2 - p_1 v_1}{\gamma - 1}$$



# Laws of thermodynamics

## First Law

The first law of thermodynamics is the application of the conservation of energy principle to heat and thermodynamic processes.

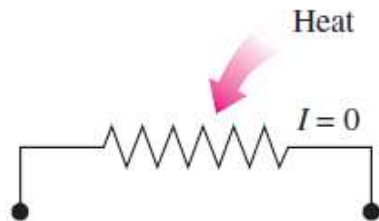
The First Law of Thermodynamics states that heat is a form of energy, and thermodynamic processes are therefore subject to the principle of conservation of energy. This means that heat energy cannot be created or destroyed. It can, however, be transferred from one location to another and converted to and from other forms of energy.





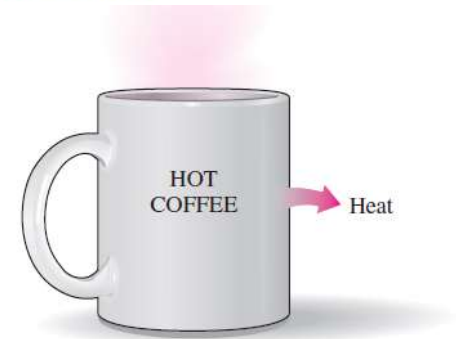
## Laws of Thermodynamics

As pointed out repeatedly in those chapters, energy is a conserved property, and no process is known to have taken place in violation of the first law of thermodynamics. Therefore, it is reasonable to conclude that a process must satisfy the first law to occur. However, as explained here, satisfying the first law alone does not ensure that the process will actually take place.



**FIGURE 6-2**

Transferring heat to a wire will not generate electricity.



**FIGURE 6-1**

A cup of hot coffee does not get hotter in a cooler room.



## Laws of Thermodynamics

It is clear from these arguments that processes proceed in a ***certain direction and not in the reverse direction***.

The first law places no restriction on the direction of a process, but satisfying the first law does not ensure that the process can actually occur.

This inadequacy of the first law to identify whether a process can take place is remedied by introducing another general principle, the ***second law of thermodynamics***.

A process cannot occur unless it satisfies both the first and the second laws of thermodynamics

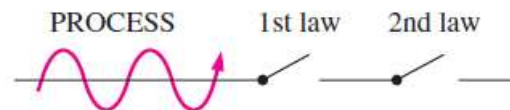


# Laws of Thermodynamics



**FIGURE 6-4**

Processes occur in a certain direction, and not in the reverse direction.



**FIGURE 6-5**

A process must satisfy both the first and second laws of thermodynamics to proceed.



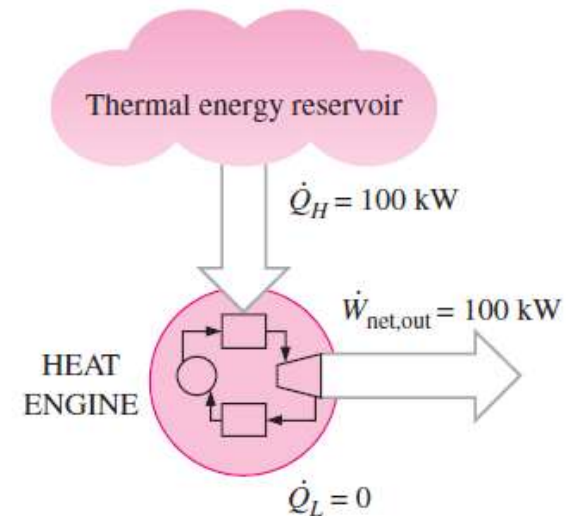
# Laws of Thermodynamics

## 2<sup>nd</sup> Law of Thermodynamics

### Kelvin-Planck Statement

It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.

No heat engine can have a thermal efficiency of 100 percent, or as for a power plant to operate, the working fluid must exchange heat with the environment as well as the furnace.



**FIGURE 6–18**

A heat engine that violates the Kelvin–Planck statement of the second law.



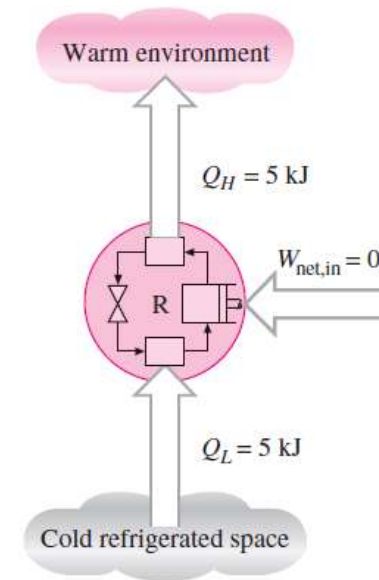
# Laws of Thermodynamics

## 2<sup>ND</sup> Law of Thermodynamics

### Clausius Statement

It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body.

To date, no experiment has been conducted that contradicts the second law, and this should be taken as sufficient proof of its validity.



**FIGURE 6-26**

A refrigerator that violates the Clausius statement of the second law.



## Laws of Thermodynamics

The Kelvin–Planck and the Clausius statements are equivalent in their consequences, and either statement can be used as the expression of the second law of thermodynamics. **Any device that violates the Kelvin–Planck statement also violates the Clausius statement, and vice versa.**



## Laws of Thermodynamics

The use of the second law of thermodynamics is not limited to identifying the direction of processes, however. The second law also asserts that **energy has quality as well as quantity**. The first law is concerned with the quantity of energy and the transformations of energy from one form to another with no regard to its quality.



# **Thermodynamical Cycles**

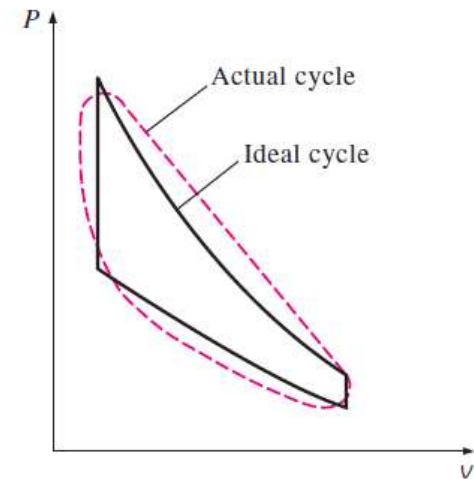
## **Part-1 Gas power cycles (Chapter 9 Cengel)**





# Thermodynamical Cycles

When the actual cycle is stripped of all the internal irreversibilities and complexities, we end up with a cycle that resembles the actual cycle closely but is made up totally of internally reversible processes. Such a cycle is called an **ideal cycle**.



**FIGURE 9-2**

The analysis of many complex processes can be reduced to a manageable level by utilizing some idealizations.



## Thermodynamical Cycles

Heat engines are designed for the purpose of converting thermal energy to work, and their performance is expressed in terms of the **thermal efficiency**  $\eta_{th}$ , which is the ratio of the net work produced by the engine to the total heat input:

$$\eta_{th} = \frac{W_{net}}{Q_{in}} \quad \text{or} \quad \eta_{th} = \frac{w_{net}}{q_{in}}$$



**FIGURE 9–3**

Care should be exercised in the interpretation of the results from ideal cycles.

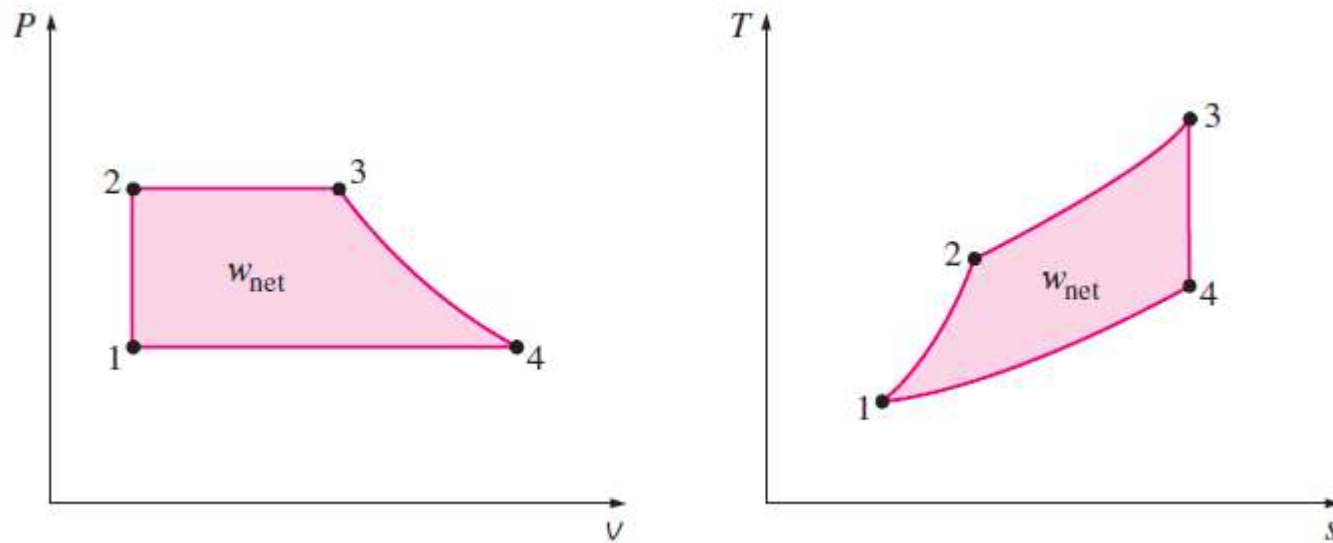


# Thermodynamcial Cycles

1. The cycle does not involve any *friction*. Therefore, the working fluid does not experience any pressure drop as it flows in pipes or devices such as heat exchangers.
2. All expansion and compression processes take place in a *quasi-equilibrium* manner.
3. The pipes connecting the various components of a system are well insulated, and *heat transfer* through them is negligible.



# Thermodynamical Cycles





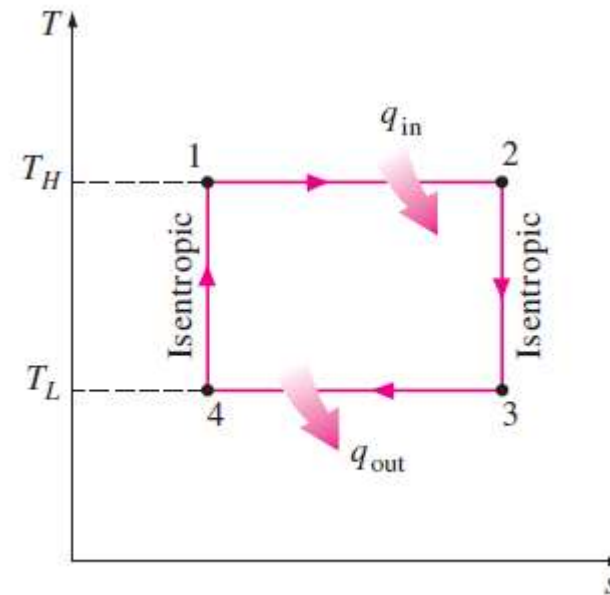
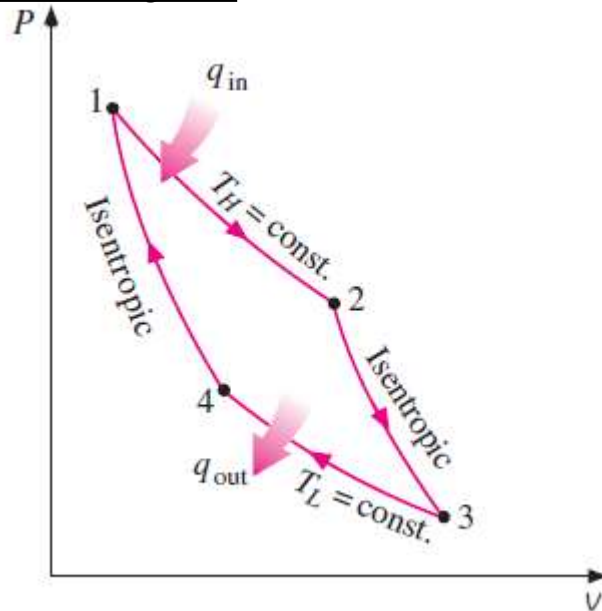
## Thermodynamical Cycles

On a  $T$ - $s$  diagram, a *heat-addition* process proceeds in the direction of increasing entropy, a *heat-rejection* process proceeds in the direction of decreasing entropy, and an *isentropic* (internally reversible, adiabatic) process proceeds at constant entropy. The area under the process curve on a  $T$ - $s$  diagram represents the heat transfer for that process. The area under the heat addition process on a  $T$ - $s$  diagram is a geometric measure of the total heat supplied during the cycle  $q_{in}$ , and the area under the heat rejection process is a measure of the total heat rejected  $q_{out}$ . The difference between these two (the area enclosed by the cyclic curve) is the net heat transfer, which is also the net work produced during the cycle. Therefore, on a  $T$ - $s$  diagram, the ratio of the area enclosed by the cyclic curve to the area under the heat-addition process curve represents the thermal efficiency of the cycle. Any modification that increases the ratio of these two areas will also increase the thermal efficiency of the cycle.



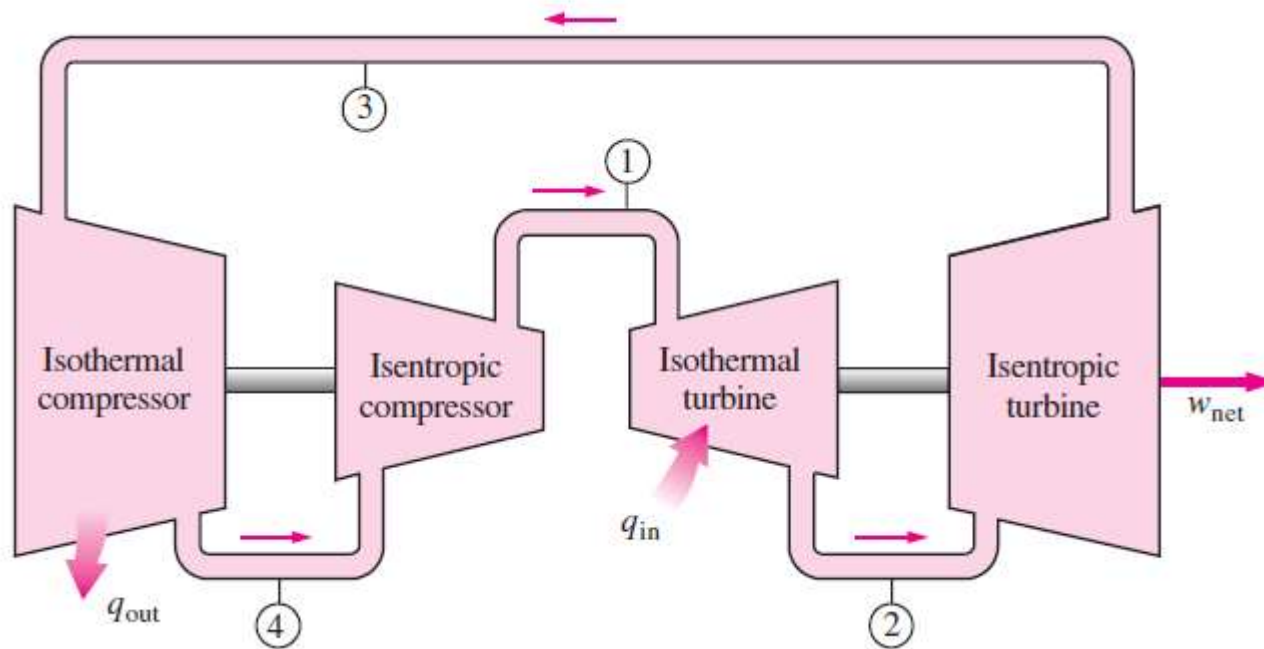
# Thermodynamical Cycles

## Carnot Cycle





# Thermodynamical Cycles



The Carnot cycle is the most efficient cycle that can be executed between a heat source at temperature  $T_H$  and a sink at temperature  $T_L$

$$\eta_{th,Carnot} = 1 - \frac{T_L}{T_H}$$



## Thermodynamical Cycles

Reversible isothermal heat transfer is very difficult to achieve in reality because it would require **very large heat exchangers and it would take a very long time** (a power cycle in a typical engine is completed in a fraction of a second). Therefore, it is not practical to build an engine that would operate on a cycle that closely approximates the Carnot cycle.

3000 rpm=50 rps

1 s= 25 working cycles

1 working cycle= 0.04 s= 720° rotation of crank shaft





# Thermodynamical Cycles

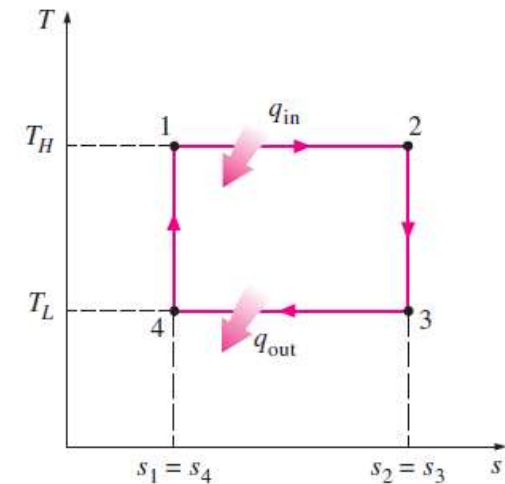
The real value of the Carnot cycle comes from its being a standard against which the actual or the ideal cycles can be compared. The thermal efficiency of the Carnot cycle is a function of the sink and source temperatures only, and the thermal efficiency relation for the Carnot cycle (Eq. 9–2) conveys an important message that is equally applicable to both ideal and actual cycles: *Thermal efficiency increases with an increase in the average temperature at which heat is supplied to the system or with a decrease in the average temperature at which heat is rejected from the system.*



# Thermodynamical Cycles

## Carnot Cycle

$$\eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_L(s_2 - s_1)}{T_H(s_2 - s_1)} = 1 - \frac{T_L}{T_H}$$

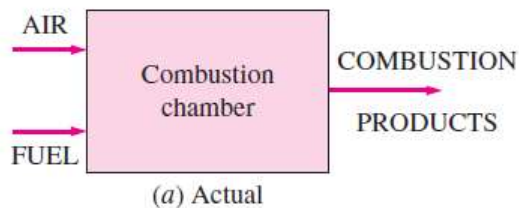


**FIGURE 9-8**

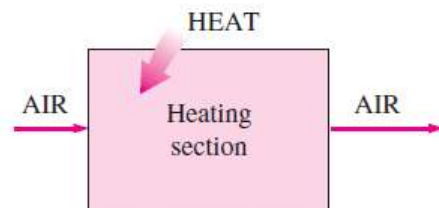
*T-s* diagram for Example 9-1.



# Air Standard Assumptions



(a) Actual



(b) Ideal

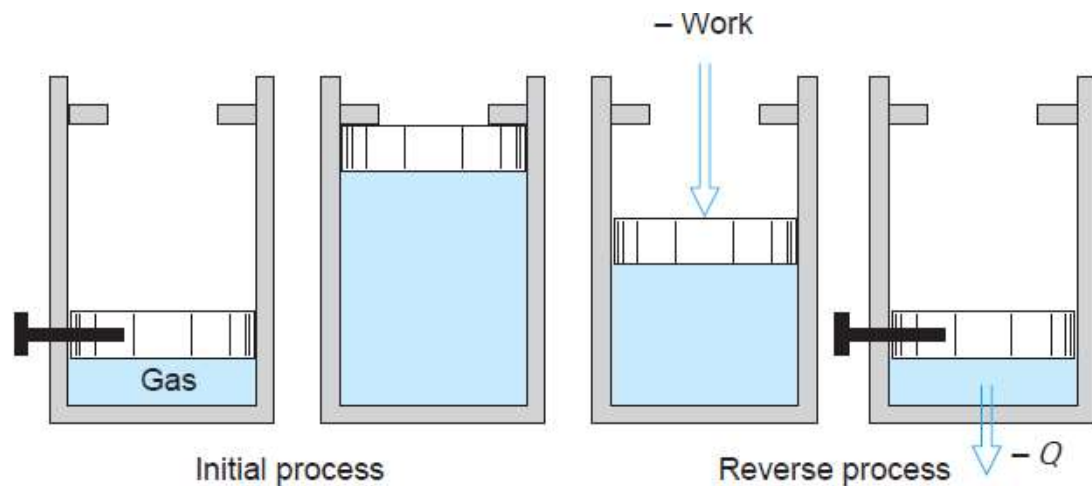
1. The working fluid is air, which continuously circulates in a closed loop and always behaves as an ideal gas.
2. All the processes that make up the cycle are internally reversible.
3. The combustion process is replaced by a heat-addition process from an external source (Fig. 9–9).
4. The exhaust process is replaced by a heat-rejection process that restores the working fluid to its initial state.



## Air standard assumptions

A **reversible process** for a system is defined as a process that, once having taken place, can be reversed and in so doing leave no change in either system or surroundings.

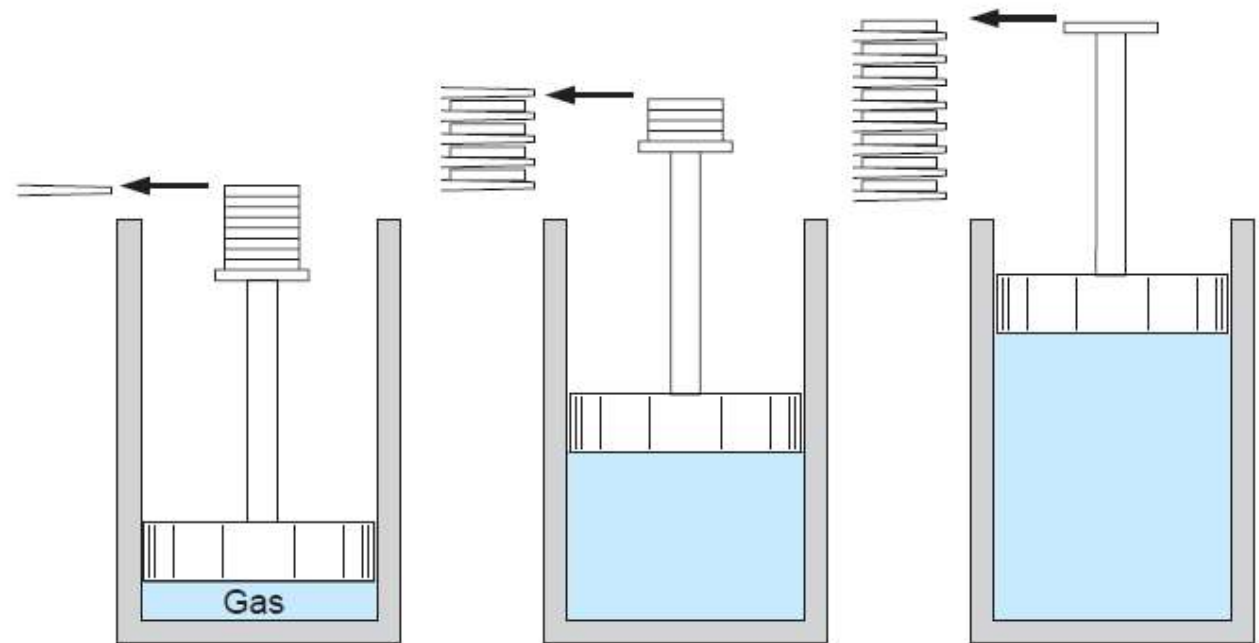
**FIGURE 7.12** An example of an irreversible process.





## Air standard assumptions

**FIGURE 7.13** An example of a process that approaches reversibility.

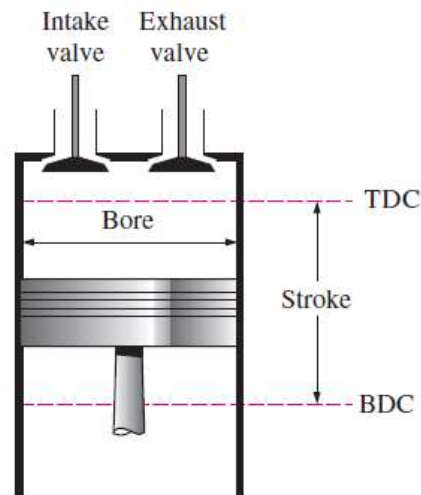




There are many factors that make processes irreversible. Four of those factors—friction, unrestrained expansion, heat transfer through a finite temperature difference, and mixing of two different substances—are considered in this section.

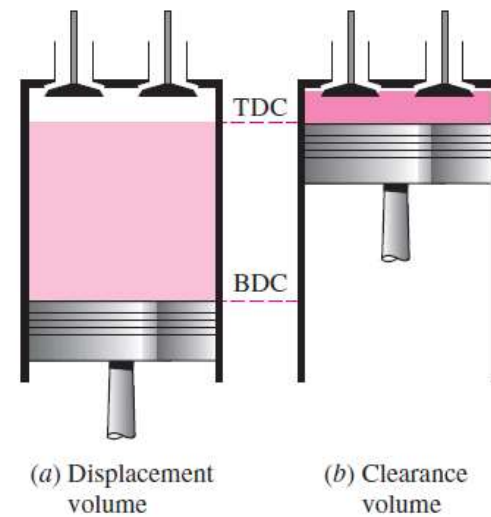


# Reciprocating Internal Combustion Engines



**FIGURE 9-10**

Nomenclature for reciprocating engines.



**FIGURE 9-11**

Displacement and clearance volumes of a reciprocating engine.



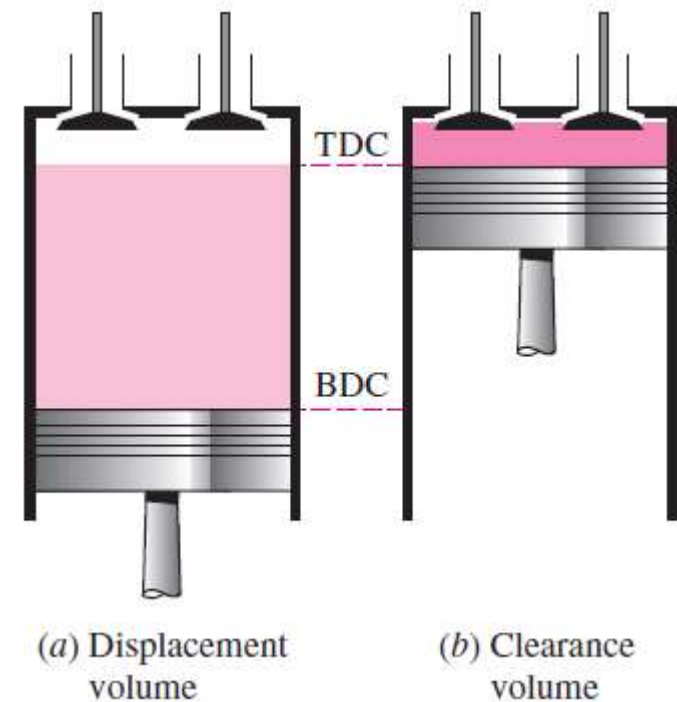
# Internal Combustion Engines

compression ratio

$$r = \frac{V_{\max}}{V_{\min}} = \frac{V_{\text{BDC}}}{V_{\text{TDC}}}$$

mean effective pressure (MEP)

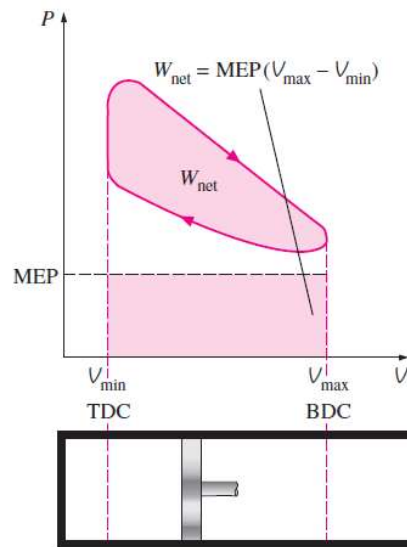
$$\text{MEP} = \frac{W_{\text{net}}}{V_{\max} - V_{\min}} = \frac{w_{\text{net}}}{v_{\max} - v_{\min}}$$







# Internal Combustion Engines

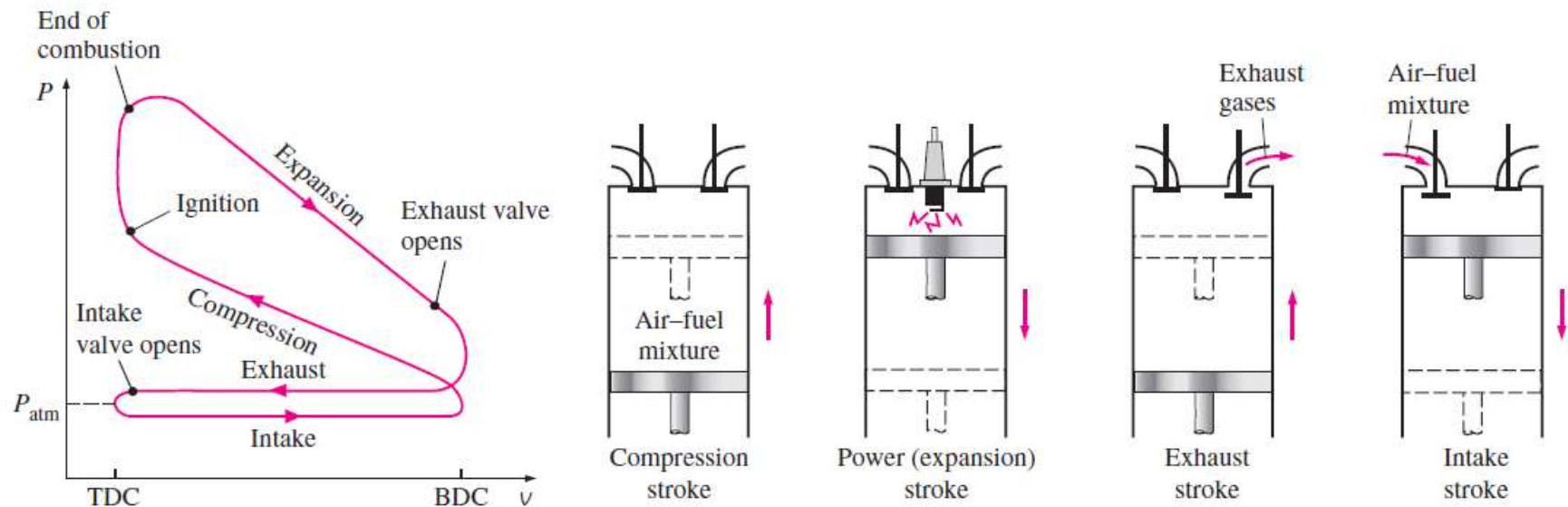


**FIGURE 9-12**

The net work output of a cycle is equivalent to the product of the mean effective pressure and the displacement volume.



# Internal Combustion Engines

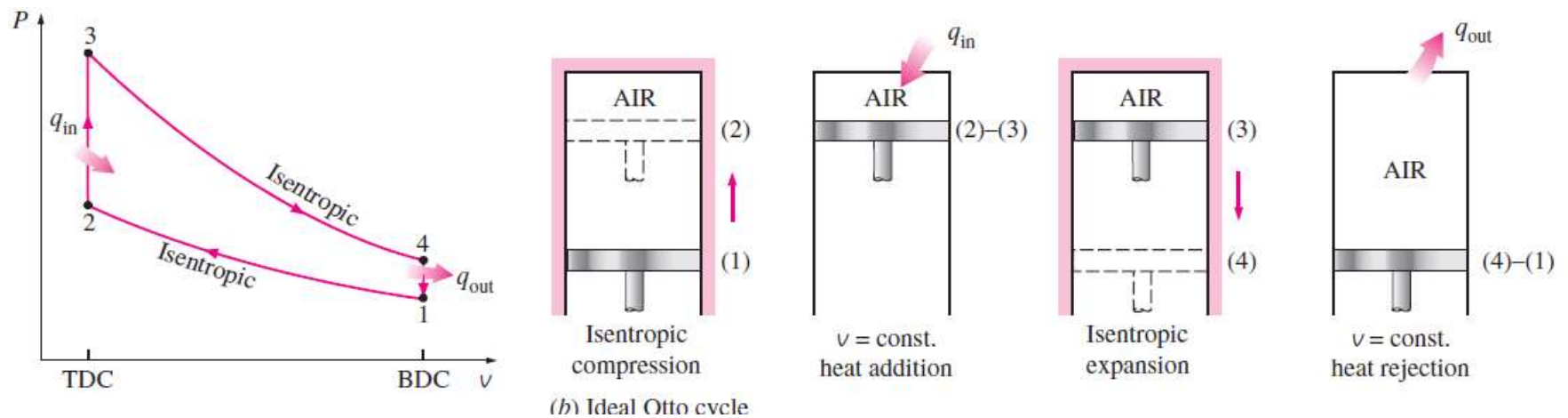




# Otto Cycle

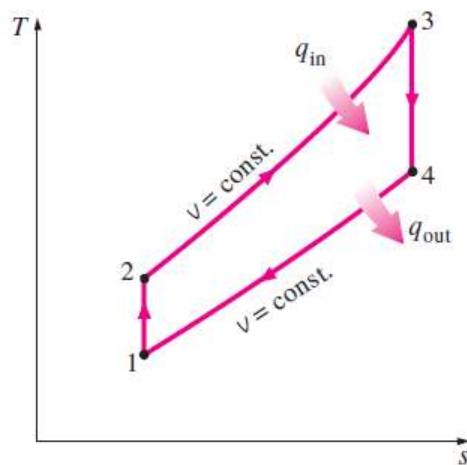


# Internal Combustion Engines





## Otto-Cycle



**FIGURE 9-16**

*T-s* diagram of the ideal Otto cycle.

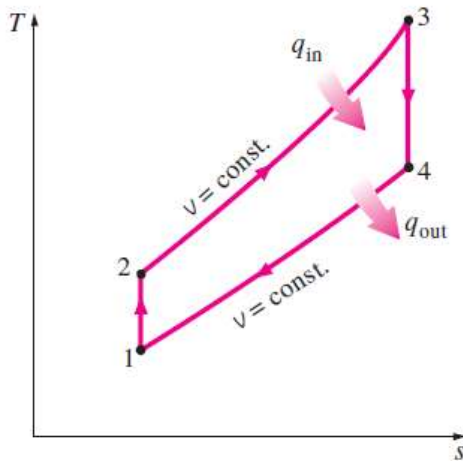
$$\eta_{\text{th, Otto}} = \frac{w_{\text{net}}}{q_{\text{in}}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$$

$$\frac{T_1}{T_2} = \left( \frac{v_2}{v_1} \right)^{k-1} = \left( \frac{v_3}{v_4} \right)^{k-1} = \frac{T_4}{T_3}$$

$$\eta_{\text{th, Otto}} = 1 - \frac{1}{r^{k-1}}$$

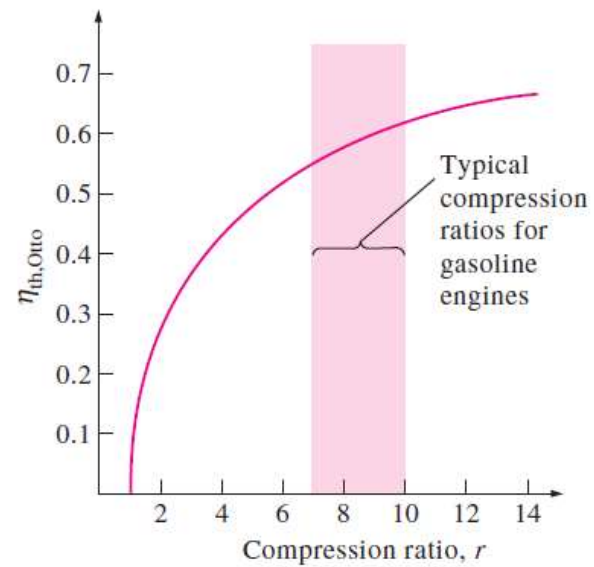


# Otto Cycle



**FIGURE 9-16**

*T-s* diagram of the ideal Otto cycle.



**FIGURE 9-17**

Thermal efficiency of the ideal Otto cycle as a function of compression ratio ( $k = 1.4$ ).



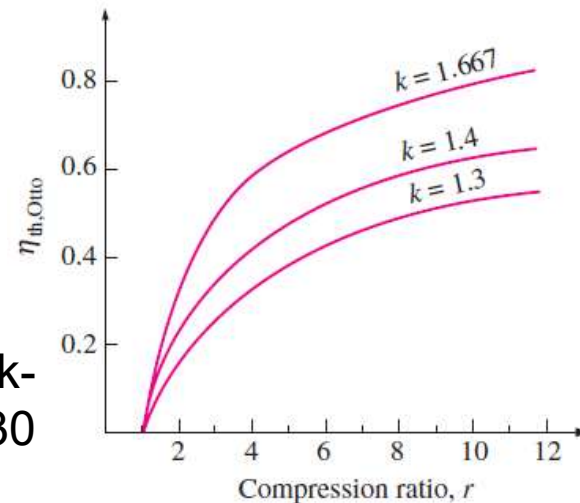
## Otto-Cycle

For a given compression ratio, the thermal efficiency of an actual spark-ignition engine is less than that of an ideal Otto cycle because of the irreversibilities, such as friction, and other factors such as incomplete combustion.



## Otto-Cycle

The thermal efficiencies of actual spark-ignition engines range from about 25 to 30 percent.



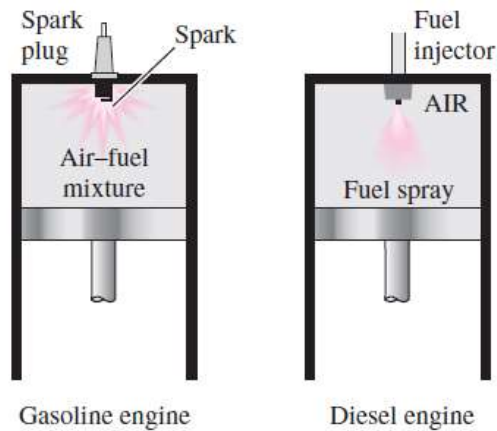
**FIGURE 9-18**

The thermal efficiency of the Otto cycle increases with the specific heat ratio  $k$  of the working fluid.



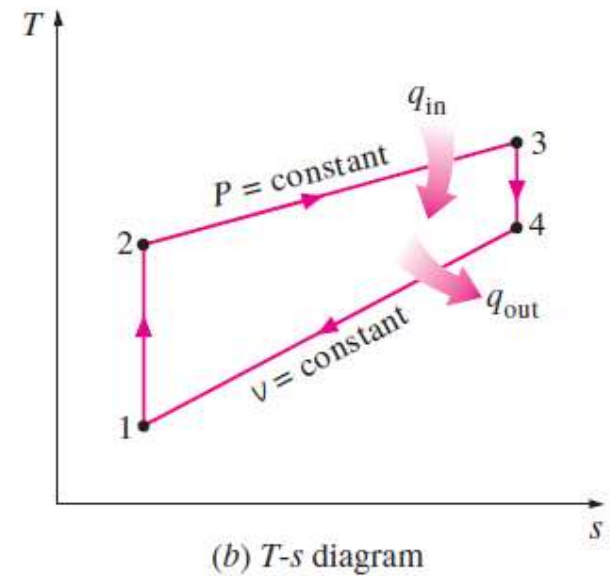
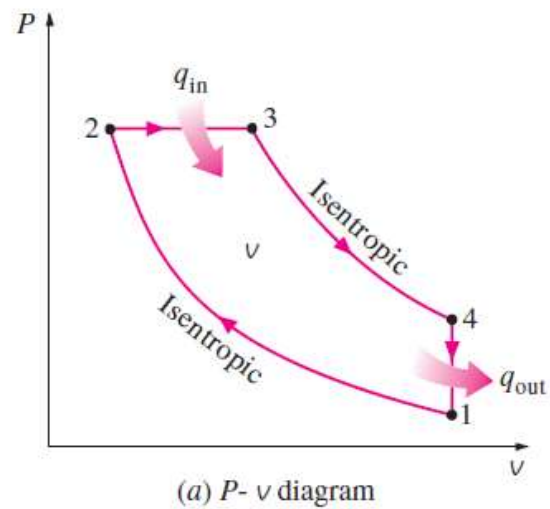


# Diesel Cycle



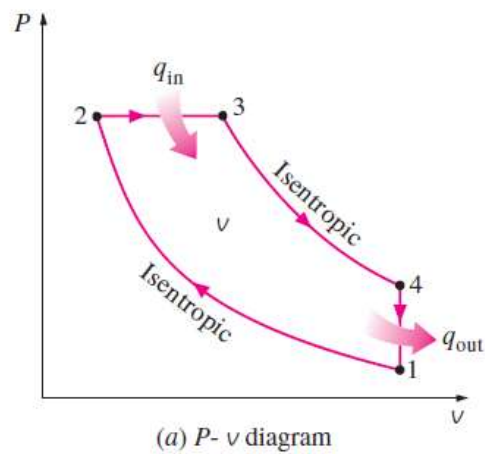
**FIGURE 9-20**

In diesel engines, the spark plug is replaced by a fuel injector, and only air is compressed during the compression process.





# Diesel Cycle



$$\eta_{th,Diesel} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{k(T_3 - T_2)} = 1 - \frac{T_1(T_4/T_1 - 1)}{kT_2(T_3/T_2 - 1)}$$

$$r_c = \frac{V_3}{V_2} = \frac{V_3}{V_2}$$

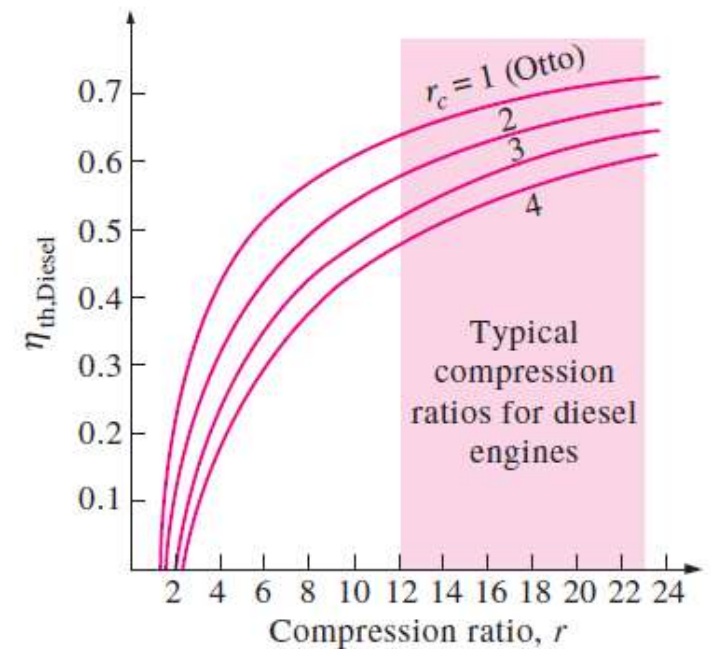
$$\eta_{th,Diesel} = 1 - \frac{1}{r^{k-1}} \left[ \frac{r_c^k - 1}{k(r_c - 1)} \right]$$



## Diesel cycle

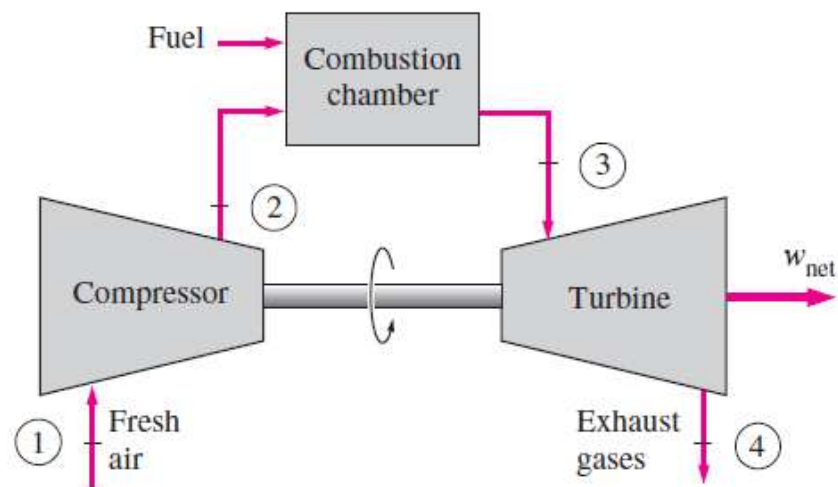
$$\eta_{th,Otto} > \eta_{th,Diesel}$$

Diesel engines operate at **much higher compression ratios** and thus are usually more efficient than the spark-ignition (gasoline) engines. Thermal efficiencies of large diesel engines range from about 35 to 40 percent



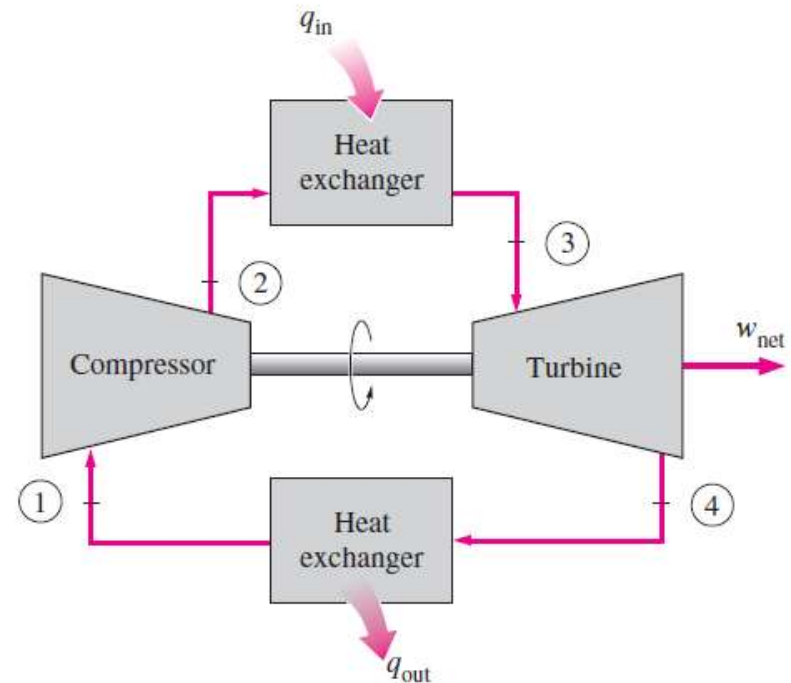


# Brayton Cycle



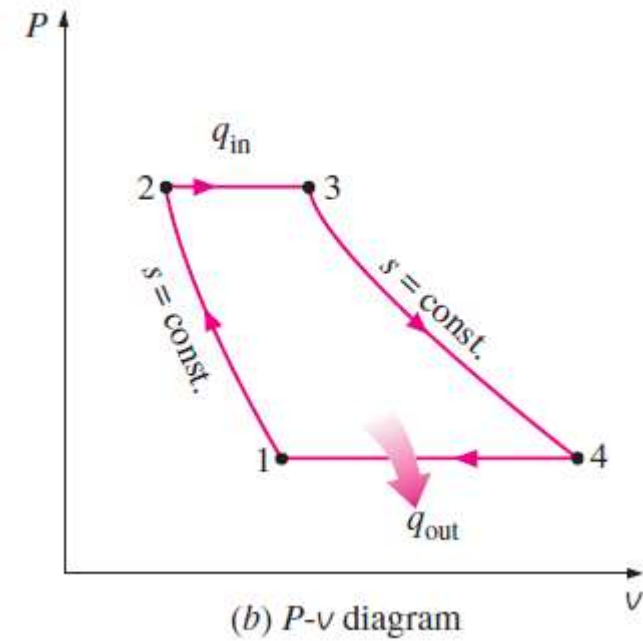
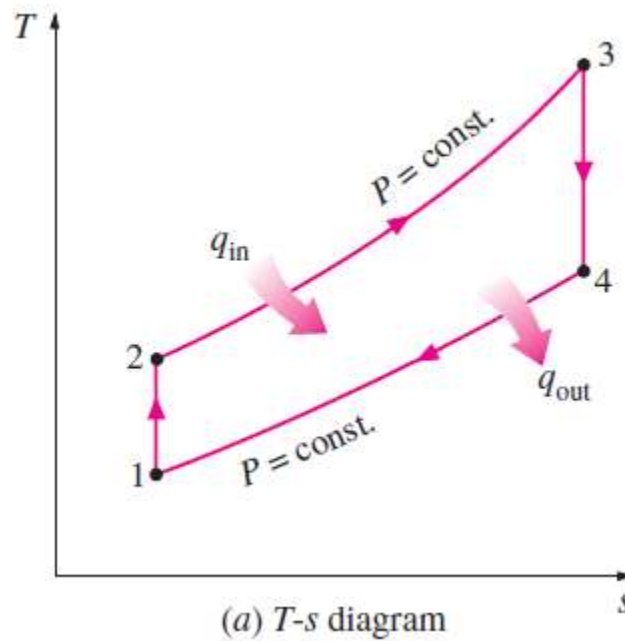
**FIGURE 9-29**

An open-cycle gas-turbine engine.



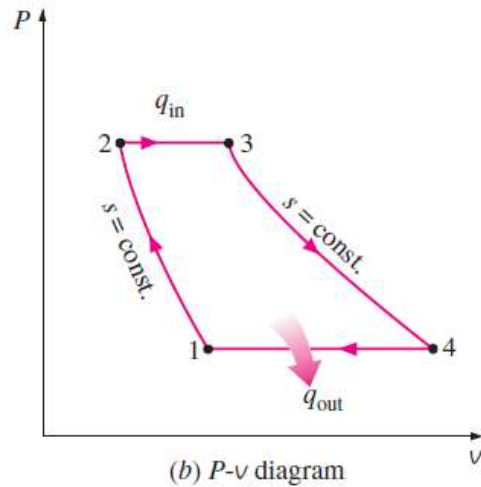


# Brayton cycle





# Brayton Cycle



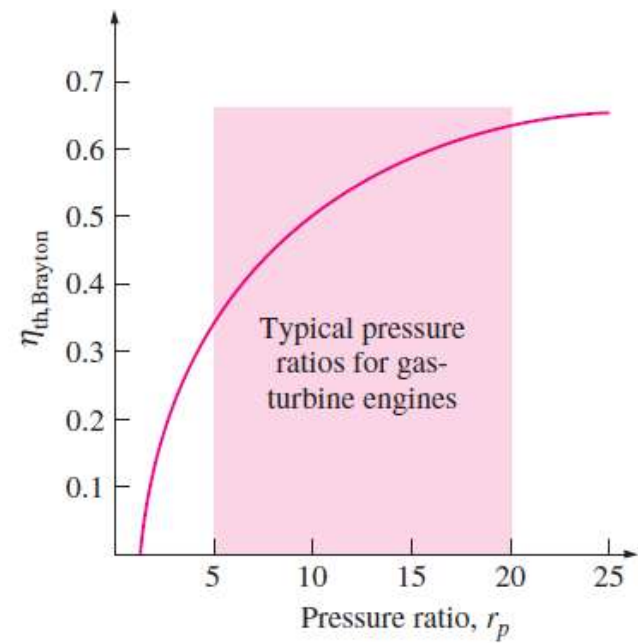
$$\eta_{\text{th,Brayton}} = \frac{w_{\text{net}}}{q_{\text{in}}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{c_p(T_4 - T_1)}{c_p(T_3 - T_2)} = 1 - \frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = \left(\frac{P_3}{P_4}\right)^{(k-1)/k} = \frac{T_3}{T_4}$$

$$\eta_{\text{th,Brayton}} = 1 - \frac{1}{r_p^{(k-1)/k}}$$



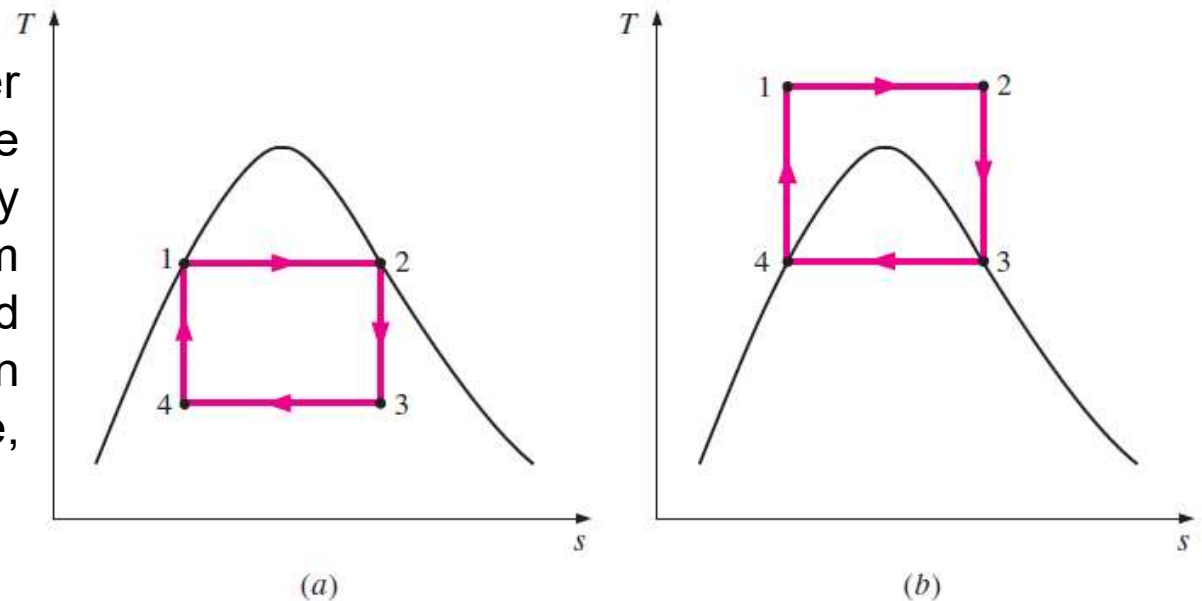
# Brayton Cycle





## Vapor power cycles (Chapter 10)

Limiting the heat transfer processes to two-phase systems, however, severely limits the maximum temperature that can be used in the cycle (it has to remain under the critical-point value, which is  $374^{\circ}\text{C}$  for water).





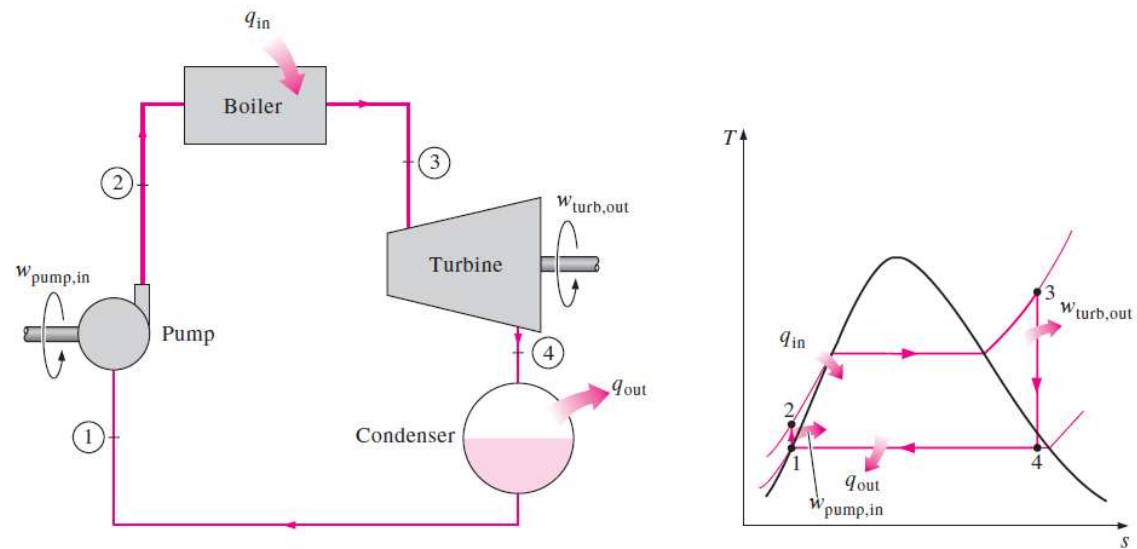


The impingement of liquid droplets on the turbine blades causes erosion and is a major source of wear. Thus steam with qualities less than about 90 percent cannot be tolerated in the operation of power plants.

It is not easy to control the condensation process so precisely as to end up with the desired quality at state 4. Second, it is not practical to design a compressor that handles two phases.



# Ideal Rankine Cycle



**FIGURE 10-2**

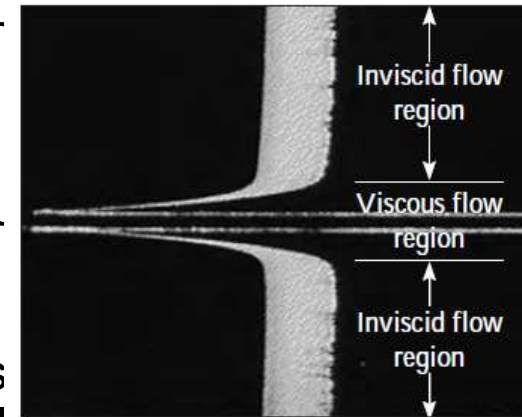
The simple ideal Rankine cycle.



## Types of Fluid Flow

When two fluid layers move relative to each other, a friction force develops between them and the slower layer tries to slow down the faster layer.

Viscosity is caused by cohesive forces between the molecules in liquids and by molecular collisions in gases. **Flows in which the frictional effects are significant are called viscous flows.** However, in many flows of practical interest there are regions where viscous forces are negligibly small compared to inertial or pressure forces. **Neglecting the viscous terms in such inviscid flow regions greatly simplifies the analysis without much loss in accuracy.**



**FIGURE 1-15**

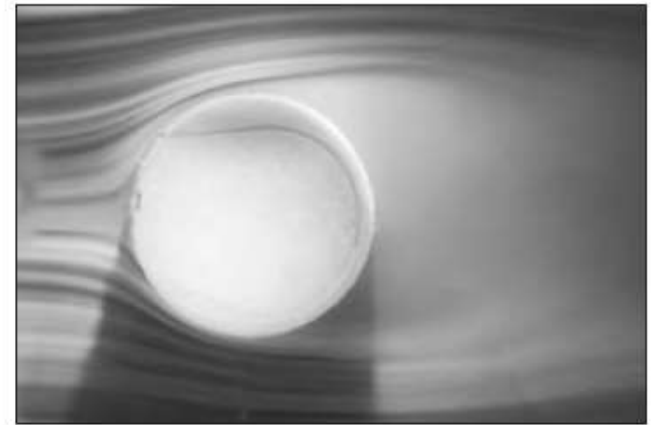
The flow of an originally uniform fluid stream over a flat plate, and the regions of viscous flow (next to the plate on both sides) and inviscid flow (away from the plate).



## Internal vs External flow

A fluid flow is classified as being internal or external, depending on whether the fluid is forced to flow in a confined channel or over a surface.

**The flow of an unbounded fluid over a surface such as a plate, a wire, or a pipe is external flow. The flow in a pipe or duct is internal flow if the fluid is completely bounded by solid surfaces.**



**FIGURE 1-16**

External flow over a tennis ball, and the turbulent wake region behind.



## Compressible vs Incompressible Flow

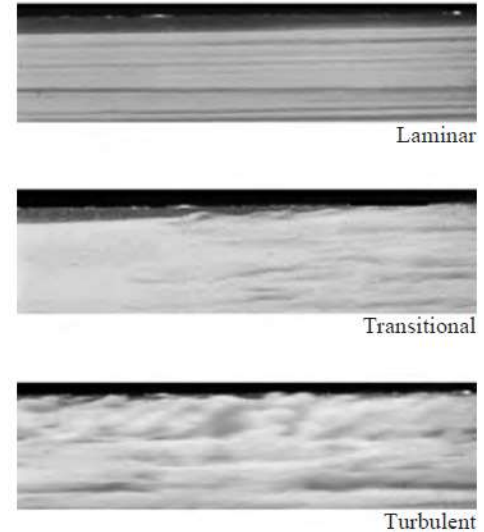
A flow is classified as being *compressible or incompressible*, depending on the level of variation of density during flow. Incompressibility is an approximation, and a flow is said to be **incompressible if the density remains** nearly constant throughout.



## Laminar and Turbulent Flow

The highly ordered fluid motion characterized by smooth layers of fluid is called **laminar**. The word ***laminar comes from the movement of adjacent fluid*** particles together in “laminates.”

The highly disordered fluid motion that typically occurs at high velocities and is characterized by velocity fluctuations is called **turbulent**.



**FIGURE 1-17**

Laminar, transitional, and turbulent flows.



## Natural vs Forced flow

A fluid flow is said to be natural or forced, depending on how the fluid motion is initiated. In **forced flow**, a **fluid is forced to flow over a surface or** in a pipe by external means such as a pump or a fan.



## Steady vs Unstead flow

The term steady implies *no change at a point with time*. The opposite of steady is unsteady.

The term uniform implies *no change with location over a specified region*.





## One, two and three dimensional flow

A flow field is best characterized by the velocity distribution, and thus a flow is said to be one, two, or three-dimensional if the flow velocity varies in one, two, or three primary dimensions, respectively.

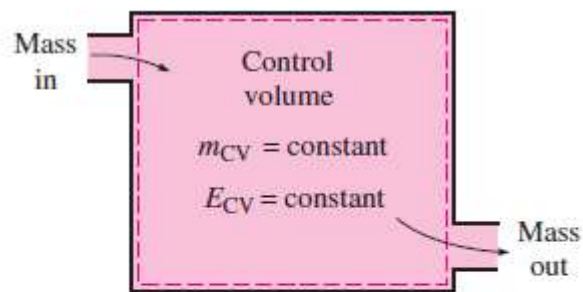


## Steady flow

A process during which a fluid flows through a control volume steadily.

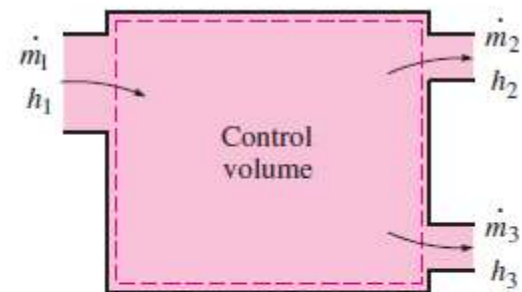
That is the fluid properties can change from point to point within the control volume, but at any point, they remain constant during the entire process.

(Remember, steady means no change with time.)



**FIGURE 5–18**

Under steady-flow conditions, the mass and energy contents of a control volume remain constant.

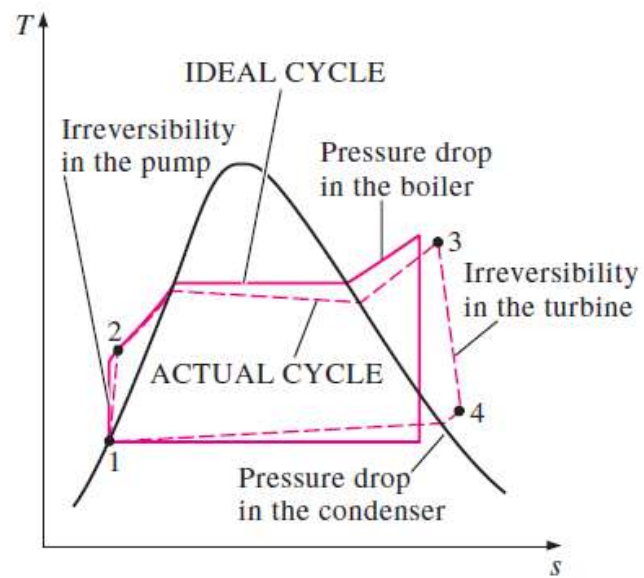


**FIGURE 5–19**

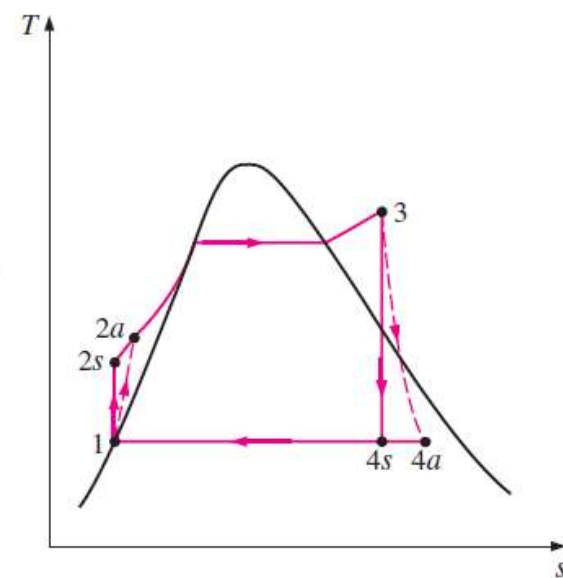
Under steady-flow conditions, the fluid properties at an inlet or exit remain constant (do not change with time).



## Actual vs Ideal cycle



(a)

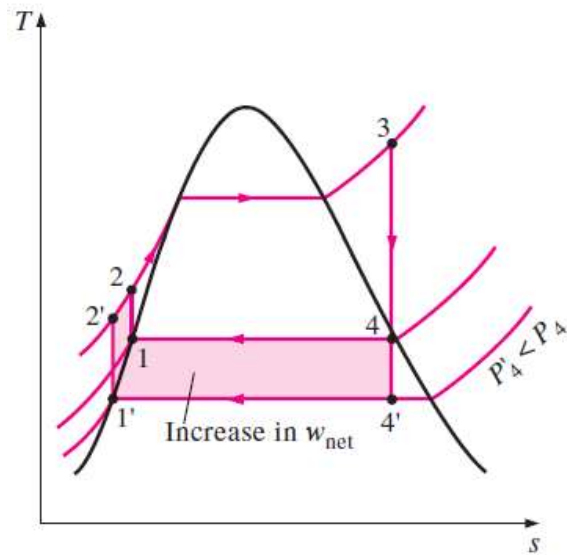


(b)



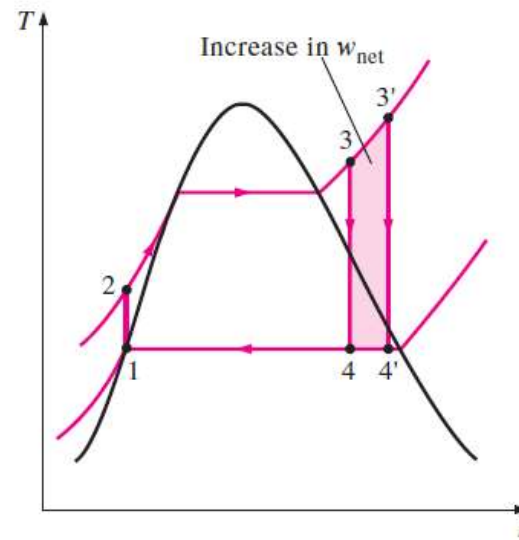
$$\eta_P = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

$$\eta_T = \frac{w_a}{w_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$



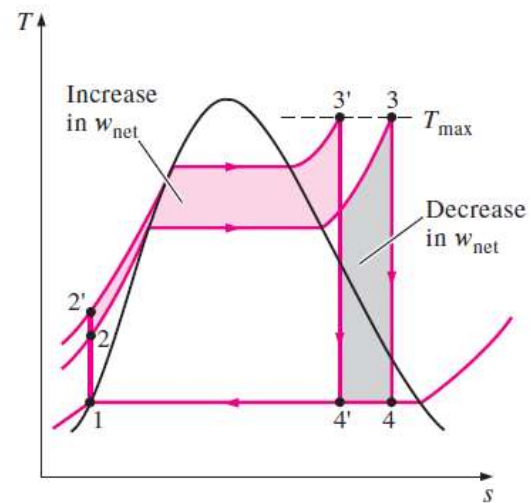
**FIGURE 10-6**

The effect of lowering the condenser pressure on the ideal Rankine cycle.



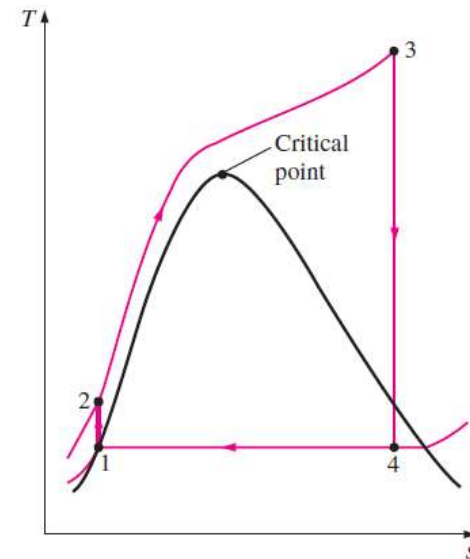
**FIGURE 10-7**

The effect of superheating the steam to higher temperatures on the ideal Rankine cycle.



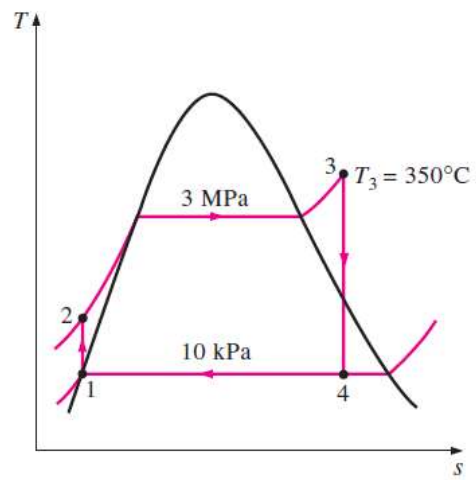
**FIGURE 10-8**

The effect of increasing the boiler pressure on the ideal Rankine cycle.

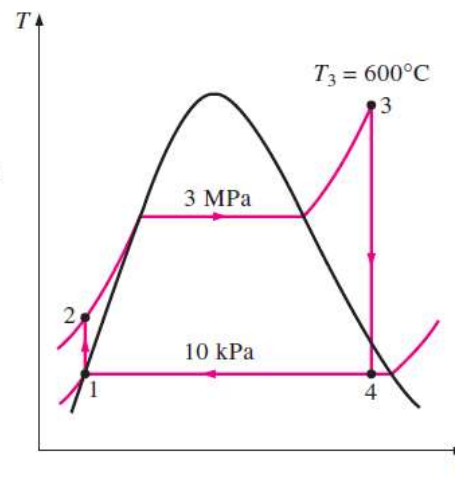


**FIGURE 10-9**

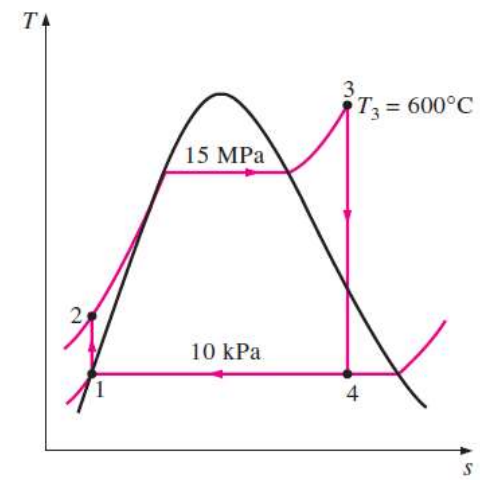
A supercritical Rankine cycle.



(a)



(b)



(c)





# Laws of thermodynamics

## First Law

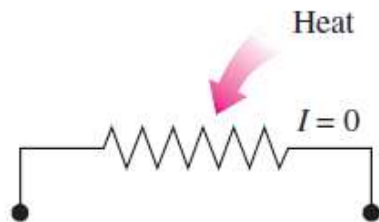
The first law of thermodynamics is the application of the conservation of energy principle to heat and thermodynamic processes.

The First Law of Thermodynamics states that heat is a form of energy, and thermodynamic processes are therefore subject to the principle of conservation of energy. This means that heat energy cannot be created or destroyed. It can, however, be transferred from one location to another and converted to and from other forms of energy.



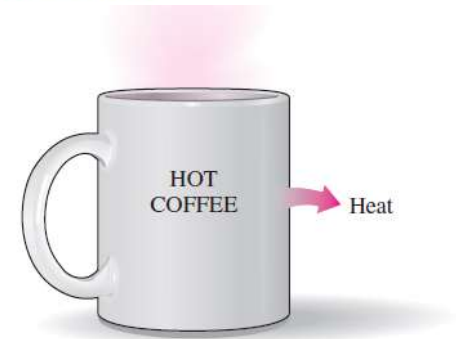
## Laws of Thermodynamics

As pointed out repeatedly in those chapters, energy is a conserved property, and no process is known to have taken place in violation of the first law of thermodynamics. Therefore, it is reasonable to conclude that a process must satisfy the first law to occur. However, as explained here, satisfying the first law alone does not ensure that the process will actually take place.



**FIGURE 6-2**

Transferring heat to a wire will not generate electricity.



**FIGURE 6-1**

A cup of hot coffee does not get hotter in a cooler room.



## Laws of Thermodynamics

It is clear from these arguments that processes proceed in a ***certain direction and not in the reverse direction***.

The first law places no restriction on the direction of a process, but satisfying the first law does not ensure that the process can actually occur.

This inadequacy of the first law to identify whether a process can take place is remedied by introducing another general principle, the ***second law of thermodynamics***.

A process cannot occur unless it satisfies both the first and the second laws of thermodynamics

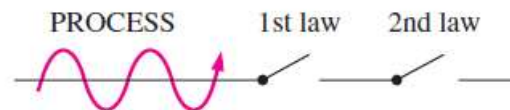


# Laws of Thermodynamics



**FIGURE 6-4**

Processes occur in a certain direction, and not in the reverse direction.



**FIGURE 6-5**

A process must satisfy both the first and second laws of thermodynamics to proceed.



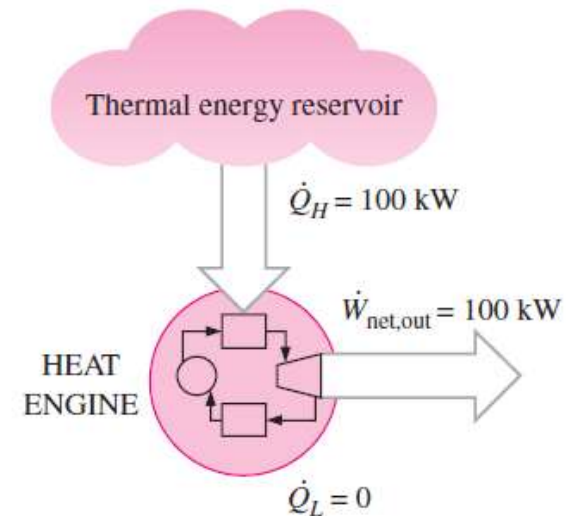
# Laws of Thermodynamics

## 2<sup>nd</sup> Law of Thermodynamics

### Kelvin-Planck Statement

It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.

No heat engine can have a thermal efficiency of 100 percent, or as for a power plant to operate, the working fluid must exchange heat with the environment as well as the furnace.



**FIGURE 6–18**

A heat engine that violates the Kelvin–Planck statement of the second law.



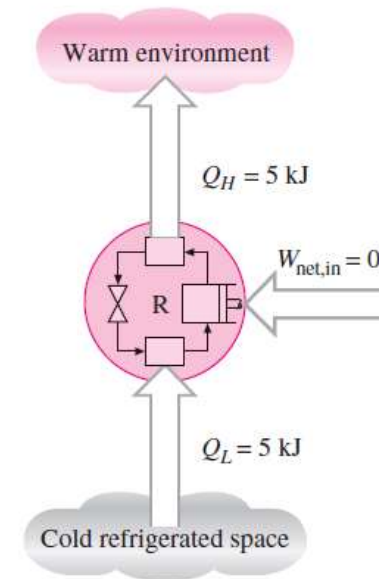
# Laws of Thermodynamics

## 2<sup>ND</sup> Law of Thermodynamics

### Clausius Statement

It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body.

To date, no experiment has been conducted that contradicts the second law, and this should be taken as sufficient proof of its validity.



**FIGURE 6-26**

A refrigerator that violates the Clausius statement of the second law.

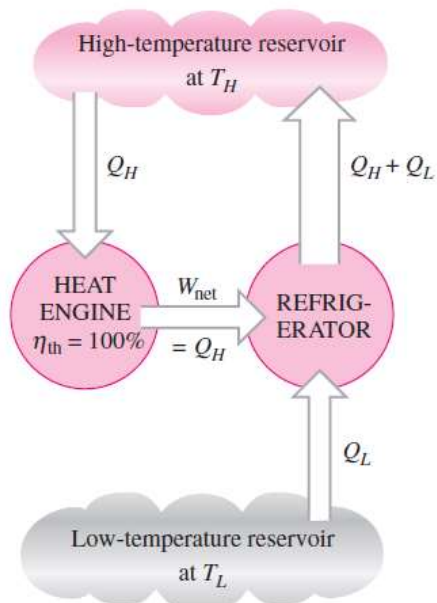


## Laws of Thermodynamics

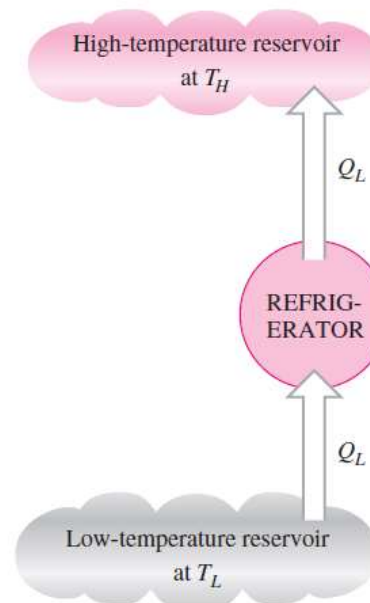
The Kelvin–Planck and the Clausius statements are equivalent in their consequences, and either statement can be used as the expression of the second law of thermodynamics. **Any device that violates the Kelvin–Planck statement also violates the Clausius statement, and vice versa.**



# Laws of Thermodynamics



(a) A refrigerator that is powered by a 100 percent efficient heat engine



(b) The equivalent refrigerator

**FIGURE 6-27**

Proof that the violation of the Kelvin–Planck statement leads to the violation of the Clausius statement.





## Laws of Thermodynamics

The use of the second law of thermodynamics is not limited to identifying the direction of processes, however. The second law also asserts that **energy has quality as well as quantity**. The first law is concerned with the quantity of energy and the transformations of energy from one form to another with no regard to its quality.



# Laws of Thermodynamics

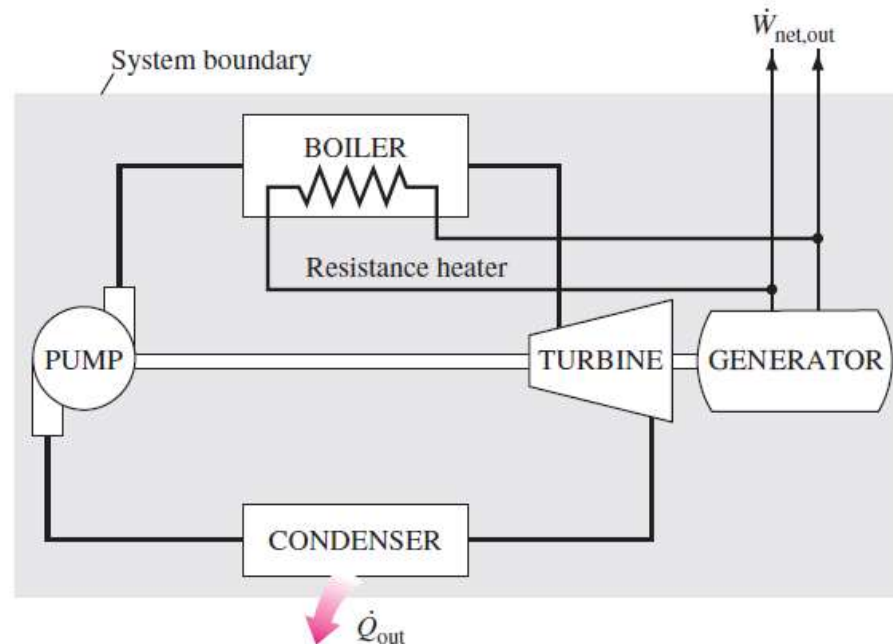
Perpetual motion machine

Perpetual motion machine of first kind (PMM1)

Perpetual motion machine of second kind (PMM2)

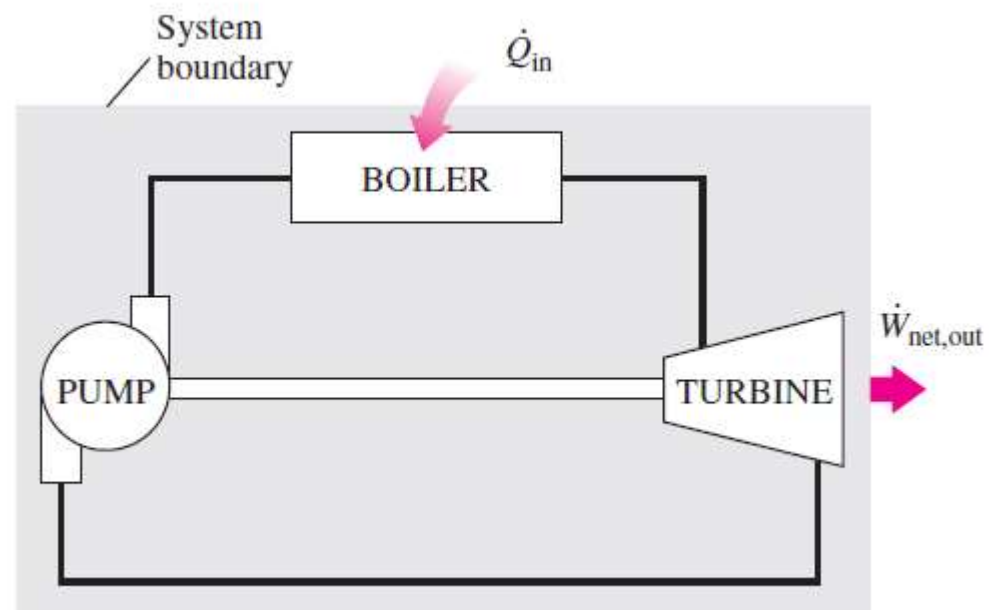


# Laws of Thermodynamics





# Laws of Thermodynamics





## Entropy (Chapter 7 by Cengel)

The concept of entropy originated around the mid 19th century, from the study of heat, temperature, work and energy.

The study of how heat could be most efficiently converted to mechanical work was of prime interest.

It was understood that there was a relationship between heat and temperature. Generally speaking, the more heat you applied to an object, the hotter it got. It was also understood that heat and work represented different forms of energy and that under the right circumstances, you could convert one into the other.



# Entropy

One of the difficulties was knowing how much heat energy was stored in the hot reservoir. One couldn't measure the heat content directly. What could be measured was the reservoir's temperature. If we know the relationship between the temperature and the heat content for that reservoir, we can use the temperature to calculate the heat content.

This became the operational definition of a newly conceived property of systems, a property which came to be known as **entropy**. (The term was coined in 1865 by Rudolf Clausius who thought of it as representing a kind of "internal work of transformation".) Simply stated, **entropy is the relationship between the temperature of a body and its heat content** (more precisely, its kinetic heat energy). Entropy, **S**, is the heat content, **Q**, divided by the body's temperature, **T**.

The definition of **entropy, as originally conceived in classical thermodynamics had nothing to do with order or disorder**



# Entropy

The significance of entropy in the study of heat engines and chemical reactions is that, for a given temperature, a system can hold only a certain amount of heat energy - no more and no less - depending on the entropy of the system. If the entropy of the system changes, some energy will be released or absorbed in one form or another. **For heat engines that means that if you wanted to convert heat into mechanical work, you needed to make sure that more heat flowed out of the hot reservoir than could "fit" into the cold reservoir.**



# Entropy

With time, more was learned about the role of molecules in determining the classical thermodynamic variables such as pressure, temperature, and heat. **Pressure**, it turned out, was just the total force exerted by individual molecules, colliding with themselves and the walls of the container, averaged over the surface area of the container. **Temperature** was determined to be the average kinetic energy of all the different ways the molecules could move, tumble or vibrate. This more detailed, molecular, perspective of thermodynamics and the mathematics associated with it became known as **statistical thermodynamics**.





# Entropy

From the molecular description of heat content and temperature, Boltzmann showed that entropy must represent the total number of different ways the molecules could move, tumble or vibrate. The idea was that heat was just kinetic energy on a scale that could not be observed directly but that manifested itself in the aggregate as the thermodynamic properties that could be observed. Heat flowed from a hot body to a cold body as kinetic energy was transferred through molecular collisions occurring at the boundary between the two bodies and further distributed throughout the body as molecules collided with each other within the body. At each collision, kinetic energy was exchanged. On average, molecules with more kinetic energy lost kinetic energy as they collided and molecules with less kinetic gained kinetic energy as they collided, until, on average, the kinetic energy was optimally distributed among all the molecules and their various modes of movement.



# Entropy

The net result was that the more ways a system could move internally, the more molecular kinetic energy the system could hold for a given temperature. This was because temperature was just the average kinetic energy per mode of movement. You could think of these modes of movements as "pockets" that can hold kinetic energy.

If each pocket, on average, could hold the same amount of kinetic energy, then the more pockets a system had, the more total kinetic energy the system contained. The greater the number of kinetic energy pockets a system had, the greater its entropy.



# Entropy

It was Boltzmann who advocated the idea that entropy was related to disorder. In Boltzmann's mind, **the more ways a system could move internally, the more disorderly the system was.** A system in "perfect order" was one in which all the molecules were locked in perfect array without any freedom of movement whatsoever. A dynamic system in perfect equilibrium represented, according to statistical thermodynamics, a system in "perfect disorder". The idea of entropy as a measure of disorder was embraced and perpetuated by his colleagues in the field of statistical thermodynamics.



# Entropy

Entropy should not and does not depend on our perception of order in the system. The amount of heat a system holds for a given temperature does not change depending on our perception of order.

**Entropy, like pressure and temperature is an independent thermodynamic property of the system.**



# Entropy

A better word that captures the essence of entropy on the molecular level is diversity. **Entropy represents the diversity of internal movement of a system.** The greater the diversity of movement on the molecular level, the greater the entropy of the system.



# Entropy

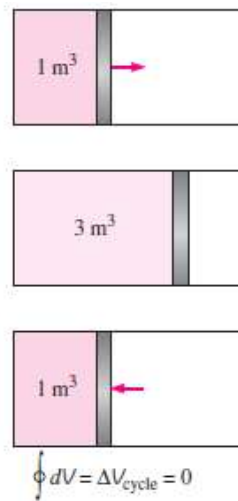
## Clausius inequality

It was first stated by the German physicist R. J. E. Clausius (1822–1888), one of the founders of thermodynamics, and is expressed as

$$\oint \frac{\delta Q}{T} \leq 0$$

*That is, the cyclic integral of  $\delta Q/T$  is always less than or equal to zero.*

This inequality is valid for all cycles, reversible or irreversible.



**FIGURE 7-2**

The net change in volume (a property) during a cycle is always zero.

$$\oint dV = 0$$

Clausius realized in 1865 that he had discovered a new thermodynamic property, and he chose to name this property **entropy**. It is designated **S** *and* is defined as

$$dS = \left( \frac{\delta Q}{T} \right)_{\text{int rev}} \quad (\text{kJ/K})$$



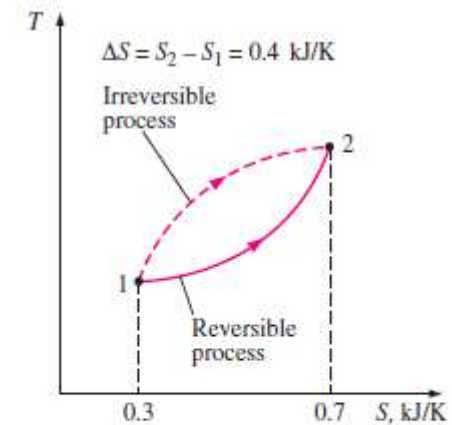
Entropy is an extensive property of a system and sometimes is referred to as total entropy

$$\Delta S = S_2 - S_1 = \int_1^2 \left( \frac{\delta Q}{T} \right)_{\text{int rev}} \quad (\text{kJ/K})$$





Note that entropy is a property, and like all other properties, it has fixed values at fixed states. Therefore, the entropy change  $S$  *between two specified* states is the same no matter what path, reversible or irreversible, is followed during a process



**FIGURE 7-3**

The entropy change between two specified states is the same whether the process is reversible or irreversible.



# Entropy

The first law is simply an energy balance. However, the second law leads to an inequality; an *irreversible* process is less efficient than a reversible process. Another important inequality in thermodynamics is the **Clausius inequality**:

$$\oint \frac{\delta Q}{T} \leq 0$$

That is, the cyclic integral of  $\delta Q / T$  is always less than or equal to zero. This is valid for all cycles, reversible or irreversible.

For internally reversible cycles, it can be shown that:

$$\oint \frac{\delta Q}{T} \Big|_{\text{int, rev}} = 0$$



# Entropy

Entropy change of a closed system during an irreversible process is greater than the integral of  $\delta Q / T$  evaluated for the process. In the limiting case of a reversible process, they become equal.

$$dS \geq \frac{\delta Q}{T}$$

The entropy generated during a process is called *entropy generation*, and is denoted by  $S_{gen}$ ,

$$\Delta S = S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + S_{gen}$$



## Refrigeration & Air Conditioning

HVAC stands for heating, ventilation, and air conditioning is the technology of indoor and vehicular environmental comfort. Its goal is to provide thermal comfort and acceptable indoor air quality. HVAC systems control the ambient environment (temperature, humidity, air flow, and air filtering). HVAC is an important part of residential structures which making it safe and habitable.



# Heating

Is the process of generating heat used to warm the space to be via the following applications (boiler , furnace, electricity or heat pump) to heat water or air in central location.



## Ventilation

Ventilation is the process of changing or replacing air in any space to control temperature or remove any combination of moisture, odors, smoke, heat, dust, airborne bacteria, or carbon dioxide, and to replenish oxygen. Ventilation includes both the exchange of air with the outside as well as circulation of air within the building. It is one of the most important factors for maintaining acceptable indoor air quality in buildings



# Refrigeration

Refrigeration is only maintaining/controlling the temperature of a closed area below atmospheric region.

Where as Air conditioning is maintaining the temperature as well as humidity of air and odor.



## Refrigerators and heat pumps

If the main purpose of the machine is to cool some object the machine is named as refrigerator

If the main purpose of machine to heat a medium warmer than the surroundings, the machine is termed as heat pump.



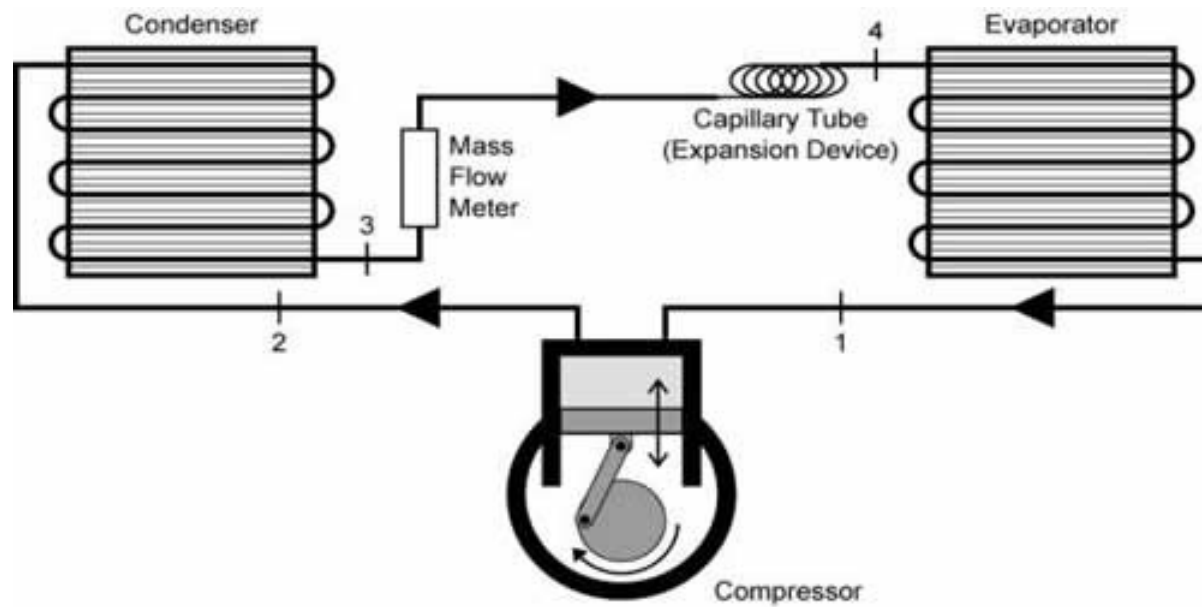


## **Applications of Refrigeration**

- In chemical industries, for separating and liquefying the gases.
- In manufacturing and storing ice.
- For the preservation of perishable food items in cold storages.
- For cooling water.
- For controlling humidity of air manufacture and heat treatment of steels.
- For chilling the oil to remove wax in oil refineries.
- For the preservation of tablets and medicines in pharmaceutical industries.
- For the preservation of blood tissues etc.,
- For comfort air conditioning the hospitals, theatres, etc.,



# Vapour Compression Refrigeration System

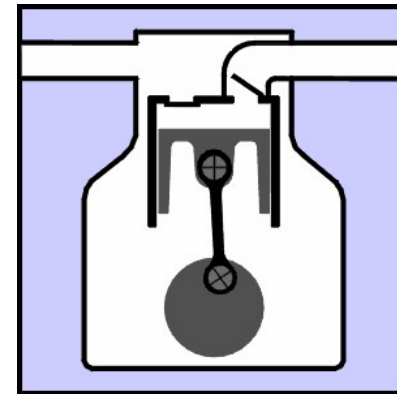




## Vapour Compression Refrigeration System - **Construction**

This system consists of a compressor, condenser, a receiver tank, an expansion valve and an evaporator.

Compressor : Reciprocating compressors generally used. For very big plants centrifugal compressors directly coupled with high speed rotating engines (gas turbine) are used.



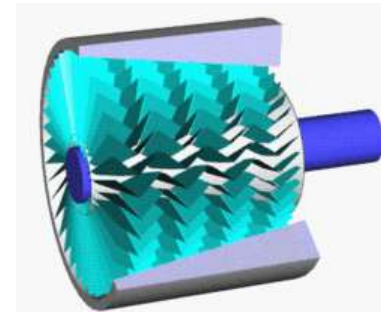


# Vapour Compression Refrigeration System - **Construction**

**Compressor:** For very big plants

**Centrifugal compressors**

directly coupled with high  
speed rotating engines  
(gas turbine) are used





## Vapour Compression Refrigeration System - **Construction**

**Condenser :** It is a coil of tubes made of copper.

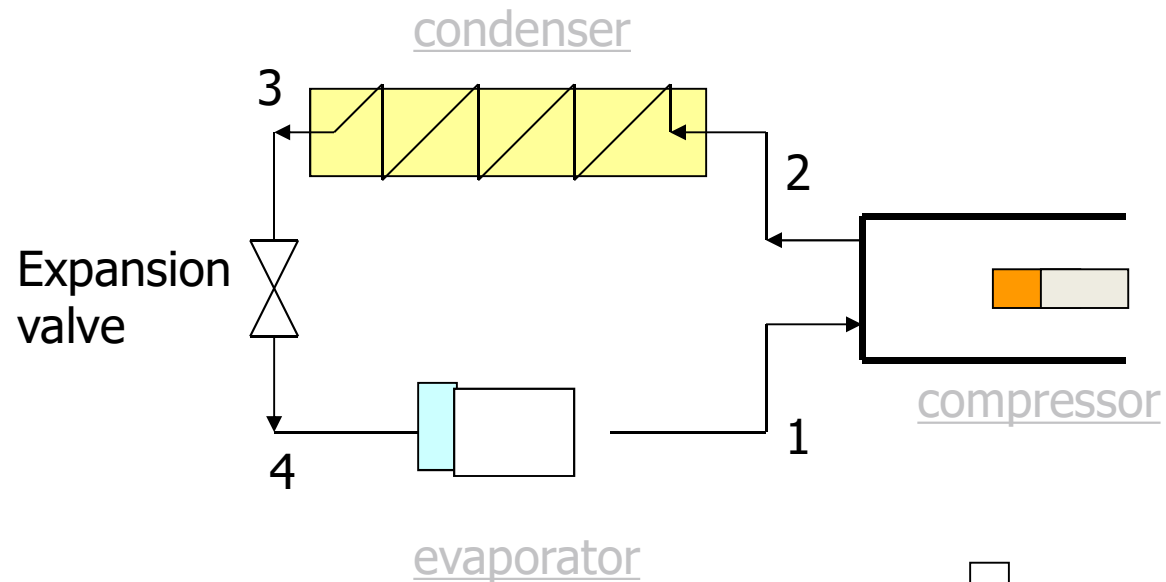
**Expansion Valve:** This is a throttle valve. High pressure refrigerant is made to flow at a controlled rate through this valve.

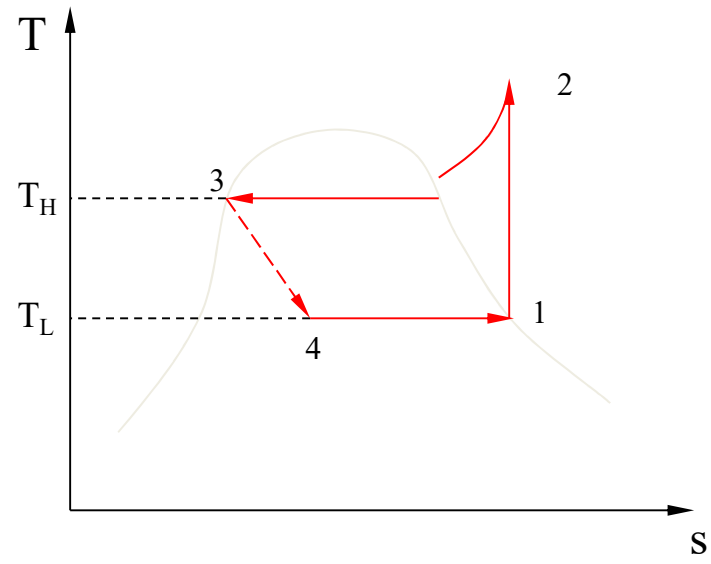
**Evaporator :** It is the actual cooler and kept in the space to be cooled. The evaporator is a coil of tubes made of copper

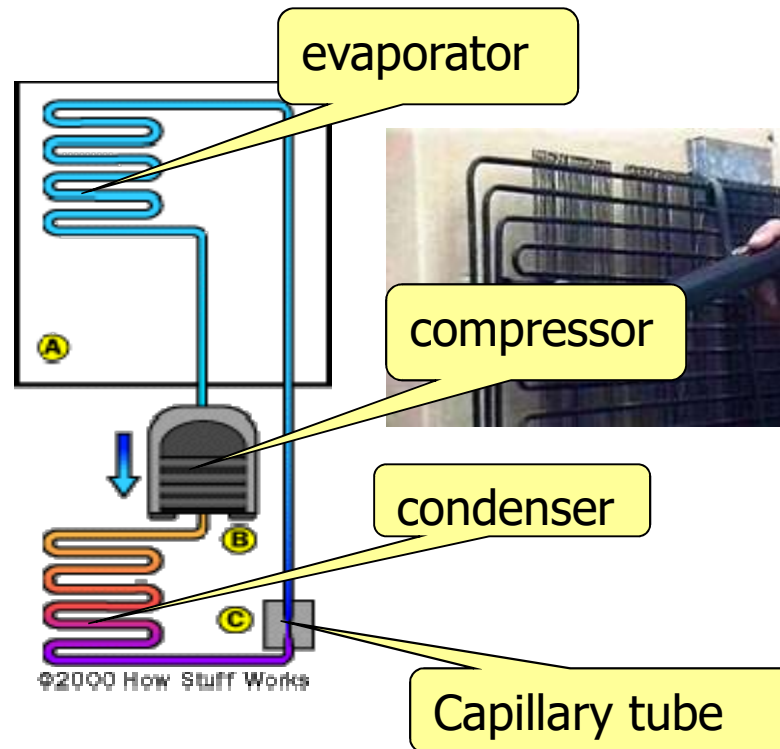


## 10-1-2 The Ideal Vapor-Compression Refrigeration Cycle

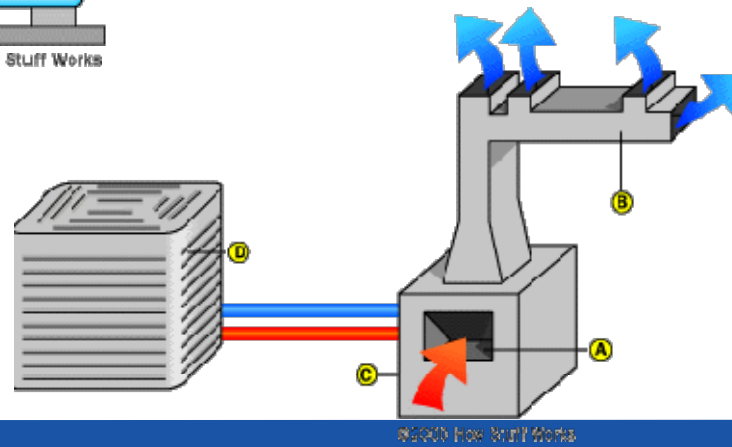
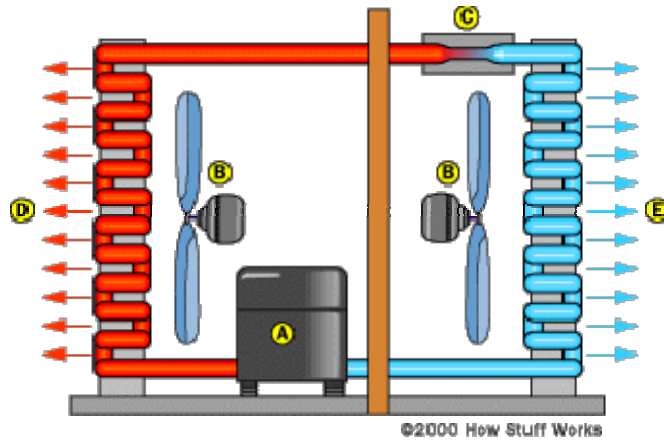
Equipments:





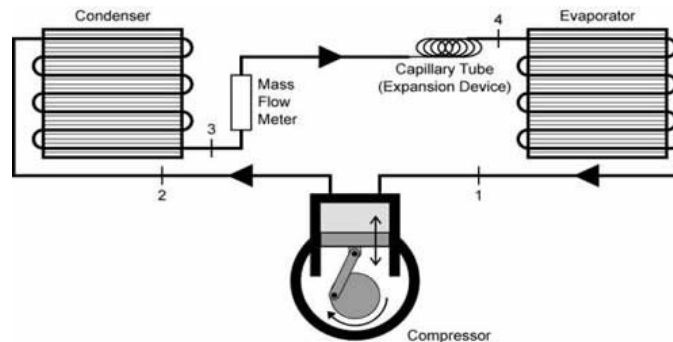








# Vapour Compression Refrigeration System - **Working**

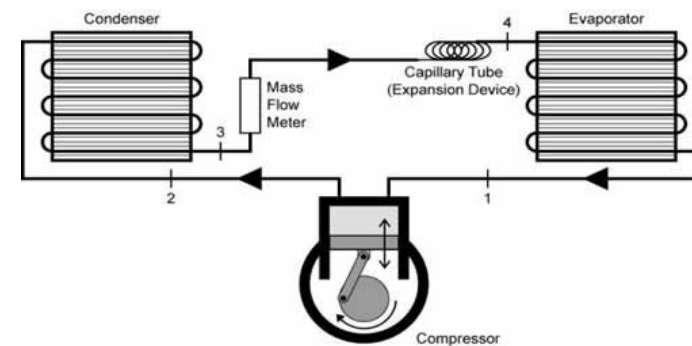


## Working :

1. The low pressure refrigerant vapour coming out of the evaporator flows into the compressor.
2. The compressor is driven by a prime mover.
3. In the compressor the refrigerant vapour is compressed.
4. The high pressure refrigerant vapour from the compressor is then passed through the condenser.
5. The refrigerant gives out the heat it had taken in the evaporator (N)



# Vapour Compression Refrigeration System - **Working**

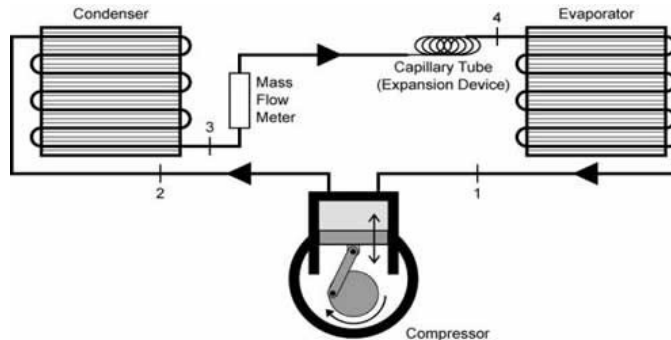


## Working :

6. The heat equivalent of work done on it ( $w$ ) on the compressor.
7. This heat is carried by condenser medium which may be air or water.
8. The high pressure liquid refrigerant then enters the expansion valve.
9. This valve allows the high pressure liquid refrigerant to flow at a controlled rate into the evaporator.
10. While passing through this valve the liquid partially evaporates.



# Vapour Compression Refrigeration System - **Working**



## Working :

11. Most of the refrigerant is vapourised only in the evaporator, at a low pressure.
12. In the evaporator the liquid refrigerant absorbs its latent heat of vapourisation from the material which is to be cooled.
13. Thus the refrigerating effect (N) is obtained.
14. Then the low pressure refrigerant enters the compressor and the cycle is repeated.



## 10-2 Refrigerant

Good refrigerant



High enthalpy of vaporization  
Not too low evaporator pressure  
Not too high condenser pressure  
Nontoxic  
Noncorrosive  
Chemically stable  
Low cost

- Ammonia
- CFC(chlorofluorocarbons)
- water



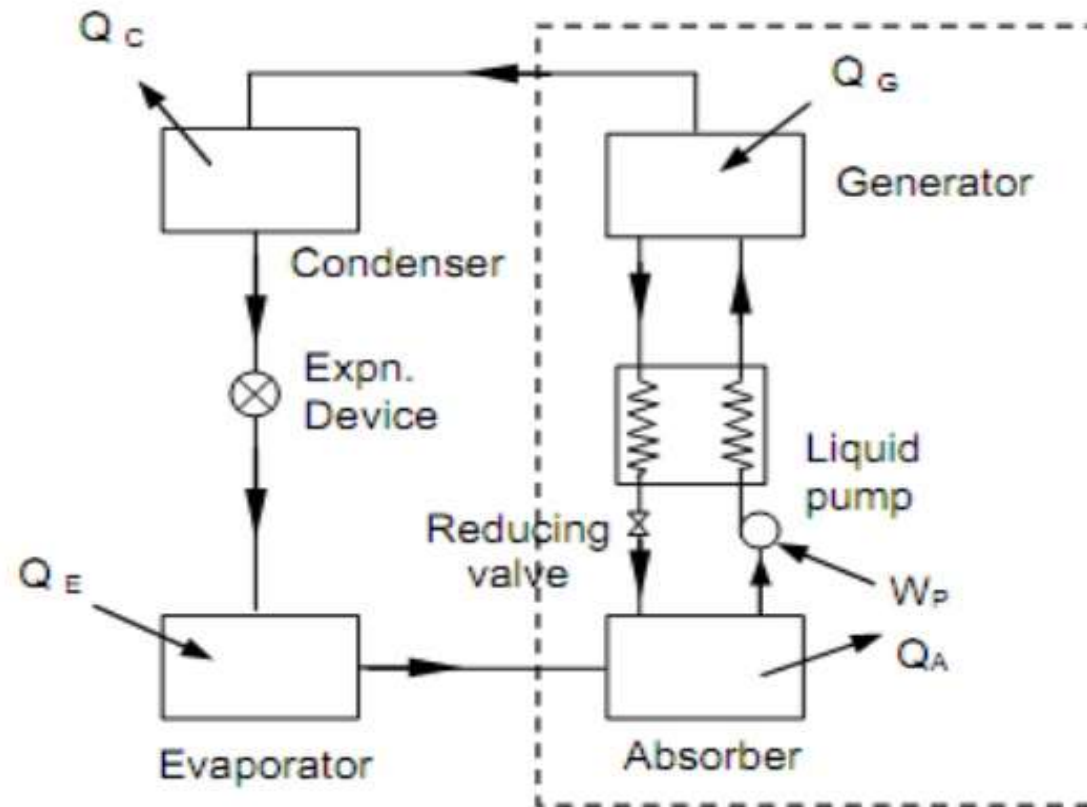
## Vapour Absorption Refrigeration system

In this system compression process of vapour compression cycle is eliminated. Instead of that the following three processes are carried out.

1. *Absorbing ammonia vapour into water.*
2. *Pumping this solution to a high pressure cycle*
3. *Producing ammonia vapours from ammonia solution by heating.*



# Vapor Absorption Refrigeration Cycle





**Refrigerating Effect (N):** It is defined as the quantity of heat extracted from a cold body or space to be cooled in a given time.

$$N = \frac{\text{Heat extracted from the cold space}}{\text{Time taken}}$$

**Specific Heat of water and ice :** It is the quantity of heat required to raise or lower the temperature of one kg of water (or ice), through one kelvin or ( $1^{\circ}\text{C}$ ) in one second.

Specific heat of water,  $C_{pw} = 4.19 \text{ kJ/kg K}$

Specific heat of ice,  $C_{pice} = 2.1 \text{ kJ/kg K}$ .





## Capacity of a Refrigeration Unit :

Capacity of a refrigerating machines are expressed by their cooling capacity.

The standard unit used for expressing the capacity of refrigerating machine is ***ton of refrigeration***.

1 tonne of **refrigeration** is the rate of heat removal required to freeze a metric **ton** (1000 kg) of water at 0°C in 24 hours.

$$1 \text{ TOR} = 3.52 \text{ kW}$$



## Performance of Refrigerators (Co efficient of Refrigerators) :

The performance of heat engine is expressed by its thermal efficiency.

The performance of a refrigerator cannot be expressed in terms of efficiency.

In case of a refrigerator the aim is to extract maximum quantity of heat from the sink with minimum of work input.

Hence a new term **Co efficient of Performance** is brought into use to express the performance of refrigerator.



**Co efficient of Performance:** It is defined as the ratio of heat extracted in a given time (refrigerating effect) to the work input.

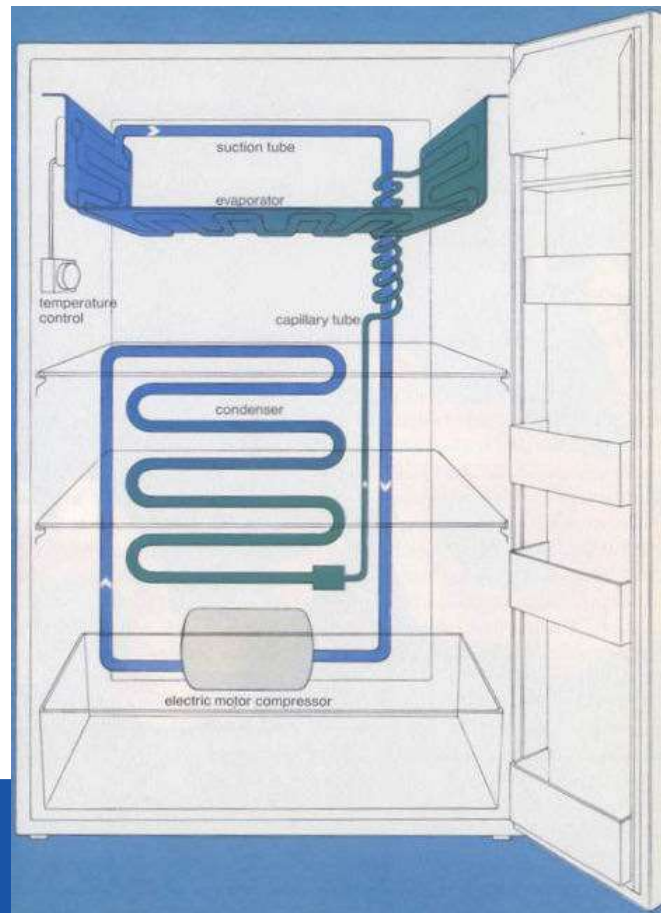
$$\text{Co efficient of performance} = \frac{\text{Heat extracted in evaporator}}{\text{Work Input}}$$

$$\text{Co efficient of performance} = \frac{\text{Refrigerating Effect}}{\text{Work Input}}$$

*The COP is always greater than 1 and known as theoretical coefficient of performance.*

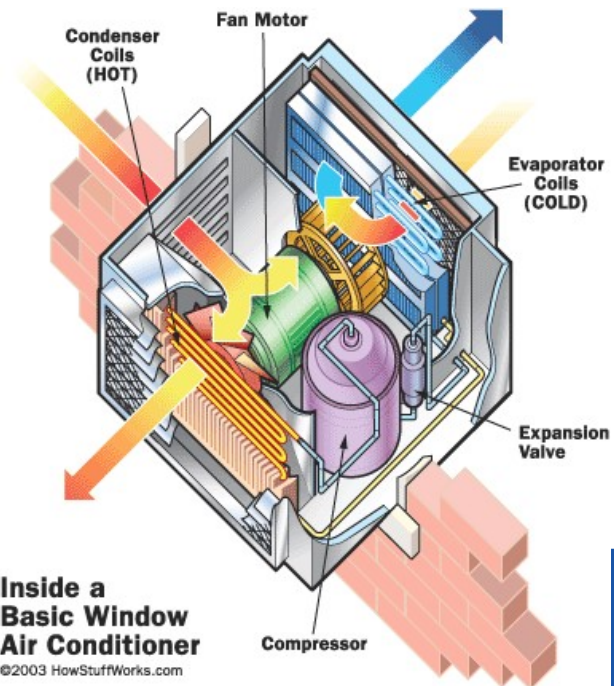
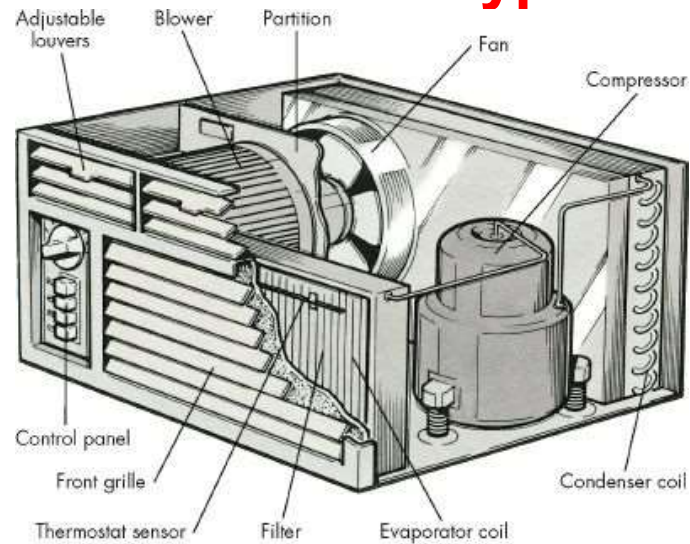


## Layout of Domestic Refrigerator





## Window Type Air Conditioner



**Inside a Basic Window Air Conditioner**  
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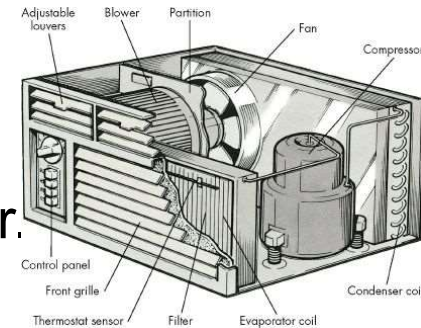


## Window Type Air Conditioner - Construction

This is also called room air conditioner.

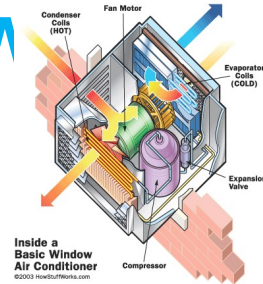
This unit consists of the following.

1. A cooling system to cool and dehumidify the air involves a condenser, a compressor and a refrigerant coil.
2. A filter to any impurities in the air. The filter is made of mesh, glass wool or fibre.
3. A fan and adjustable grills to circulate the air.
4. Controls to regulate the equipment operation.





## Window Type Air Conditioner - V

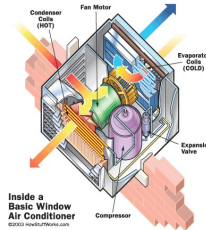


The low pressure refrigerant vapour is drawn from the evaporator to the hermetic compressor through suction pipe.

It is compressed from low pressure to the high pressure and supplied to the condenser.

It is condensed in the condenser by passing the outdoor air over the condenser coil by a fan.

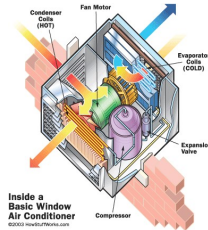
The liquid refrigerant is passed through the capillary into the evaporator.



## Window Type Air Conditioner - Working

5. In the evaporator the liquid refrigerant picks up the heat from the refrigerator surface and gets vaporized.
6. A motor driven fan draws air from the room through the air filter and this air is cooled by losing its heat to the low temperature refrigerant and cold air is circulated back into the room.
7. The vapour refrigerant from the evaporator goes to the compressor from evaporator and the cycle is repeated.
8. Thus the room is air conditioned



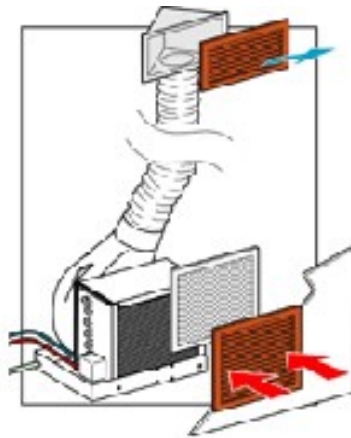


## Window Type Air Conditioner - Working

9. The quantity of air circulated can be controlled by the dampers.
10. The moisture in the air passing over the evaporator coil is dehumidified and drips into the trays.
11. This water evaporator to certain extent and thus helps in cooling the compressor and condenser.
12. The unit automatically stops when the required temperature is reached in the room. This is accomplished by the thermostat and control panel.



## Split Type Air Conditioner - Construction





Good luck for Exam