# Applied Thermodynamics

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1st Semester,2025

7th Edition

# Applied Thermodynamics
# MCET211

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**Applied Thermodynamics: An Engineering Approach**
**Seventh Edition in SI Units**
**Yunus A. Cengel, Michael A. Boles**
**McGraw-Hill, 2011**

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1st Semester,2026

# PROBLEM-SOLVING TECHNIQUE

- Step 1: Problem Statement
- Step 2: Schematic
- Step 3: Assumptions and Approximations
- Step 4: Physical Laws
- Step 5: Properties
- Step 6: Calculations
- Step 7: Reasoning, Verification, and Discussion

**EES (Engineering Equation Solver)** (Pronounced as ease): EES is a program that solves systems of linear or nonlinear algebraic or differential equations numerically. It has a large library of built-in thermodynamic property functions as well as mathematical functions. Unlike some software packages, EES does not solve engineering problems; it only solves the equations supplied by the user.

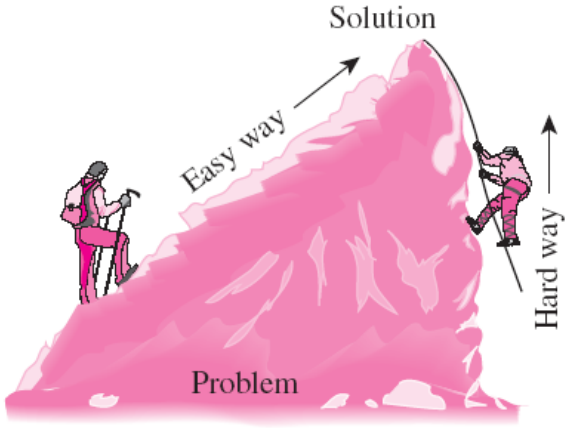



**FIGURE 1–61**
A step-by-step approach can greatly simplify problem solving.

**Given**: Air temperature in Denver

**To be found**: Density of air

**Missing information**: Atmospheric pressure

**Assumption #1**: Take $P = 1$ atm (Inappropriate. Ignores effect of altitude. Will cause more than 15% error.)

**Assumption #2**: Take $P = 0.83$ atm (Appropriate. Ignores only minor effects such as weather.)

**FIGURE 1–62**
The assumptions made while solving an engineering problem must be reasonable and justifiable.



**FIGURE 1–65**
An excellent word-processing program does not make a person a good writer; it simply makes a good writer a more efficient writer.

# SOURCE OF ENERGY (INTRODUCTORY)

Modul 1.0

## Energy resources

### Non-renewable

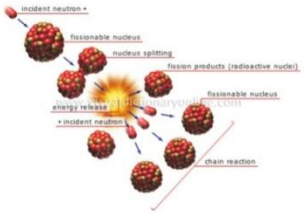
- Natural gas

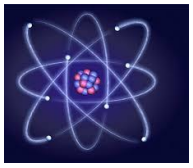


- oil



- Nuclear



### Renewable

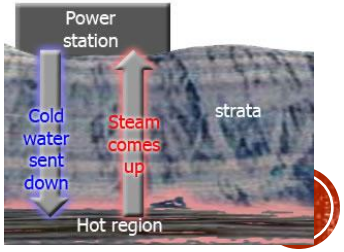
- Solar



- Wind

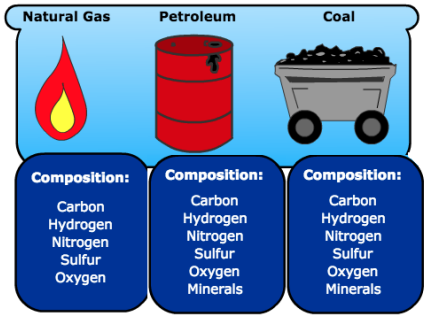


- Geothermal



# FUELS

- **Definition**: It is any material that stores energy which is extracted as heat in an exothermic reaction (combustion).
- **Content:** most fuels are called hydrocarbon because they contains Carbon and Hydrogen




- **Classification:**
  - **Solid fuels**: Wood, Coal.
  - **Liquid fuels**: Gasoline, Diesel, Ethanol.
  - **Gaseous fuels**: Natural gas.



- **Fuel types:**
  - **Fossil fuel**: Oil, Natural gas and Coal.
  - **Nuclear fuel**: Uranium and Plutonium.
  - **Biofuel**: Bioethanol and Biodiesels.



- **Price of fuels depends on:**
  - Calorific value.
  - Combustion products
  - Handling and storage cost

# FUEL PROPERTIES

- **Flash point:** It is the lowest temperature at which the fuel can be vaporized to form an ignitable mixture in air by means of ignition source. Below the flash point, the fuel can be handled safely.



- **Fire point:** It is the point at which the fuel continue to burn without ignition source for at least five seconds.

- **Cloud point:** It is the temperature at which the dissolved wax content of the oil separate forming a cloudy appearance.



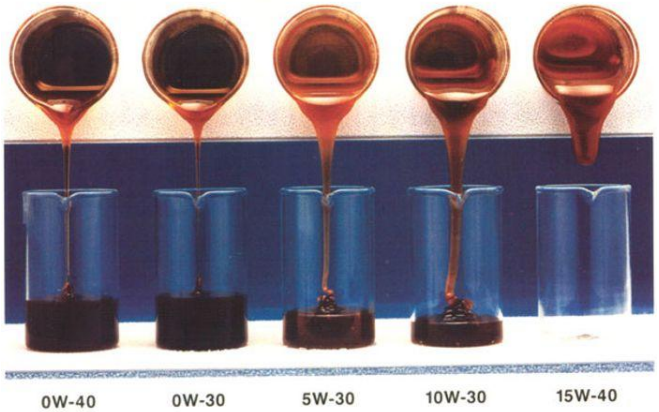
- **Pour point:** it is the lowest temperature at which the fuel becomes semi solid and loses its flow characteristics. In crude oil the high pour point indicates a high paraffin content.

# FUEL PROPERTIES

- **Calorific value:** it is the heat released by complete combustion of 1kg of fuel under specified conditions (kJ/kg).

| Fuel | Calorific Value (kJ/kg) |
|---|---|
| Cow dung cake | 6000-8000 |
| Wood | 17000-22000 |
| Coal | 25000-33000 |
| Petrol | 45000 |
| Kerosene | 45000 |
| Diesel | 45000 |
| Methane | 50000 |
| CNG | 50000 |
| LPG | 55000 |
| Biogas | 35000-40000 |
| Hydrogen | 150000 |

- **Viscosity:** (It is the measure of a fluid's resistance to flow) it is a measure of the fluid resistance to gradual deformation by shear stress or tensile stress.



# COMBUSTION

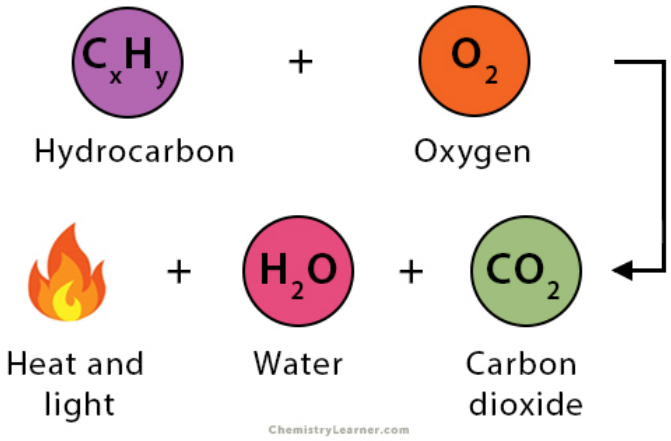
- **Definition:** Exothermic chemical reaction between fuel and oxidant (air) that produces heat and light.

**Fuel + Oxidant → Heat/light, $CO_2$, $H_2O$ etc.**

**Reactants** **Products**



## Combustion Reaction




## Examples of Combustion reactions

- Methane
- $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

- Naphthalene
- $C_{10}H_4 + 12O_2 \rightarrow 10CO_2 + 4H_2O$

- Ethane
- $2C_2H_6 + 7O_2 \rightarrow 4CO_2 + 6H_20$

# COMBUSTION

- **Combustion products:**
  - Carbon dioxide ($CO_2$)
  - Carbon monoxide (CO)
  - Nitrogen oxide ($NO_x$)
  - Sulfur oxide ($SO_x$)
  - Water vapor ($H_2O$)
- **Complete combustion:** the combustion process that produces limited number of products.
  - C → $CO_2$
  - H → $H_2O$
  - S → $SO_2$
- **Incomplete combustion:**
  - not enough oxygen
  - mixing is not complete.
  - produces carbon monoxide, unburned hydrocarbons and soot.



# COMBUSTION

- **Combustion quality depends on:**
  - The amount of oxidant (air).
  - Fuel / Oxidant mixture.
  - Combustion time.
  - Combustion chamber heat losses.

# REVIEW QUESTION

1. Write the complete combustion equation for $C_3H_8$ and $C_8H_{18}S_2$ with Oxygen , $O_2$ and air ($O_2$+3.76$N_2$).
2. What can happen with nitrogen ($N_2$) in air when fuel is burned with air?
3. Arrange these temperature of a fuel sample in the table below: - 10°C, 5°C, 50°C, 70°C

| Fire point | Pour point | Flash point | Cloud point |
|---|---|---|---|
| | | | |

# Thermodynamics: An Engineering Approach

Seventh Edition in SI Units

Yunus A. Cengel, Michael A. Boles

McGraw-Hill, 2011

MODULE 2.1

# ENERGY, ENERGY TRANSFER, AND GENERAL ENERGY ANALYSIS

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# THERMODYNAMICS AND ENERGY

- **Thermodynamics**: The science of *energy.*
- **Energy**: The ability to cause changes.
- The name *thermodynamics* stems from the Greek words *therme* (heat) and *dynamis* (power).
- **Conservation of energy principle**: During an interaction, energy can change from one form to another but the total amount of energy remains constant.
- Energy cannot be created or destroyed.
- **The first law of thermodynamics**: An expression of the conservation of energy principle.
- The first law asserts that *energy* is a thermodynamic property.

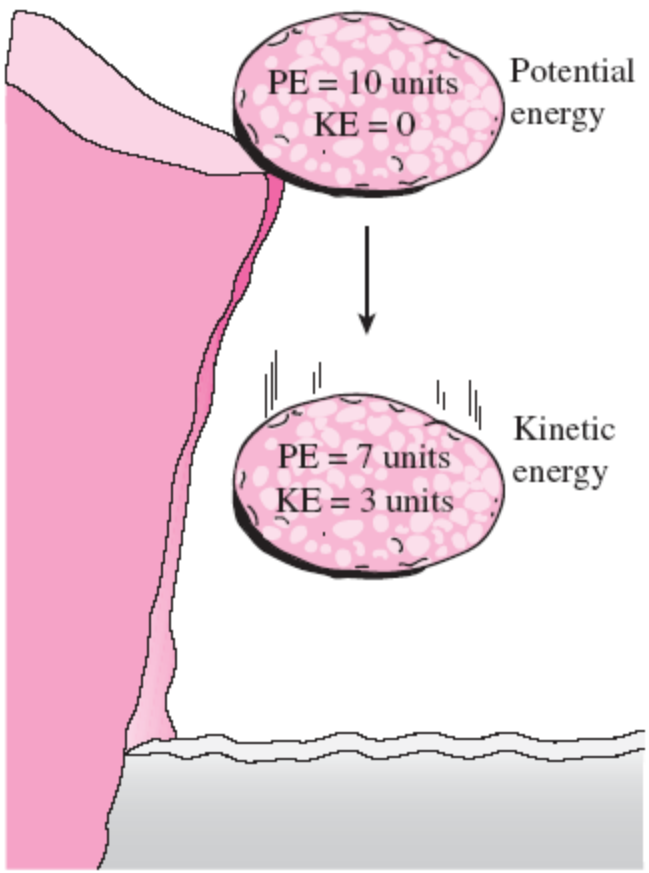



**FIGURE 1–1**
Energy cannot be created or destroyed; it can only change forms (the first law).

- **The second law of thermodynamics:** It asserts that energy has *quality* as well as *quantity,* and actual processes occur in the direction of decreasing quality of energy.
- **Classical thermodynamics**: A macroscopic approach to the study of thermodynamics that does not require a knowledge of the behavior of individual particles.
- It provides a direct and easy way to the solution of engineering problems and it is used in this text.
- **Statistical thermodynamics**: A microscopic approach, based on the average behavior of large groups of individual particles.
- It is used in this text only in the supporting role.

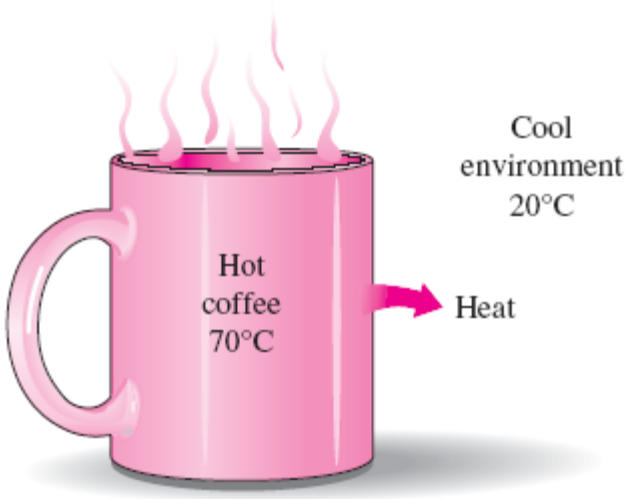



**FIGURE 1–3**
Heat flows in the direction of decreasing temperature.

# Application Areas of Thermodynamics

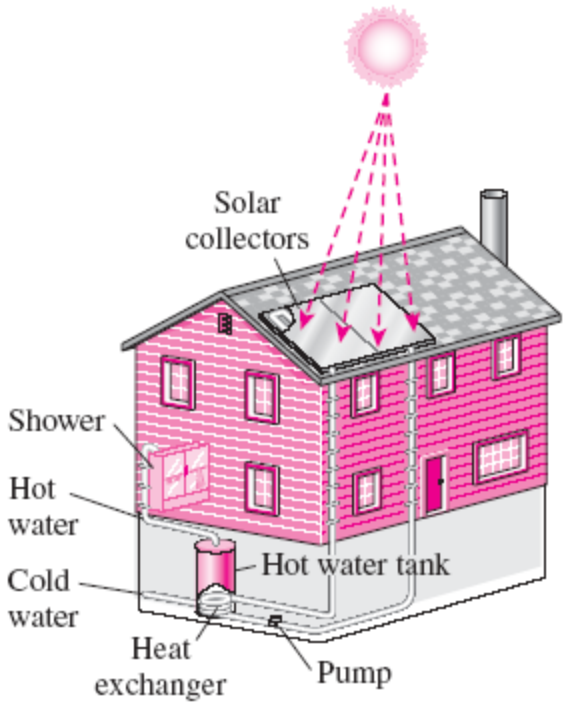



**FIGURE 1–4**
The design of many engineering systems, such as this solar hot water system, involves thermodynamics.



Refrigeration systems



Boats



Aircraft and spacecraft



Power plants

All activities in nature involve some interaction between energy and matter; thus, it is hard to imagine an area that does not relate to thermodynamics in some manner.

# IMPORTANCE OF DIMENSIONS AND UNITS

- Any physical quantity can be characterized by **dimensions**.
- The magnitudes assigned to the dimensions are called **units**.
- Some basic dimensions such as mass *m*, length *L*, time *t*, and temperature *T* are selected as **primary** or **fundamental dimensions**, while others such as velocity *V*, energy *E*, and volume *V* are expressed in terms of the primary dimensions and are called **secondary dimensions**, or **derived dimensions**.
- **Metric SI system**: A simple and logical system based on a decimal relationship between the various units.
- **English system**: It has no apparent systematic numerical base, and various units in this system are related to each other rather arbitrarily.

**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) |

**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 |

# Some SI and English Units

1 lbm = 0.45359 kg

1 ft = 0.3048 m

Force = (Mass)(Acceleration)

$$F = ma$$

$1\ \text{N} = 1\ \text{kg}\cdot\text{m/s}^2$

$1\ \text{lbf} = 32.174\ \text{lbm}\cdot\text{ft/s}^2$

Work = Force × Distance

1 J = 1 N·m

1 cal = 4.1868 J

1 Btu = 1.0551 kJ

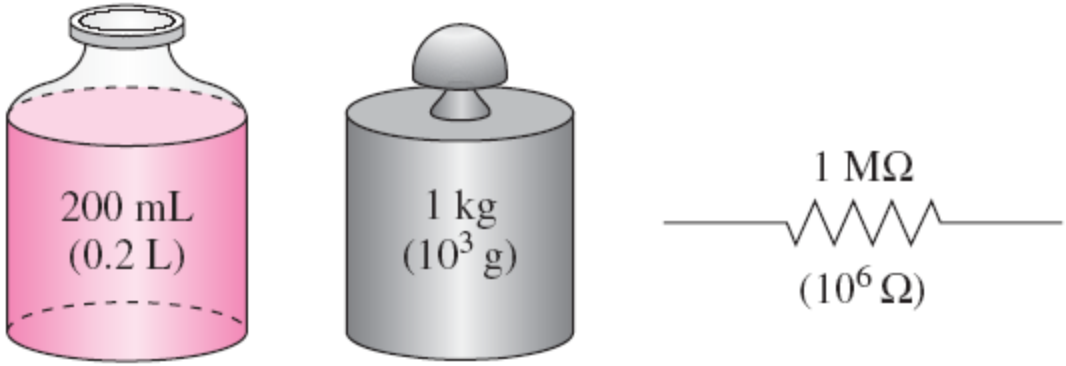



**FIGURE 1–6**
The SI unit prefixes are used in all branches of engineering.

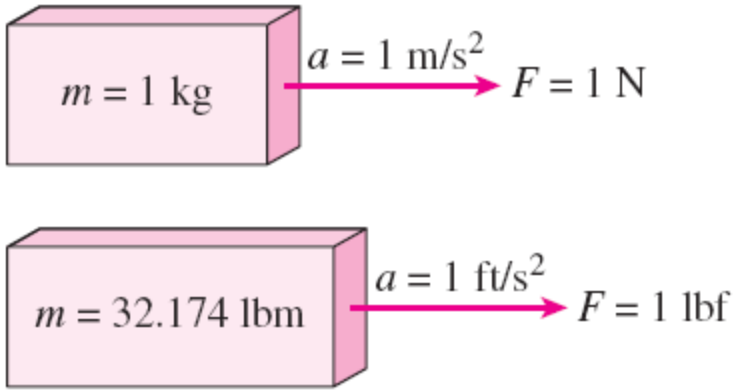



**FIGURE 1–7**
The definition of the force units.

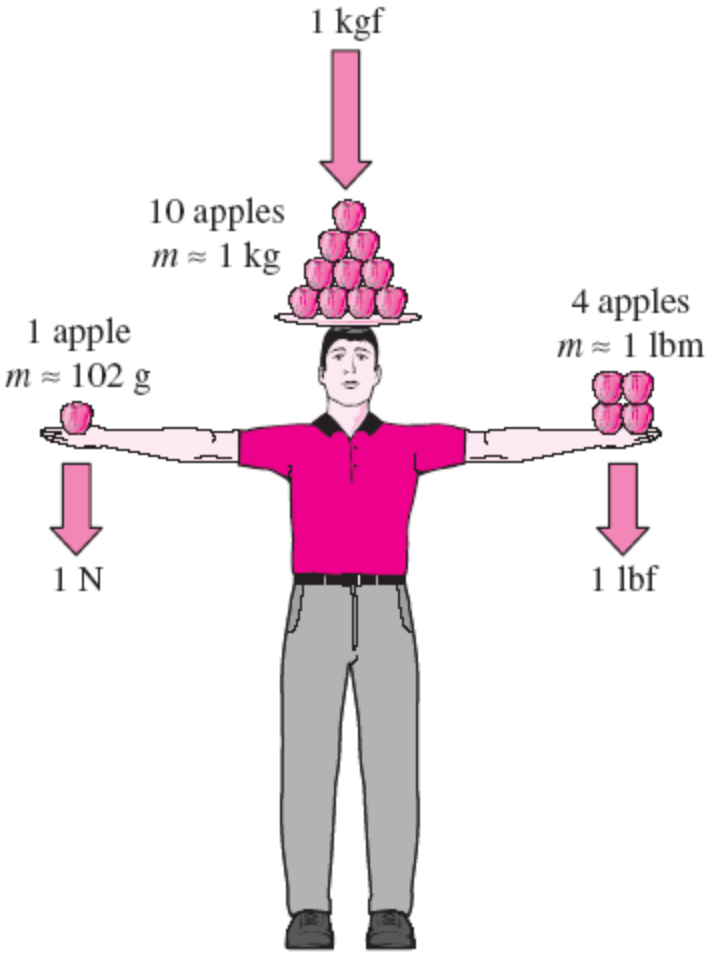



**FIGURE 1–8**
The relative magnitudes of the force units newton (N), kilogram-force (kgf), and pound-force (lbf).




A body weighing 60 kgf on earth will weigh only 10 kgf on the moon.

$$W = mg \quad (\text{N})$$

$W$ weight
$m$ mass
$g$ gravitational acceleration

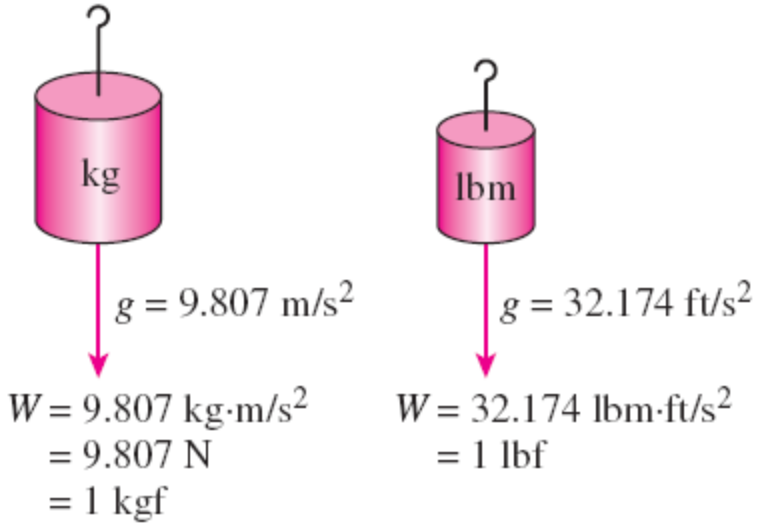



**FIGURE 1–10**
The weight of a unit mass at sea level.

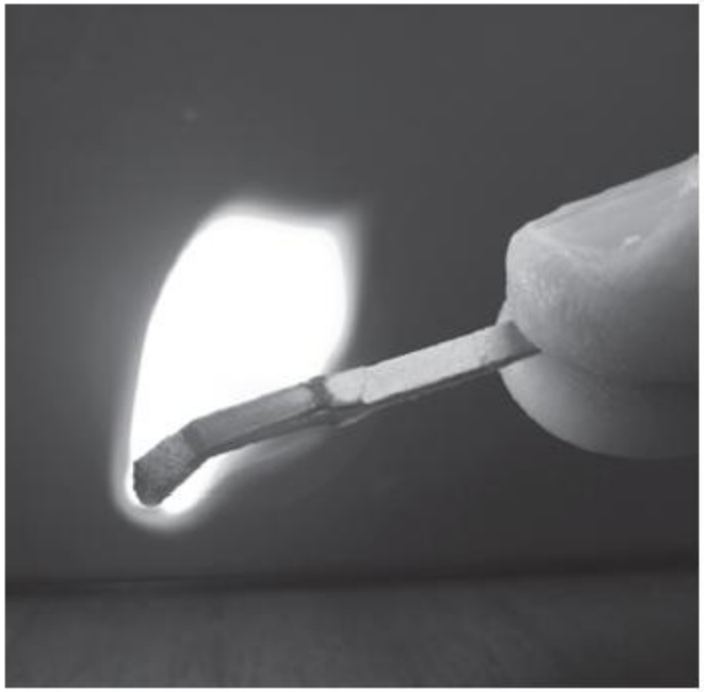


**FIGURE 1–11**
A typical match yields about one Btu (or one kJ) of energy if completely burned.

**Specific weight $\gamma$:** The weight of a unit volume of a substance.

$$\gamma = \rho g$$

# Dimensional homogeneity

All equations must be dimensionally **homogeneous**.




**FIGURE 1–12**
To be dimensionally homogeneous, all the terms in an equation must have the same dimensions.

# Unity Conversion Ratios

*All nonprimary units (secondary units) can be formed by combinations of primary units*.
Force units, for example, can be expressed as

$$\mathrm{N} = \mathrm{kg}\,\frac{\mathrm{m}}{\mathrm{s}^2} \quad \text{and} \quad \mathrm{lbf} = 32.174\ \mathrm{lbm}\,\frac{\mathrm{ft}}{\mathrm{s}^2}$$

They can also be expressed more conveniently as **unity conversion ratios** as

$$\frac{\mathrm{N}}{\mathrm{kg}\cdot\mathrm{m/s}^2} = 1 \quad \text{and} \quad \frac{\mathrm{lbf}}{32.174\ \mathrm{lbm}\cdot\mathrm{ft/s}^2} = 1$$

Unity conversion ratios are identically equal to 1 and are unitless, and thus such ratios (or their inverses) can be inserted conveniently into any calculation to properly convert units.

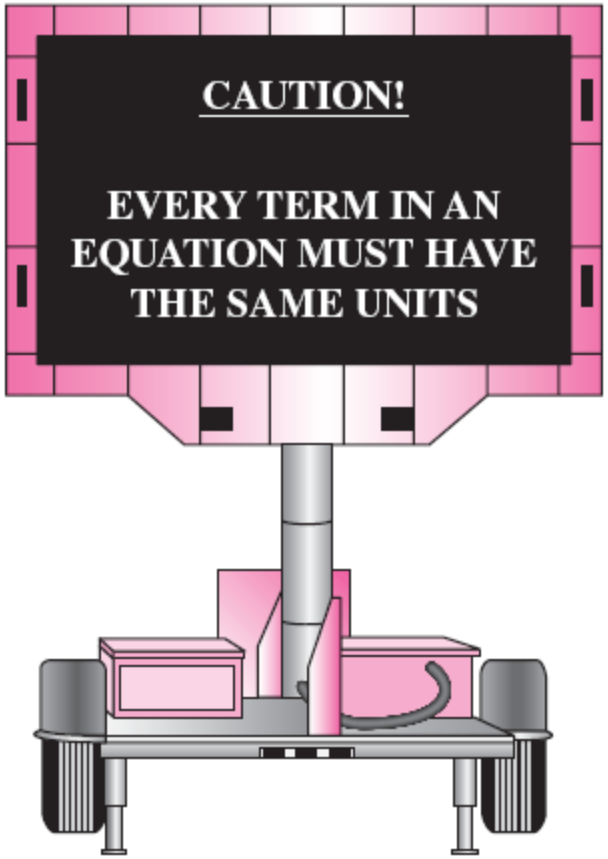



**FIGURE 1–15**
Always check the units in your calculations.

$$\left(\frac{32.174\ \text{lbm}\cdot\text{ft/s}^2}{1\ \text{lbf}}\right)\left(\frac{1\ \text{kg}\cdot\text{m/s}^2}{1\ \text{N}}\right)$$

$$\left(\frac{1\ \text{W}}{1\ \text{J/s}}\right)\left(\frac{1\ \text{kJ}}{1000\ \text{N}\cdot\text{m}}\right)\left(\frac{1\ \text{kPa}}{1000\ \text{N/m}^2}\right)$$

$$\left(\frac{0.3048\ \text{m}}{1\ \text{ft}}\right)\left(\frac{1\ \text{min}}{60\ \text{s}}\right)\left(\frac{1\ \text{lbm}}{0.45359\ \text{kg}}\right)$$

**FIGURE 1–16**
Every unity conversion ratio (as well as its inverse) is exactly equal to one. Shown here are a few commonly used unity conversion ratios.




**FIGURE 1–17**
A mass of 1 kg weighs 9.807 N on earth.

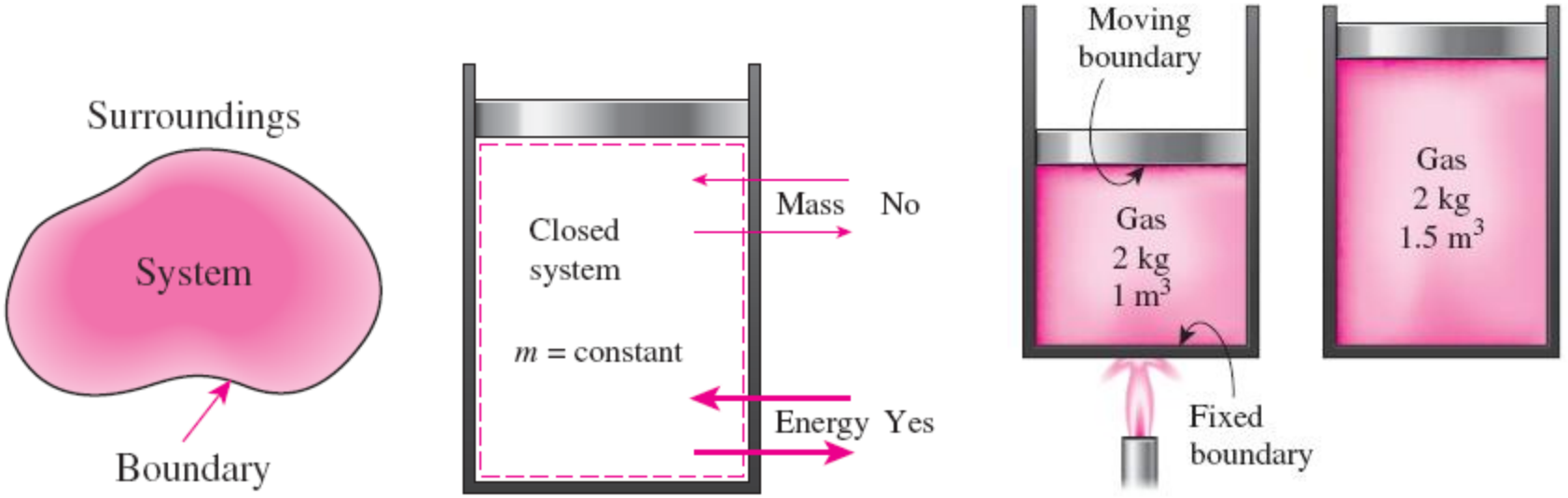



**FIGURE 1–18**
A quirk in the metric system of units.

$$W = mg = (453.6\ \text{g})(9.81\ \text{m/s}^2)\left(\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2}\right)\left(\frac{1\ \text{kg}}{1000\ \text{g}}\right) = 4.49\ \text{N}$$

# SYSTEMS AND CONTROL VOLUMES

- **System**: A quantity of matter or a region in space chosen for study.
- **Surroundings**: The mass or region outside the system
- **Boundary**: The real or imaginary surface that separates the system from its surroundings.
- The boundary of a system can be *fixed* or *movable*.
- Systems may be considered to be *closed* or *open*.
- **Closed system (Control mass):** A fixed amount of mass, and no mass can cross its boundary



- **Open system (control volume)**: A properly selected region in space.
- It usually encloses a device that involves mass flow such as a compressor, turbine, or nozzle.
- Both mass and energy can cross the boundary of a control volume.
- **Control surface**: The boundaries of a control volume. It can be real or imaginary.

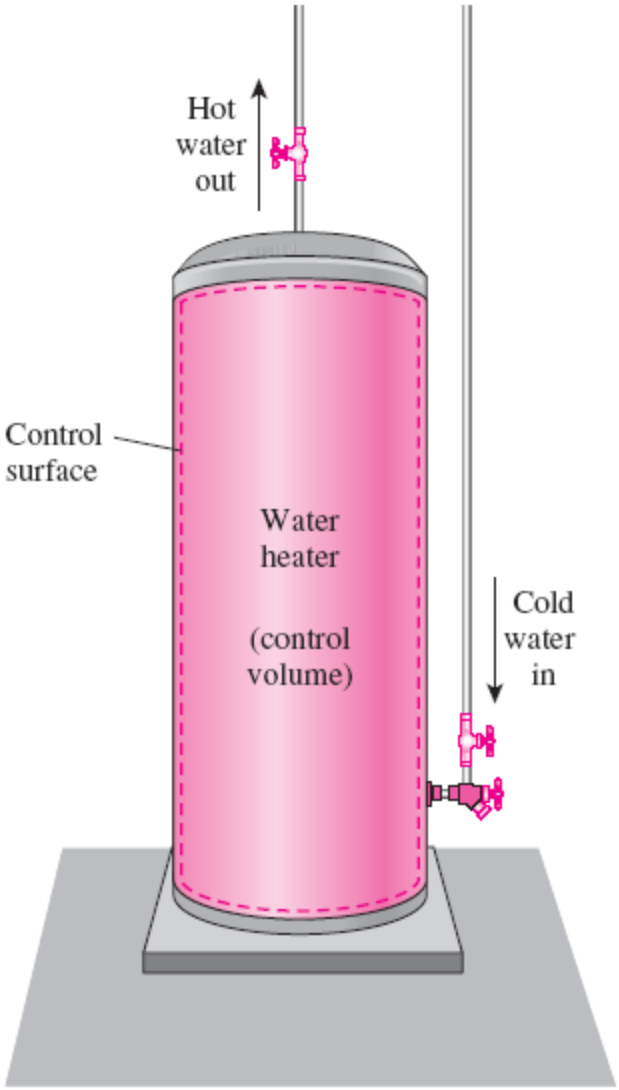
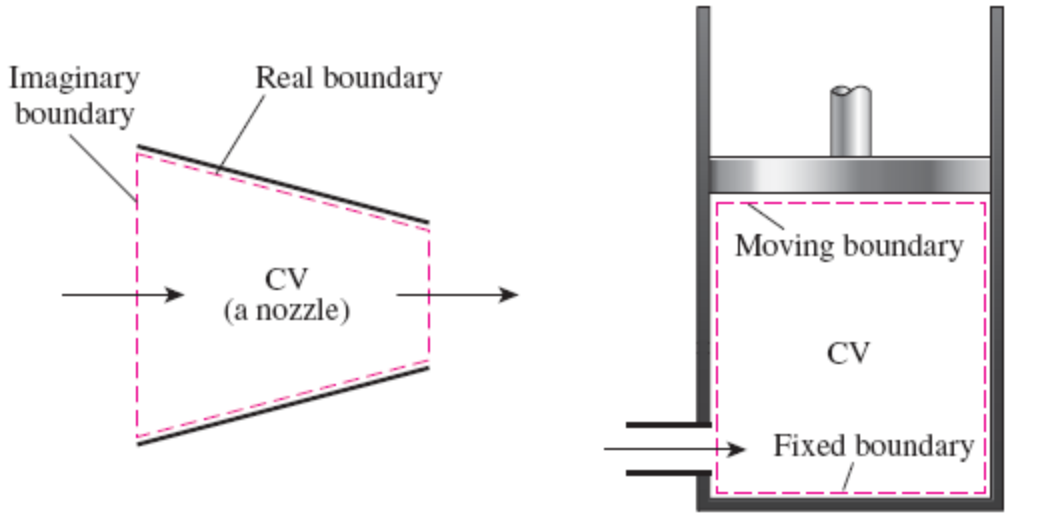



**FIGURE 1–23**
An open system (a control volume) with one inlet and one exit.




(*a*) A control volume with real and imaginary boundaries

(*b*) A control volume with fixed and moving boundaries

**FIGURE 1–22**
A control volume can involve fixed, moving, real, and imaginary boundaries.

# PROPERTIES OF A SYSTEM

- **Property:** Any characteristic of a system.
- Some familiar properties are pressure *P*, temperature *T*, volume *V*, and mass *m*.
- Properties are considered to be either *intensive* or *extensive*.
- **Intensive properties:** Those that are independent of the mass of a system, such as temperature, pressure, and density.
- **Extensive properties:** Those whose values depend on the size—or extent—of the system.
- **Specific properties:** Extensive properties per unit mass.

$$(v = V/m) \quad (e = E/m)$$

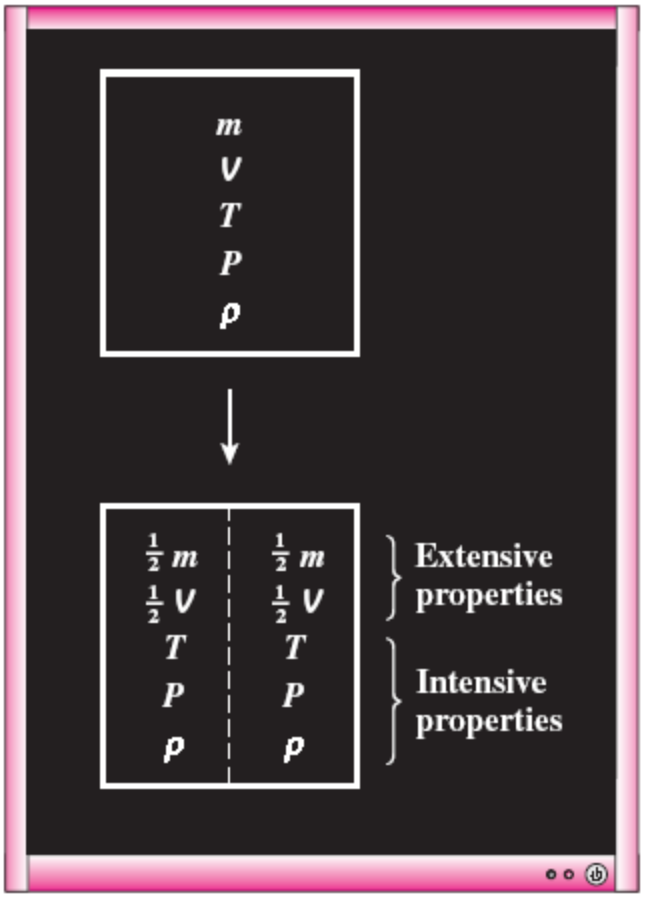



**FIGURE 1–24**
Criterion to differentiate intensive and extensive properties.

# DENSITY AND SPECIFIC GRAVITY

**Density**

$$\rho = \frac{m}{V} \qquad (\text{kg/m}^3)$$

**Specific volume**

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

**Specific gravity**: The ratio of the density of a substance to the density of some standard substance at a specified temperature (usually water at 4°C).

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

**Specific weight**: The weight of a unit volume of a substance.

$$\gamma_s = \rho g \qquad (\text{N/m}^3)$$

$V = 12\ \text{m}^3$
$m = 3\ \text{kg}$



$\rho = 0.25\ \text{kg/m}^3$

$v = \frac{1}{\rho} = 4\ \text{m}^3/\text{kg}$

Density is mass per unit volume; specific volume is volume per unit mass.

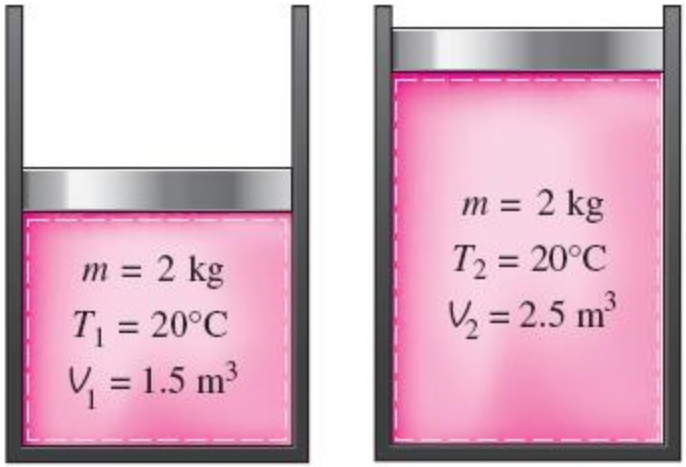
**TABLE 1–3**

Specific gravities of some substances at 0°C

| Substance | SG |
|---|---|
| Water | 1.0 |
| Blood | 1.05 |
| Seawater | 1.025 |
| Gasoline | 0.7 |
| Ethyl alcohol | 0.79 |
| Mercury | 13.6 |
| Wood | 0.3–0.9 |
| Gold | 19.2 |
| Bones | 1.7–2.0 |
| Ice | 0.92 |
| Air (at 1 atm) | 0.0013 |

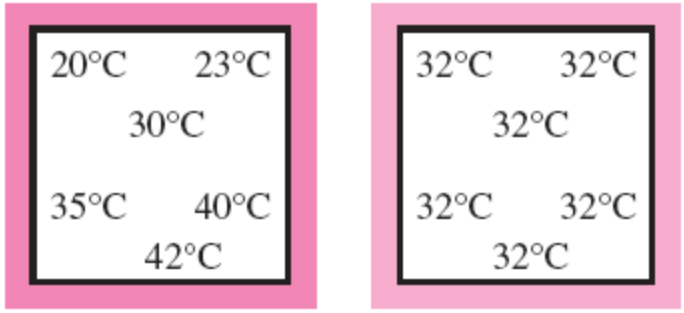
# STATE AND EQUILIBRIUM

- Thermodynamics deals with *equilibrium* states.
- **Equilibrium**: A state of balance.
- In an equilibrium state there are no unbalanced potentials (or driving forces) within the system.
- **Thermal equilibrium**: If the temperature is the same throughout the entire system.
- **Mechanical equilibrium:** If there is no change in pressure at any point of the system with time.
- **Phase equilibrium:** If a system involves two phases and when the mass of each phase reaches an equilibrium level and stays there.
- **Chemical equilibrium:** If the chemical composition of a system does not change with time, that is, no chemical reactions occur.




(*a*) State 1 (*b*) State 2

**FIGURE 1–27**
A system at two different states.




(*a*) Before (*b*) After

**FIGURE 1–28**
A closed system reaching thermal equilibrium.

# The State Postulate

- The number of properties required to fix the state of a system is given by the **state postulate**:
  - ✓ *The state of a simple compressible system is completely specified by two independent, intensive properties.*
- **Simple compressible system:** If a system involves no electrical, magnetic, gravitational, motion, and surface tension effects.




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

# PROCESSES AND CYCLES

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

**Path**: The series of states through which a system passes during a process.

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

**Quasistatic or quasi-equilibrium process:** When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times.

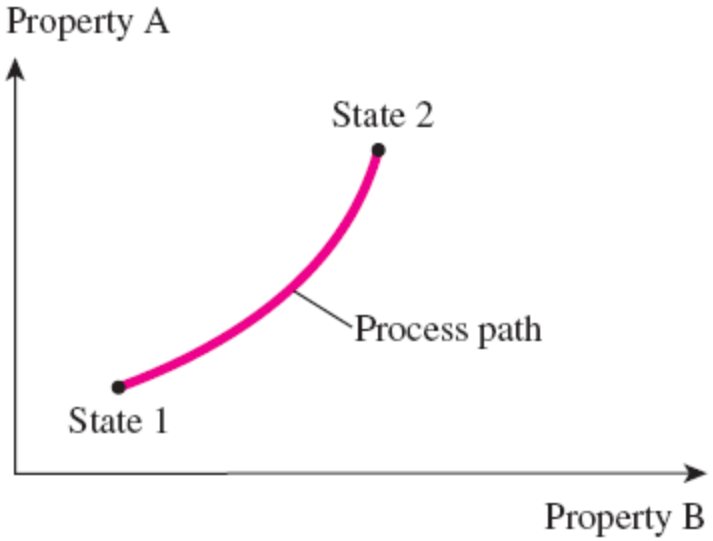



**FIGURE 1–30**
A process between states 1 and 2 and the process path.

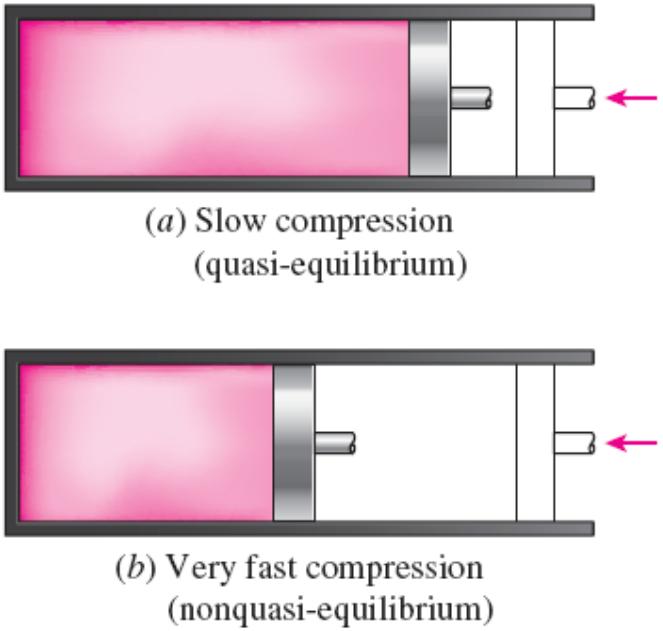



**FIGURE 1–31**
Quasi-equilibrium and nonquasi-equilibrium compression processes.

- Process diagrams plotted by employing thermodynamic properties as coordinates are very useful in visualizing the processes.
- Some common properties that are used as coordinates are temperature *T*, pressure *P*, and volume *V* (or specific volume *v*).
- The prefix *iso-* is often used to designate a process for which a particular property remains constant.
- **Isothermal process**: A process during which the temperature *T* remains constant.
- **Isobaric process**: A process during which the pressure *P* remains constant.
- **Isochoric (or isometric) process**: A process during which the specific volume *v* remains constant.
- **Cycle**: A process during which the initial and final states are identical.

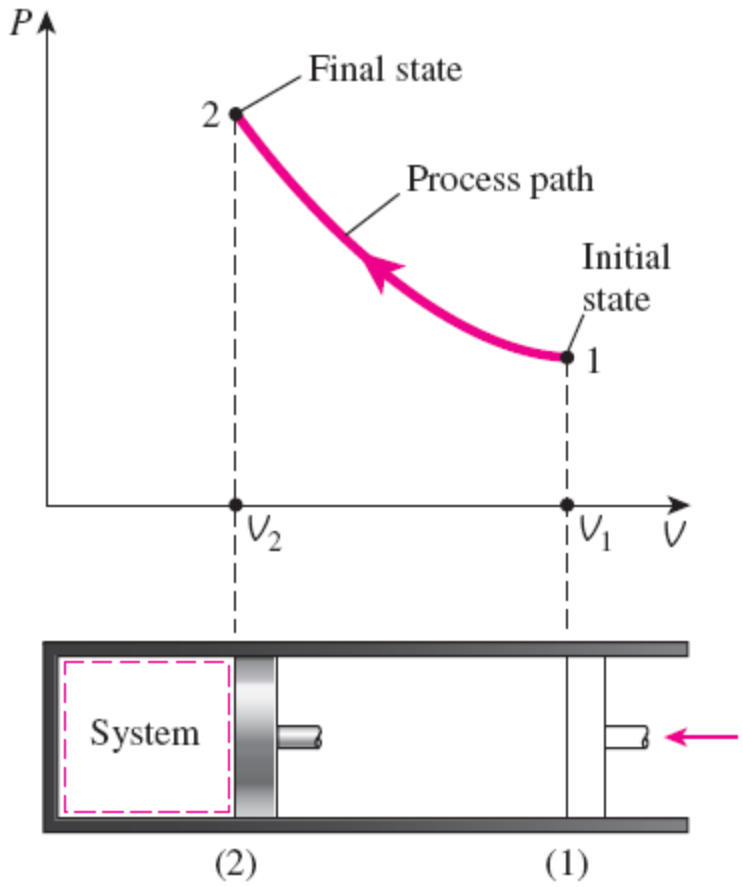



**FIGURE 1–32**
The *P*-*V* diagram of a compression process.

# TEMPERATURE AND THE ZEROTH LAW OF THERMODYNAMICS

- **The zeroth law of thermodynamics**: If two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other.
- By replacing the third body with a thermometer, the zeroth law can be restated as *two bodies are in thermal equilibrium if both have the same temperature reading even if they are not in contact*.

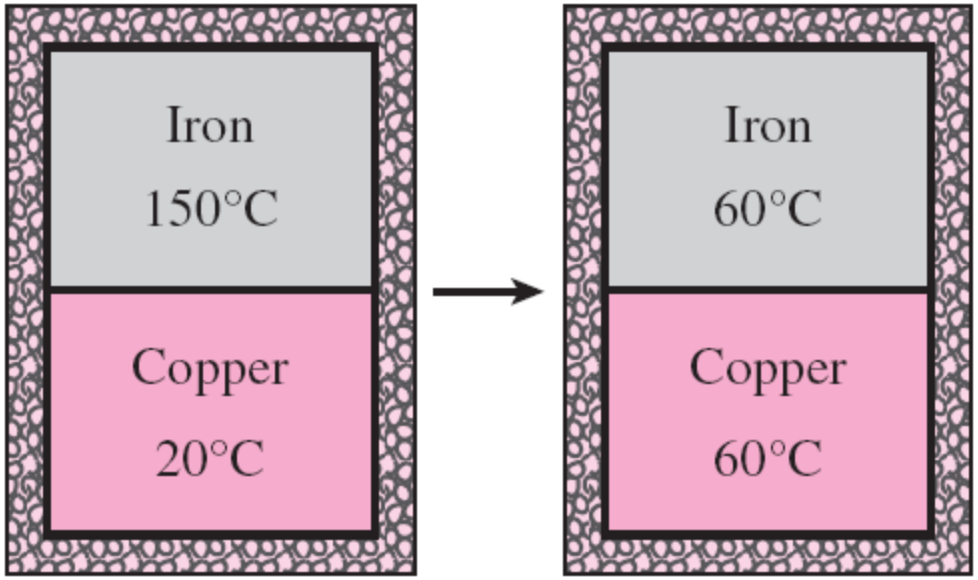


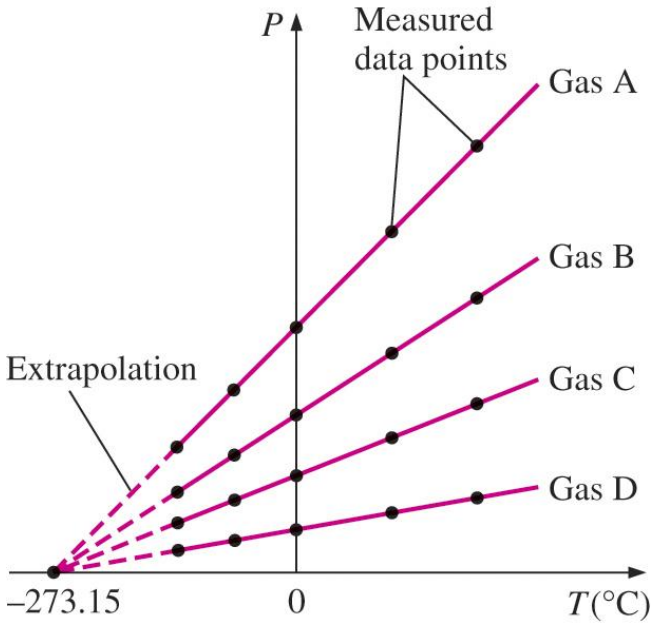

**FIGURE 1–35**

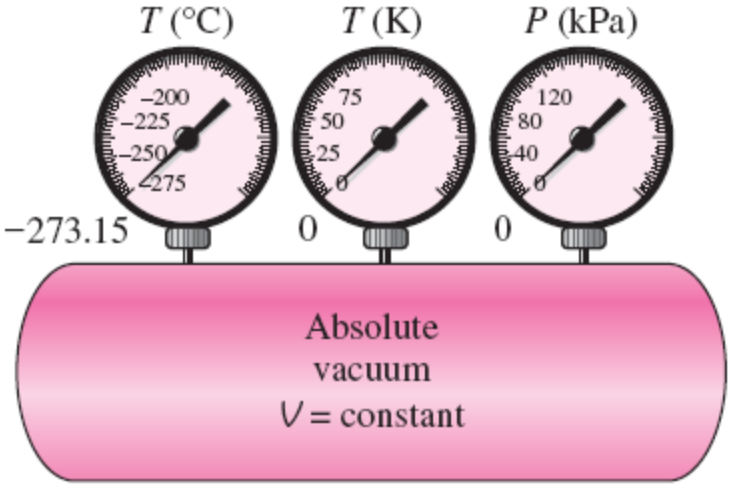
Two bodies reaching thermal equilibrium after being brought into contact in an isolated enclosure.

# Temperature Scales

- All temperature scales are based on some easily reproducible states such as the freezing and boiling points of water: the *ice point* and the *steam point.*
- **Ice point**: A mixture of ice and water that is in equilibrium with air saturated with vapor at 1 atm pressure (0°C or 32°F).
- **Steam point**: A mixture of liquid water and water vapor (with no air) in equilibrium at 1 atm pressure (100°C or 212°F).
- **Celsius scale**: in SI unit system
- **Fahrenheit scale**: in English unit system
- **Thermodynamic temperature scale**: A temperature scale that is independent of the properties of any substance.
- **Kelvin scale** (SI) **Rankine scale** (E)
- A temperature scale nearly identical to the Kelvin scale is the **ideal-gas temperature scale**. The temperatures on this scale are measured using a constant-volume gas thermometer.

*P* versus *T* plots of the experimental data obtained from a constant-volume gas thermometer using four different gases at different (but low) pressures.




A constant-volume gas thermometer would read -273.15°C at absolute zero pressure.

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

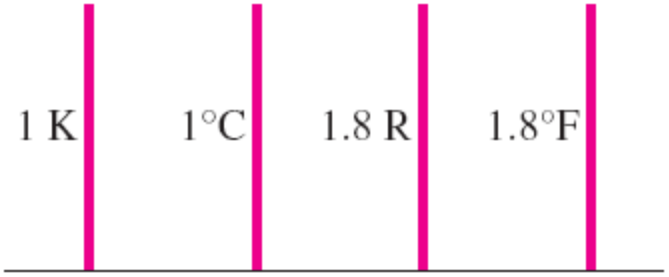
$$T(\mathrm{R}) = T(^\circ\mathrm{F}) + 459.67$$

$$T(\mathrm{R}) = 1.8T(\mathrm{K})$$

$$T(^\circ\mathrm{F}) = 1.8T(^\circ\mathrm{C}) + 32$$

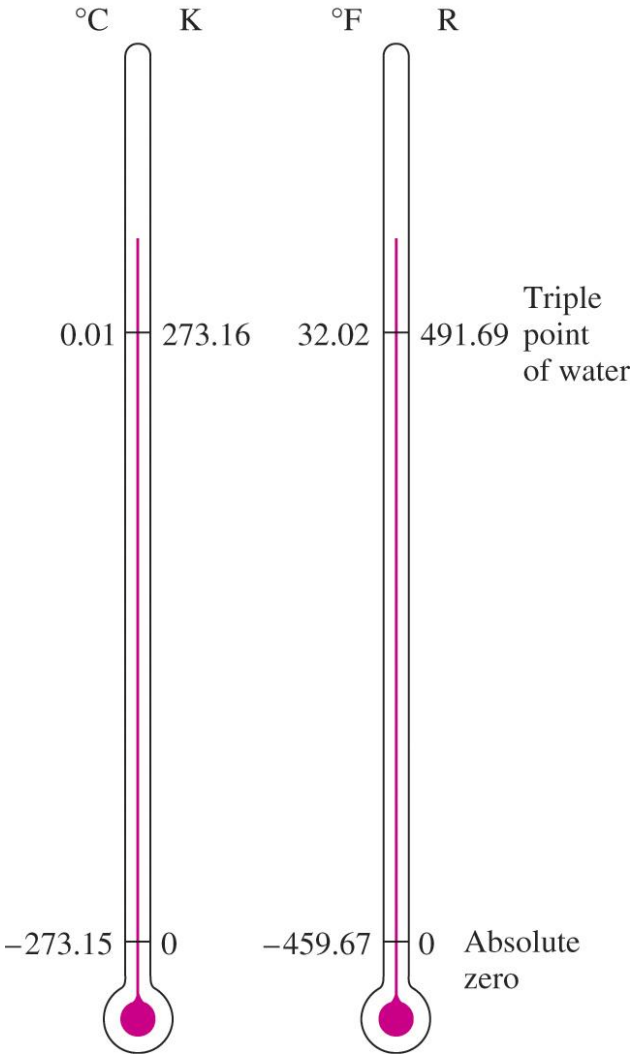
$$\Delta T(\mathrm{K}) = \Delta T(^\circ\mathrm{C})$$

$$\Delta T(\mathrm{R}) = \Delta T(^\circ\mathrm{F})$$




Comparison of magnitudes of various temperature units.

Comparison of temperature scales.




- The reference temperature in the original Kelvin scale was the ***ice point***, 273.15 K, which is the temperature at which water freezes (or ice melts).
- The reference point was changed to a much more precisely reproducible point, the ***triple point*** of water (the state at which all three phases of water coexist in equilibrium), which is assigned the value 273.16 K.

# PRESSURE

**Pressure**: A normal force exerted by a fluid per unit area

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

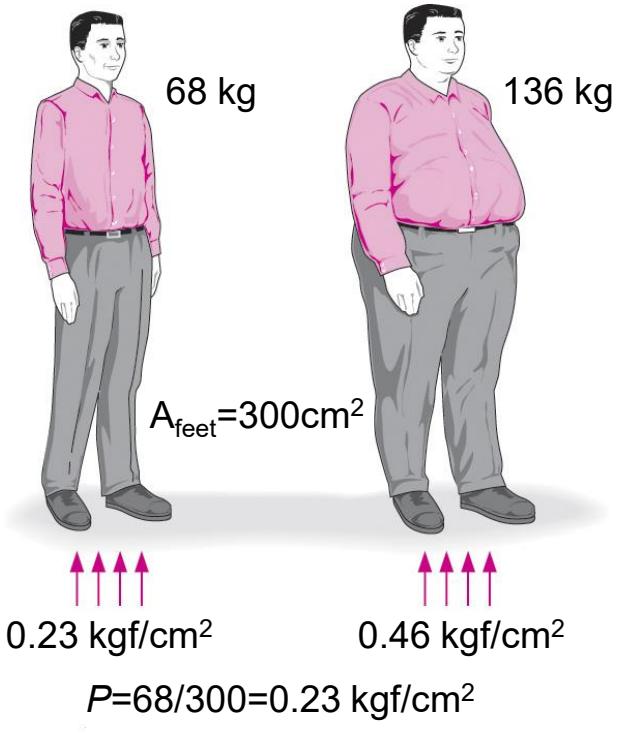
$$1\ \text{bar} = 10^5\ \text{Pa} = 0.1\ \text{MPa} = 100\ \text{kPa}$$

$$1\ \text{atm} = 101{,}325\ \text{Pa} = 101.325\ \text{kPa} = 1.01325\ \text{bars}$$

$$1\ \text{kgf/cm}^2 = 9.807\ \text{N/cm}^2 = 9.807 \times 10^4\ \text{N/m}^2 = 9.807 \times 10^4\ \text{Pa}$$

$$= 0.9807\ \text{bar}$$

$$= 0.9679\ \text{atm}$$






Some basic pressure gages.

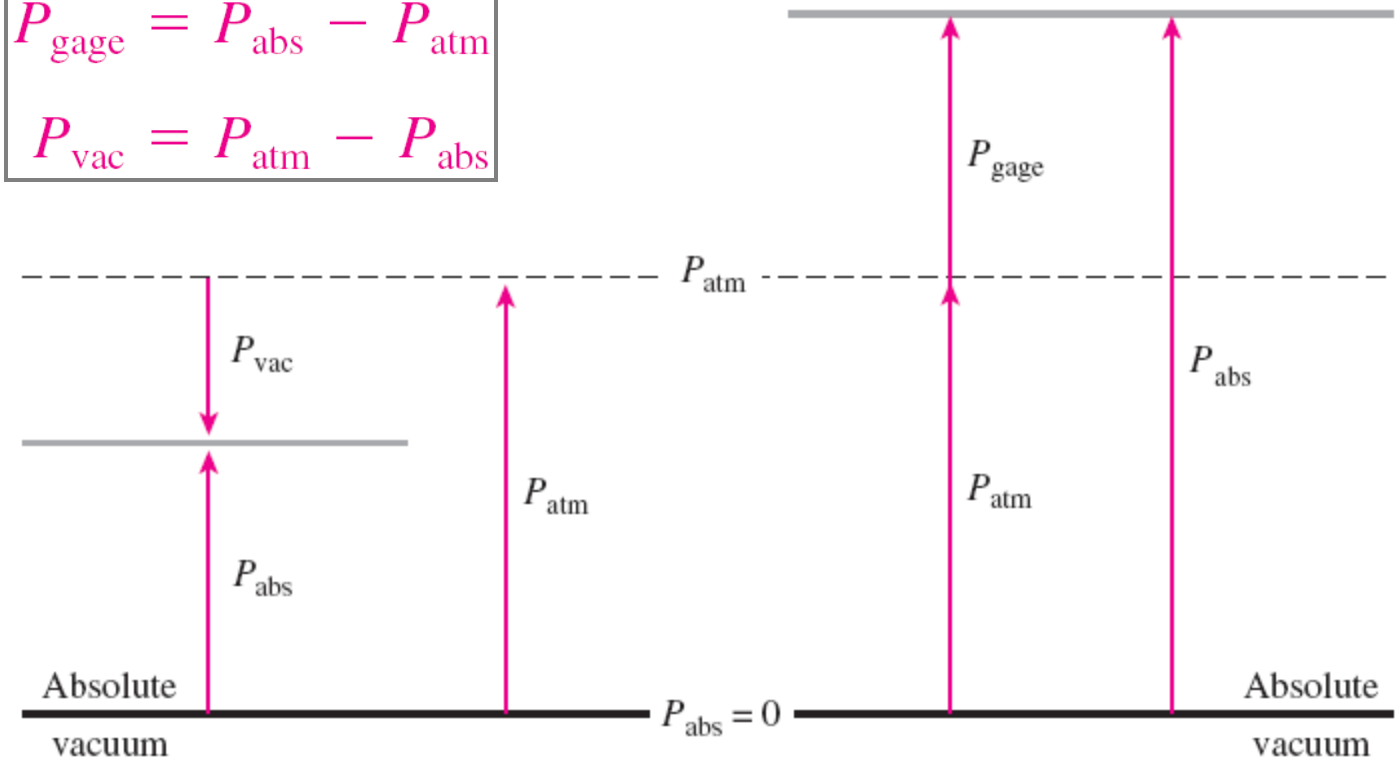
The normal stress (or "pressure") on the feet of a chubby person is much greater than on the feet of a slim person.

- **Absolute pressure**: The actual pressure at a given position. It is measured relative to absolute vacuum (i.e., absolute zero pressure).
- **Gage pressure**: The difference between the absolute pressure and the local atmospheric pressure. Most pressure-measuring devices are calibrated to read zero in the atmosphere, and so they indicate gage pressure.
- **Vacuum pressures**: Pressures below atmospheric pressure.

Throughout this text, the pressure ***P*** will denote ***absolute pressure*** unless specified otherwise.

$$P_{\text{gage}} = P_{\text{abs}} - P_{\text{atm}}$$

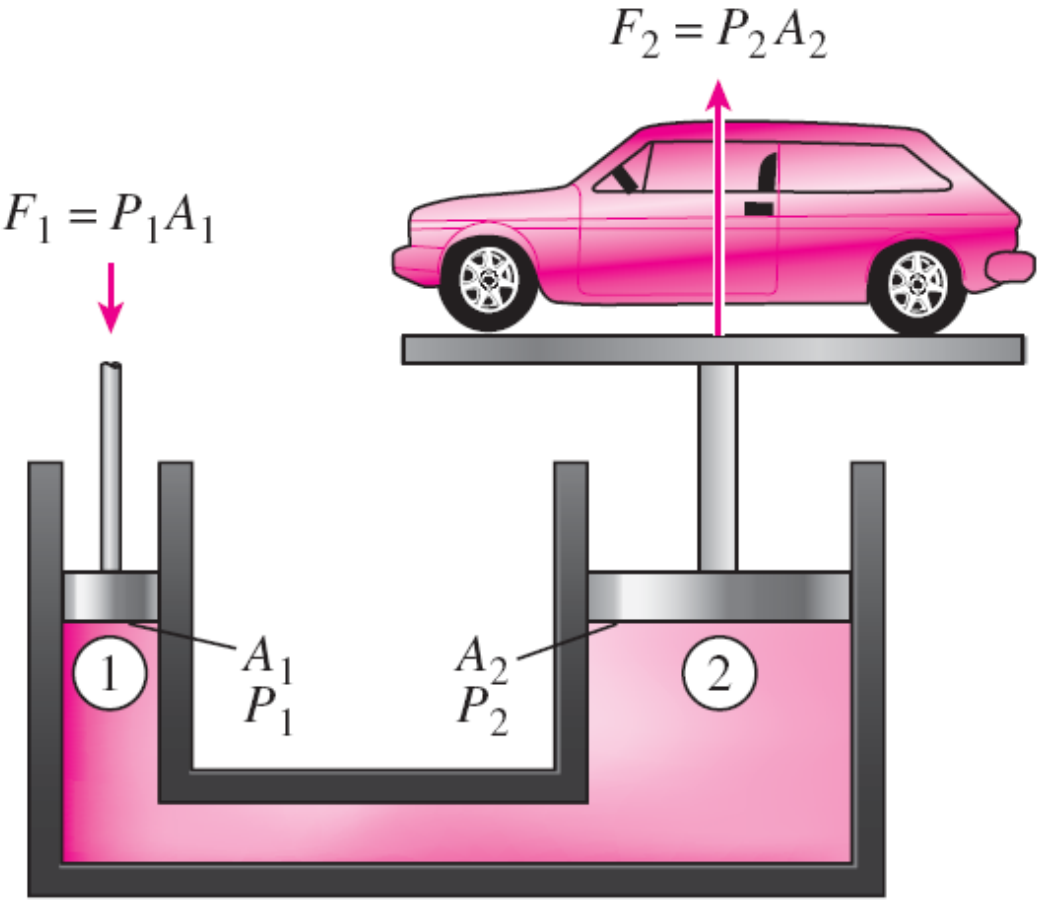
$$P_{\text{vac}} = P_{\text{atm}} - P_{\text{abs}}$$



**Pascal's law**: The pressure applied to a confined fluid increases the pressure throughout by the same amount.

$$P_1 = P_2 \quad \rightarrow \quad \frac{F_1}{A_1} = \frac{F_2}{A_2} \quad \rightarrow \quad \frac{F_2}{F_1} = \frac{A_2}{A_1}$$

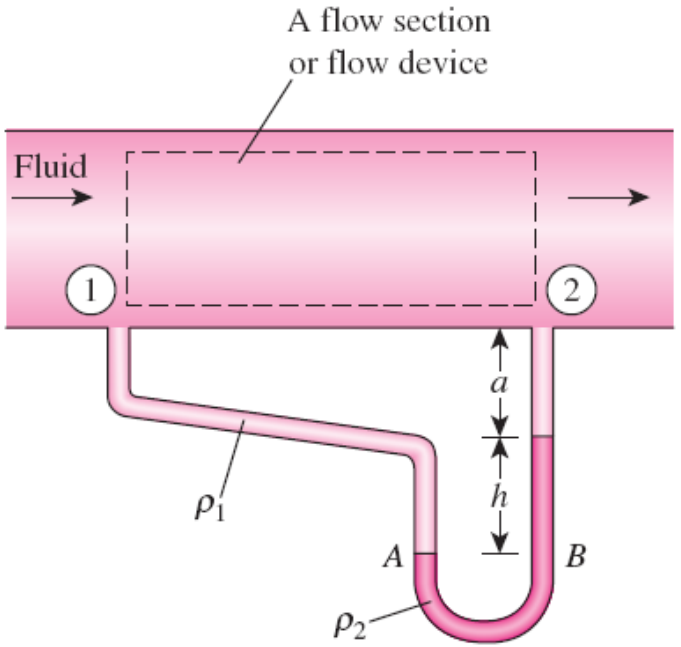
The area ratio $A_2/A_1$ is called the *ideal mechanical advantage* of the hydraulic lift.




Lifting of a large weight by a small force by the application of Pascal's law.

# The Manometer

It is commonly used to measure small and moderate pressure differences. A manometer contains one or more fluids such as mercury, water, alcohol, or oil.




Measuring the pressure drop across a flow section or a flow device by a differential manometer.

$$P_1 + \rho_1 g(a + h) - \rho_2 gh - \rho_1 ga = P_2$$

$$P_1 - P_2 = (\rho_2 - \rho_1)gh$$

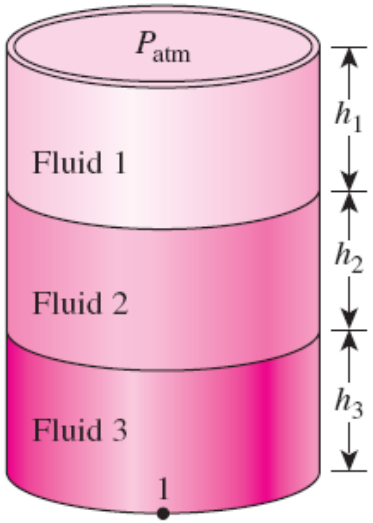
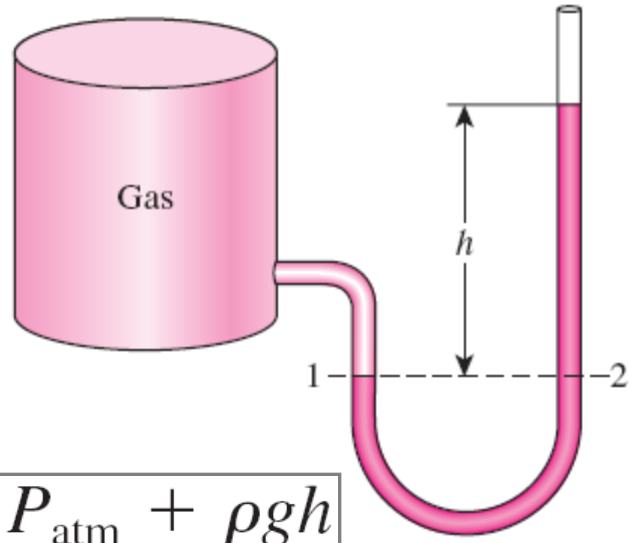



**FIGURE 1–51**
In stacked-up fluid layers, the pressure change across a fluid layer of density $\rho$ and height $h$ is $\rho gh$.

$$P_{atm} + \rho_1 gh_1 + \rho_2 gh_2 + \rho_3 gh_3 = P_1$$

The basic manometer.




$$P_2 = P_{atm} + \rho gh$$

# Other Pressure Measurement Devices

- **Bourdon tube**: Consists of a hollow metal tube bent like a hook whose end is closed and connected to a dial indicator needle.
- **Pressure transducers**: Use various techniques to convert the pressure effect to an electrical effect such as a change in voltage, resistance, or capacitance.
- Pressure transducers are smaller and faster, and they can be more sensitive, reliable, and precise than their mechanical counterparts.
- **Strain-gage pressure transducers:** Work by having a diaphragm deflect between two chambers open to the pressure inputs.
- **Piezoelectric transducers**: Also called solid-state pressure transducers, work on the principle that an electric potential is generated in a crystalline substance when it is subjected to mechanical pressure.

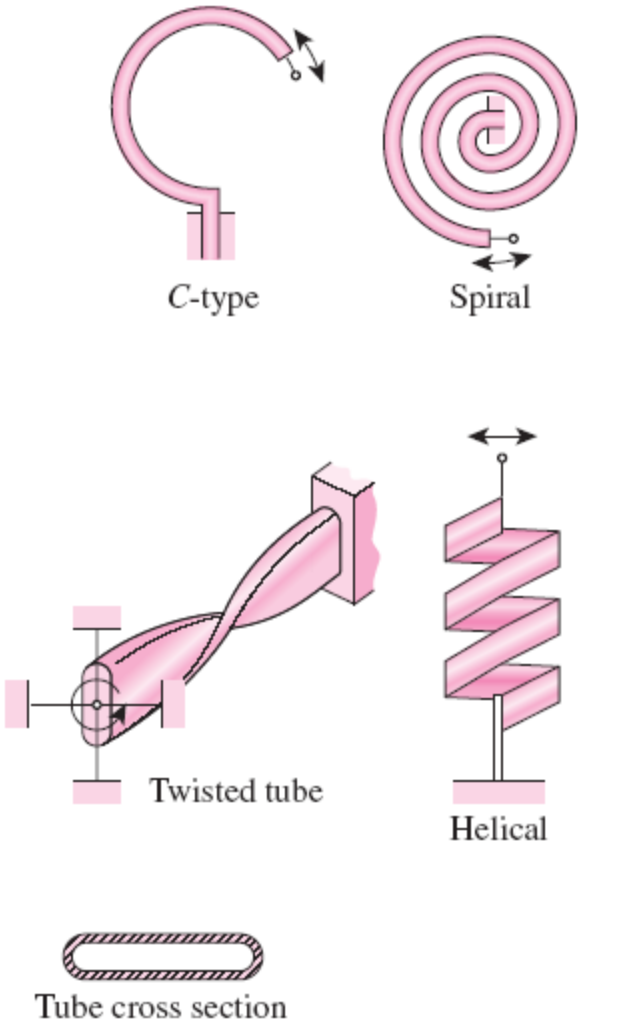



**FIGURE 1–54**
Various types of Bourdon tubes used to measure pressure.

# THE BAROMETER AND ATMOSPHERIC PRESSURE

- Atmospheric pressure is measured by a device called a **barometer**; thus, the atmospheric pressure is often referred to as the ***barometric pressure***.
- A frequently used pressure unit is the *standard atmosphere*, which is defined as the pressure produced by a column of mercury 760 mm in height at 0°C ($\rho_{Hg}$ = 13,595 kg/m$^3$) under standard gravitational acceleration ($g$ = 9.807 m/s$^2$).

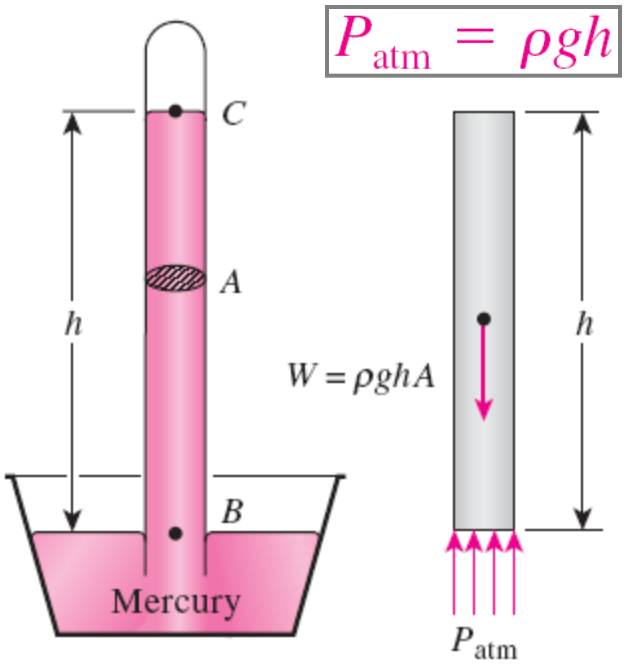
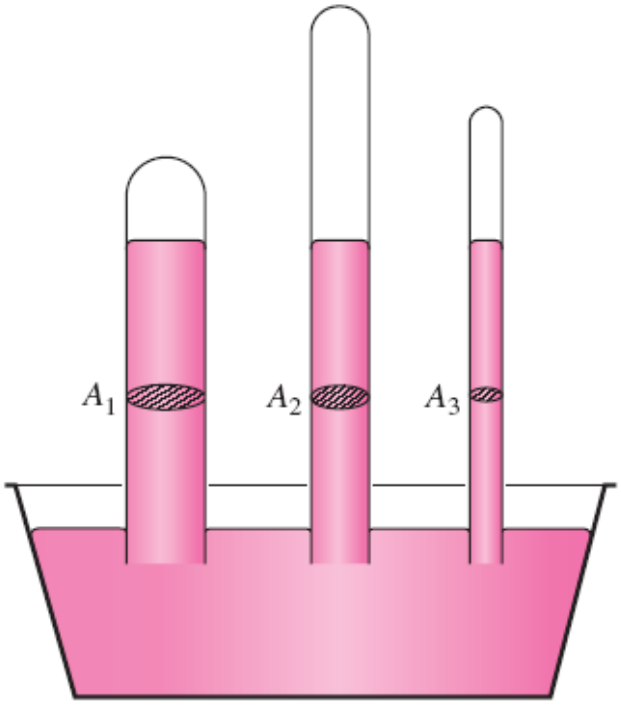



**FIGURE 1–55**
The basic barometer.

The length or the cross-sectional area of the tube has no effect on the height of the fluid column of a barometer, provided that the tube diameter is large enough to avoid surface tension (capillary) effects.



# Applied Thermodynamics: An Engineering Approach

Seventh Edition in SI Units

Yunus A. Cengel, Michael A. Boles

McGraw-Hill, 2011

MODULE 2.2

# First Law of Thermodynamics for closed and open systems

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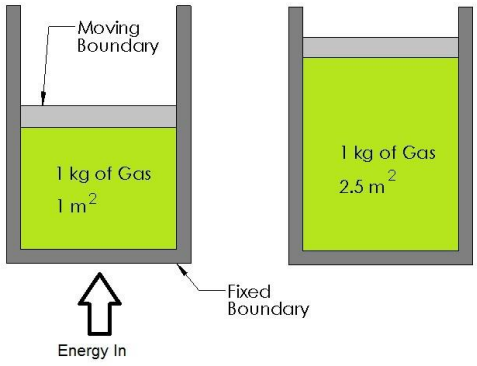
# The First Law of Thermodynamics

**A system** is defined as space or a region that chosen for study.

- **The *first law of thermodynamics* (*the conservation of energy principle*) provides a sound basis for studying the relationships among the various forms of energy and energy interactions.**
- **The first law states that *energy can be neither created nor destroyed during a process; it can only change forms.***
- **The *First Law:* For all adiabatic processes between two specified states of a closed system, the net work done is the same regardless of the nature of the closed system and the details of the process.**

**A closed system (control mass)** involves mass does not transfer (in or out) /or across a system's surrounding.




Piston cylinder
Vessel.
Closed rigid tank.





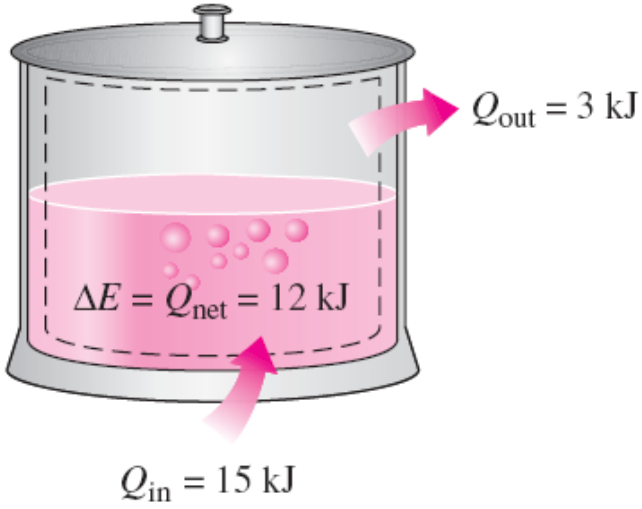



**FIGURE 2–41**
In the absence of any work interactions, the energy change of a system is equal to the net heat transfer.

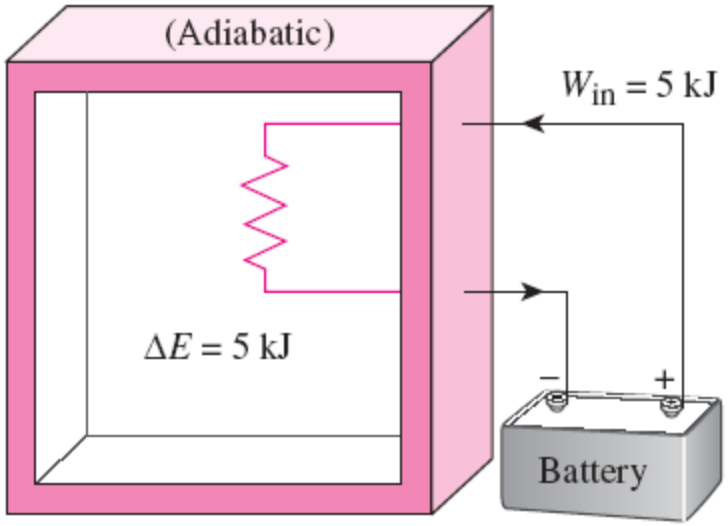



**FIGURE 2–42**
The work (electrical) done on an adiabatic system is equal to the increase in the energy of the system.

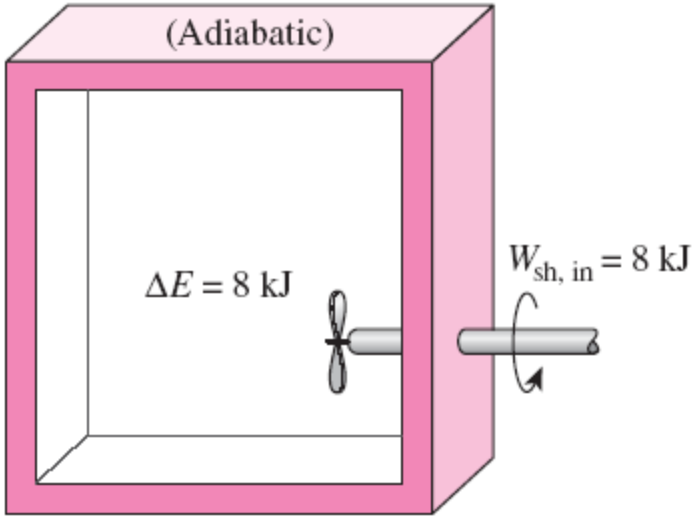



**FIGURE 2–43**
The work (shaft) done on an adiabatic system is equal to the increase in the energy of the system.

# Energy Balance

The net change (increase or decrease) in the total energy of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process.

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

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

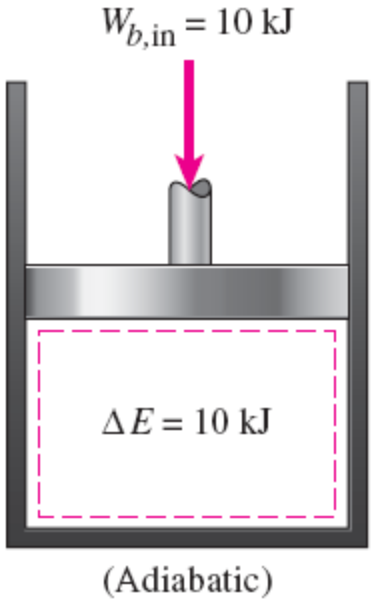



**FIGURE 2–44**
The work (boundary) done on an adiabatic system is equal to the increase in the energy of the system.

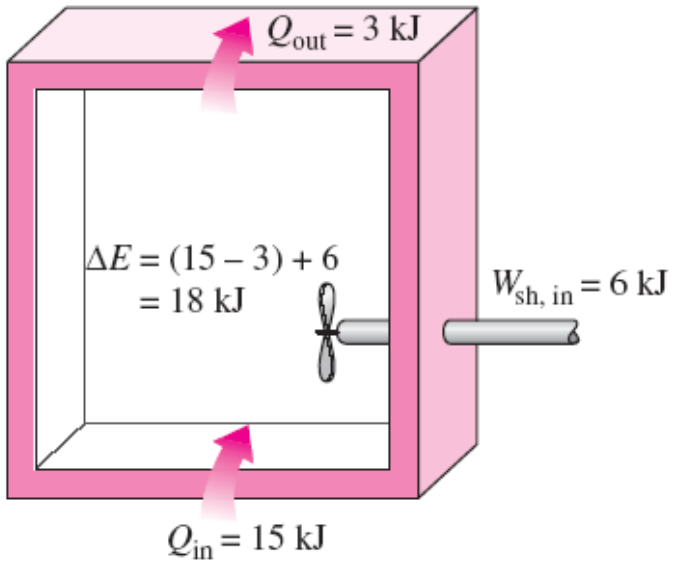
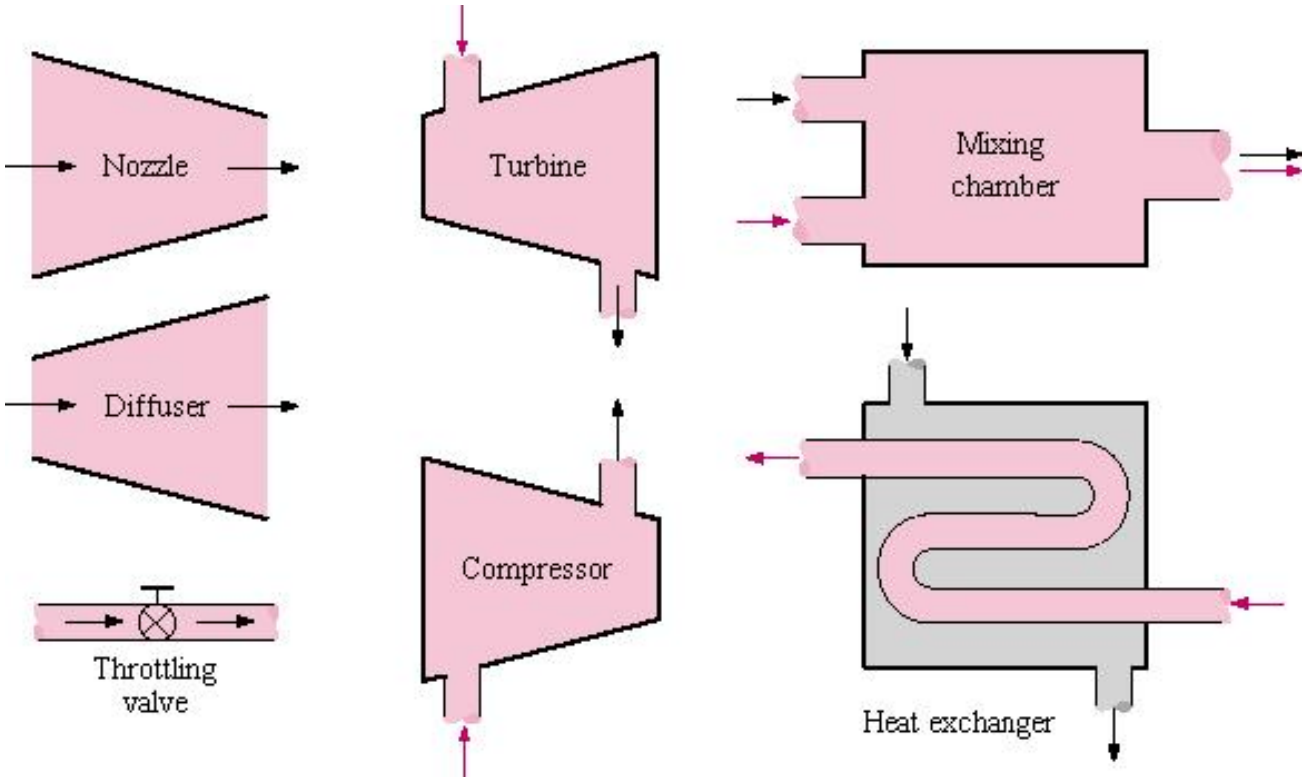



**FIGURE 2–45**
The energy change of a system during a process is equal to the *net* work and heat transfer between the system and its surroundings.

# The First Law of Thermodynamics

**Open system (A control volume)** differs from **a closed system** in that it involves mass transfer. Mass carries energy with it, and thus the mass and energy content of a system change when mass enters or leaves.



# FORMS OF ENERGY

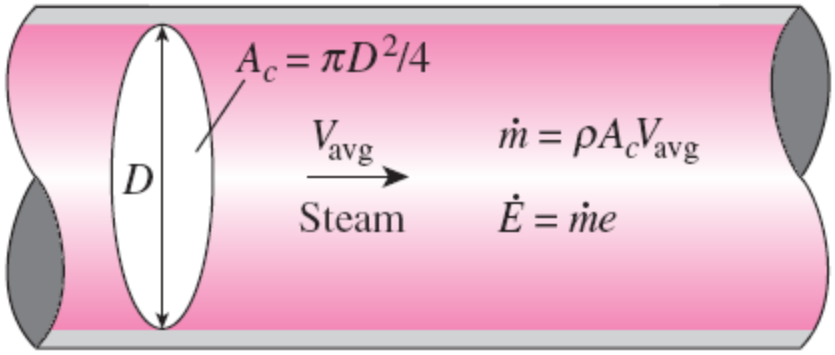
- Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear, and their sum constitutes the **total energy, *E*** of a system.
- Thermodynamics deals only with the ***change*** of the total energy.
- **Macroscopic forms of energy**: Those a system possesses as a whole with respect to some outside reference frame, such as kinetic and potential energies.
- **Microscopic forms of energy**: Those related to the molecular structure of a system and the degree of the molecular activity.
- **Internal energy, *U***: The sum of all the microscopic forms of energy.
- Kinetic energy, KE: The energy that a system possesses as a result of its motion relative to some reference frame.
- Potential energy, PE: The energy that a system possesses as a result of its elevation in a gravitational field.



The macroscopic energy of an object changes with velocity and elevation.

$$\mathrm{KE} = m\frac{V^2}{2} \quad (\mathrm{kJ})$$ Kinetic energy

$$\mathrm{ke} = \frac{V^2}{2} \quad (\mathrm{kJ/kg})$$ Kinetic energy per unit mass




$$\mathrm{PE} = mgz \quad (\mathrm{kJ})$$ Potential energy

$$\mathrm{pe} = gz \quad (\mathrm{kJ/kg})$$ Potential energy per unit mass

**Mass flow rate**

$$\dot{m} = \rho\dot{V} = \rho A_c V_{\mathrm{avg}} \quad (\mathrm{kg/s})$$

**Energy flow rate**

$$\dot{E} = \dot{m}e \quad (\mathrm{kJ/s\ or\ kW})$$

$$E = U + \mathrm{KE} + \mathrm{PE} = U + m\frac{V^2}{2} + mgz + P\forall \quad (\mathrm{kJ})$$ Total energy of a system

$$e = u + \mathrm{ke} + \mathrm{pe} = u + \frac{V^2}{2} + gz \quad (\mathrm{kJ/kg})$$ Energy of a system per unit mass

$$e = \frac{E}{m} \quad (\mathrm{kJ/kg})$$ Total energy per unit mass

# Energy Change of a System, $\Delta E_{system}$

Energy change = Energy at final state − Energy at initial state

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

$$\Delta E = \Delta U + \Delta KE + \Delta PE + \Delta P\forall$$

**Internal, kinetic, and potential energy changes**

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

$$\Delta KE = \tfrac{1}{2} m(V_2^2 - V_1^2)$$

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

**ΔE=ΔU**

$$\Delta P\forall = P_2\forall_2 - P_1\forall_1 \ (Change\ of\ flow\ energy)$$

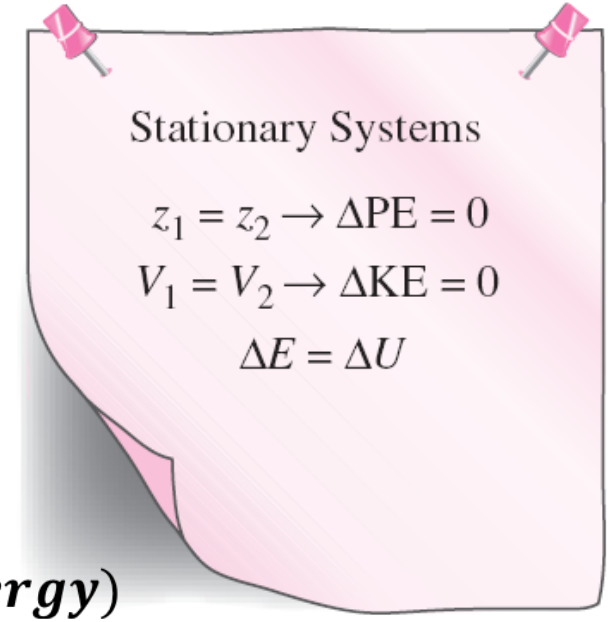



**FIGURE 2–46**

For stationary systems, $\Delta KE = \Delta PE = 0$; thus $\Delta E = \Delta U$.

# Mechanical Energy

Mechanical energy: The form of energy that can be converted to mechanical work completely and directly by an ideal mechanical device such as an ideal turbine.

Kinetic and potential energies: The familiar forms of mechanical energy.

$$e_{\text{mech}} = \frac{P}{\rho} + \frac{V^2}{2} + gz$$ Mechanical energy of a flowing fluid per unit mass

$$\dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = \dot{m}\left(\frac{P}{\rho} + \frac{V^2}{2} + gz\right)$$ Rate of mechanical energy of a flowing fluid

Mechanical energy change of a fluid during incompressible flow per unit mass

$$\Delta e_{\text{mech}} = \frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \qquad (\text{kJ/kg})$$

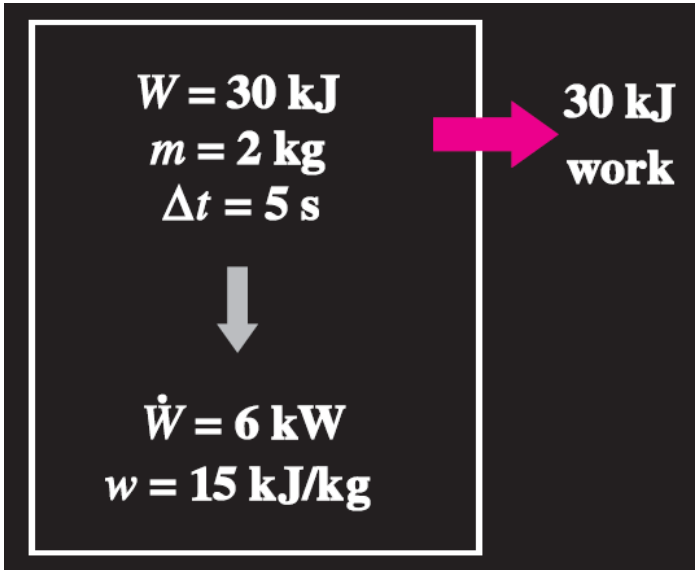
Rate of mechanical energy change of a fluid during incompressible flow

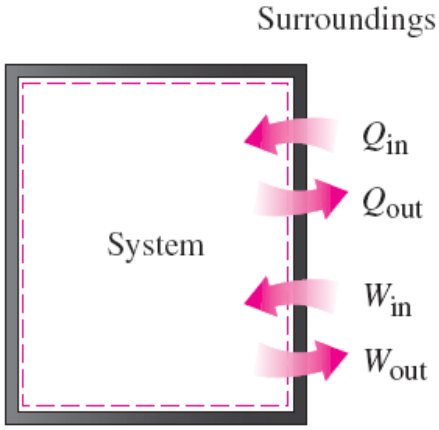
$$\Delta \dot{E}_{\text{mech}} = \dot{m}\Delta e_{\text{mech}} = \dot{m}\left(\frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right) \qquad (\text{kW})$$

# ENERGY TRANSFER BY WORK

- **Work**: The energy transfer associated with a force acting through a distance.
  - ✓ **A rising piston, a rotating shaft**, and **an electric wire crossing the system boundaries** are all associated with work interactions
- **Formal sign convention**: *Heat transfer to a system and work done by a system are positive; heat transfer from a system and work done on a system are negative*.
- Alternative to sign convention is to use the subscripts ***in*** and ***out*** to indicate direction. This is the primary approach in this text.

$$w = \frac{W}{m} \quad (\text{kJ/kg})$$ **Work done per unit mass**




**Specifying the directions of heat and work.**

**Power is the work done per unit time (kW)**

# Work Done to Raise or to Accelerate a Body

1. The work transfer needed to raise a body is equal to the change in the potential energy of the body.
2. The work transfer needed to accelerate a body is equal to the change in the kinetic energy of the body.

## Nonmechanical Forms of Work

Electrical work: The generalized force is the *voltage* (the electrical potential) and the generalized displacement is the *electrical charge*.

Magnetic work: The generalized force is the *magnetic field strength* and the generalized displacement is the total *magnetic dipole moment*.

Electrical polarization work: The generalized force is the *electric field strength* and the generalized displacement is the *polarization of the medium*.

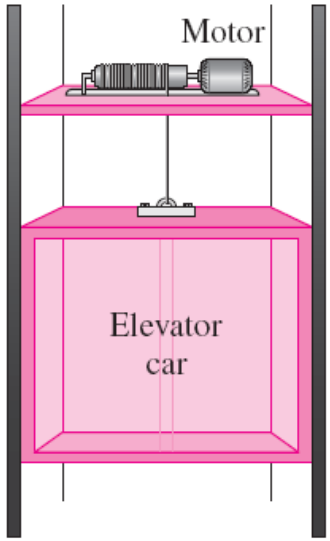



**FIGURE 2–36**
The energy transferred to a body while being raised is equal to the change in its potential energy.

# Electrical Work

Electrical work

$$W_e = \mathbf{V}N$$

Electrical power

$$\dot{W}_e = \mathbf{V}I \qquad (\mathrm{W})$$

When potential difference and current change with time

$$W_e = \int_1^2 \mathbf{V}I\,dt \qquad (\mathrm{kJ})$$

When potential difference and current remain constant

$$W_e = \mathbf{V}I\,\Delta t \qquad (\mathrm{kJ})$$

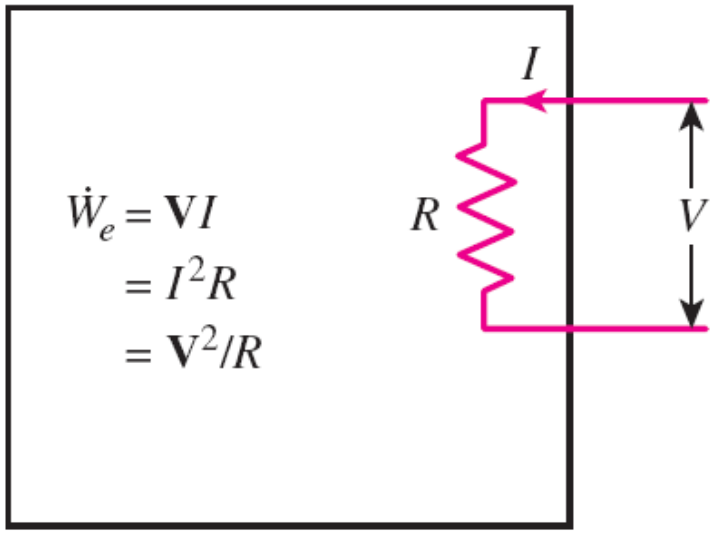



**FIGURE 2–26**
Electrical power in terms of resistance $R$, current $I$, and potential difference $\mathbf{V}$.

# MECHANICAL FORMS OF WORK

- There are two requirements for a work interaction between a system and its surroundings to exist:
  - ✓ there must be a ***force*** acting on the boundary.
  - ✓ the boundary must ***move***.

Work = Force × Distance

$$W = Fs \qquad (\text{kJ})$$

When force is not constant

$$W = \int_1^2 F\, ds \qquad (\text{kJ})$$

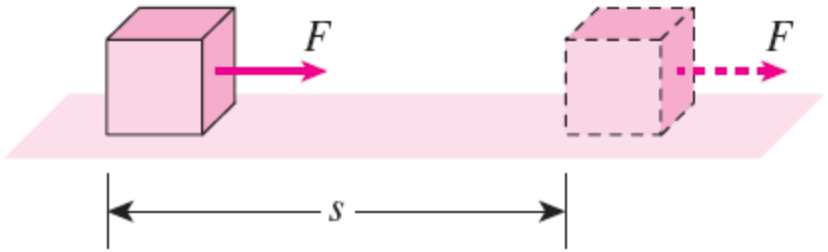



**FIGURE 2–27**
The work done is proportional to the force applied ($F$) and the distance traveled ($s$).




**FIGURE 2–28**
If there is no movement, no work is done.

# Shaft Work

A force *F* acting through a moment arm *r* generates a torque T

$$\mathrm{T} = Fr \quad \rightarrow \quad F = \frac{\mathrm{T}}{r}$$

This force acts through a distance *s*

$$s = (2\pi r)n$$

**Shaft work**

$$W_{\text{sh}} = Fs = \left(\frac{\mathrm{T}}{r}\right)(2\pi rn) = 2\pi n\mathrm{T} \qquad (\text{kJ})$$

The power transmitted through the shaft is the shaft work done per unit

$$\dot{W}_{\text{sh}} = 2\pi \dot{n}\mathrm{T} \qquad (\text{kW})$$

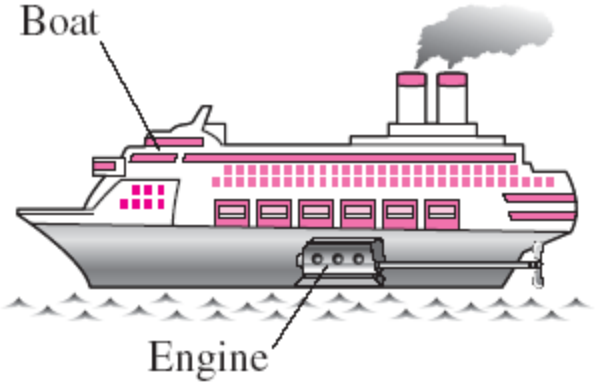



**FIGURE 2–29**
Energy transmission through rotating shafts is commonly encountered in practice.

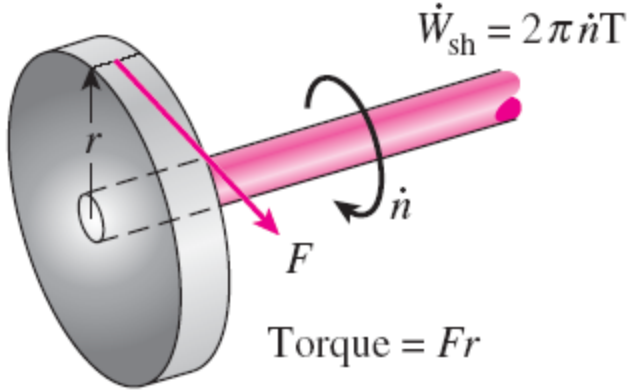



**FIGURE 2–30**
Shaft work is proportional to the torque applied and the number of revolutions of the shaft.

# Spring Work

When the length of the spring changes by a differential amount *dx* under the influence of a force *F*, the work done is

$$\delta W_{\text{spring}} = F\,dx$$

For linear elastic springs, the displacement *x* is proportional to the force applied

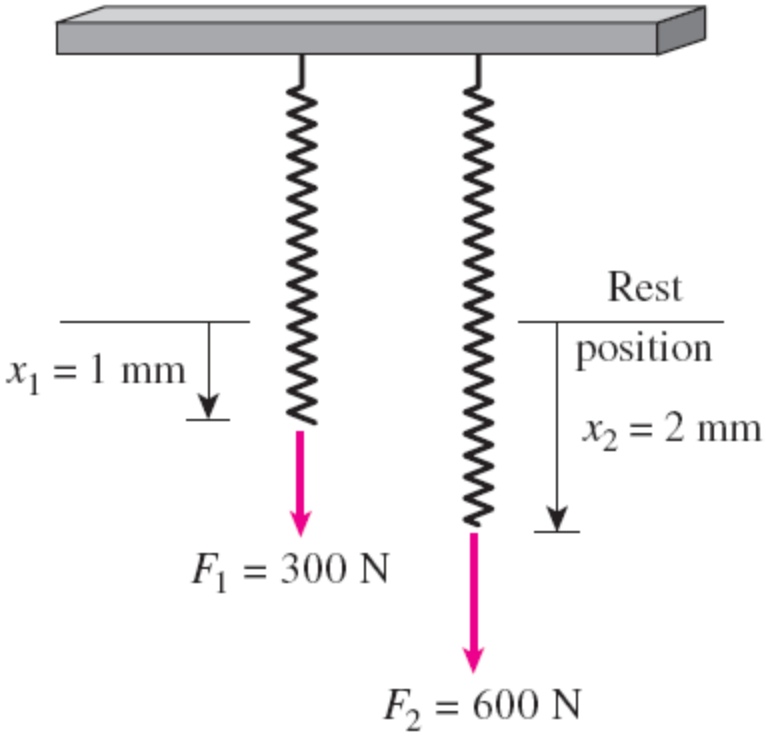
$$F = kx \qquad (\text{kN})$$

*k:* spring constant (kN/m)

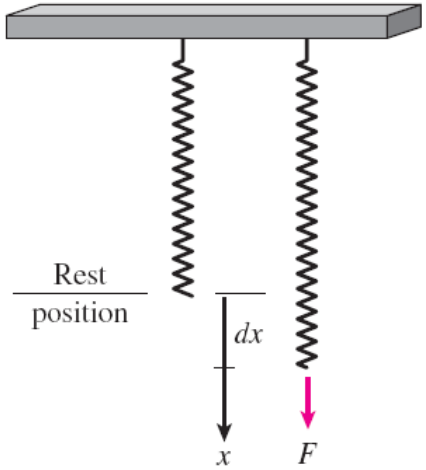
Substituting and integrating yield

$$W_{\text{spring}} = \tfrac{1}{2}k(x_2^2 - x_1^2) \qquad (\text{kJ})$$

$x_1$ and $x_2$: the initial and the final displacements




Elongation of a spring under the influence of a force.




The displacement of linear spring doubles when the force is doubled.

# Work Done on Elastic Solid Bars

$$W_{\text{elastic}} = \int_1^2 F\,dx = \int_1^2 \sigma_n A\,dx \qquad (\text{kJ})$$

# Work Associated with the Stretching of a Liquid Film

$$W_{\text{surface}} = \int_1^2 \sigma_s\,dA \qquad (\text{kJ})$$

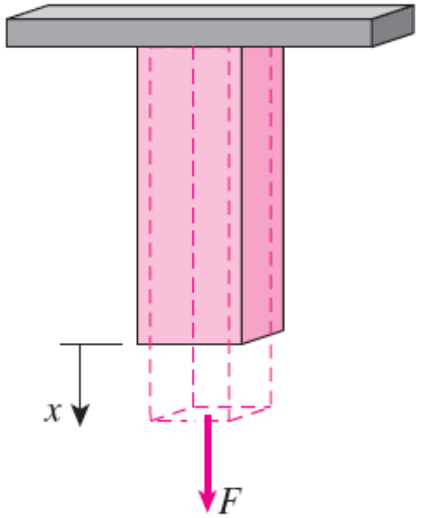



**FIGURE 2–34**
Solid bars behave as springs under the influence of a force.

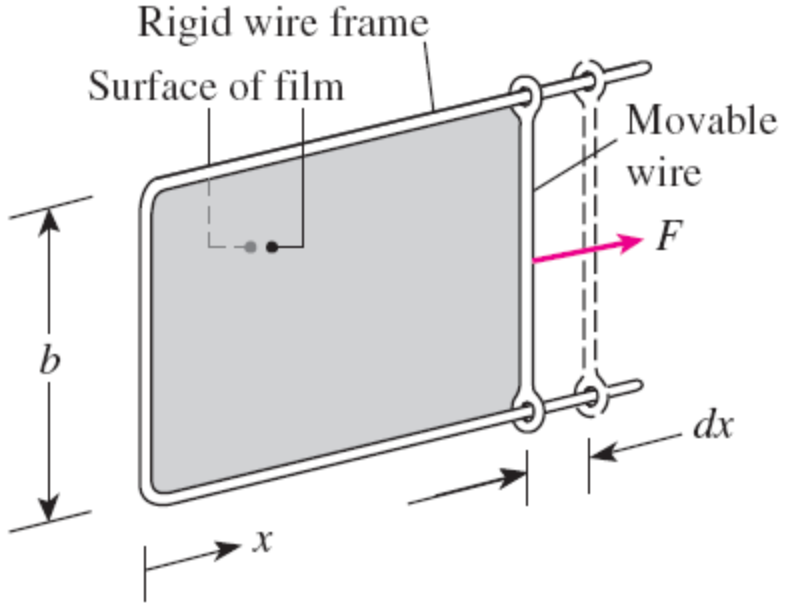



**FIGURE 2–35**
Stretching a liquid film with a movable wire.

- **Internal Energy:**

  Energy stored by system due to its state.

  It is denoted by U

- **Flow Energy:**

  Energy by virtue of displacement

  Flow work or displacement work = P.V

- **Heat Energy**

  It is denoted by Q

  Heat supplied to system is +ve (+Q)

  Heat rejected from system is -ve (-Q)

- **External Work Done:**

  It is denoted by W

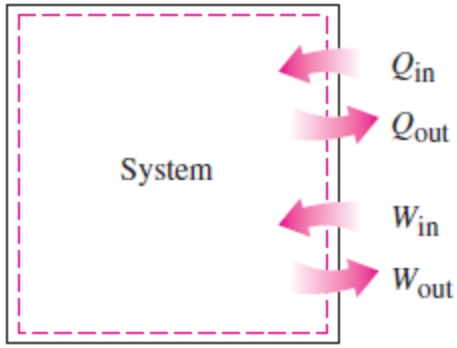
  Work is done by system is +ve (+W)

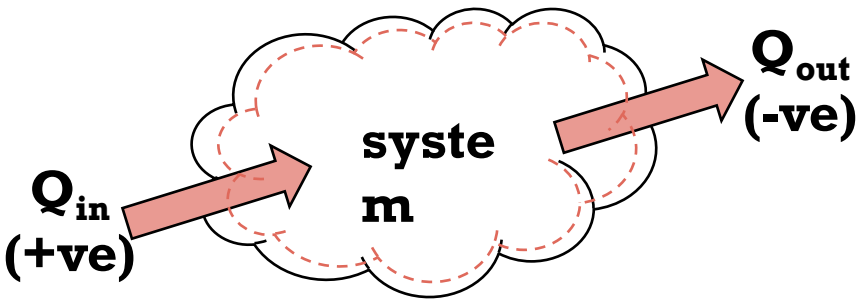
  work is done on system is -ve (-W)

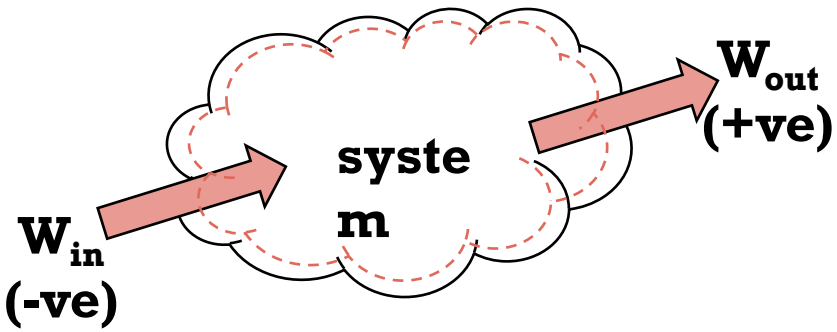
# FORMAL SIGN CONVENTION

- Heat and work are directional quantities, and thus the complete description of a heat or work interaction requires the specification of both the magnitude and direction.

| Sign | Heat | Work |
|---|---|---|
| Positive (+) | Heat transfer to the system | Work done by the system |
| Negative (-) | Heat transfer from the system | Work done on the system |

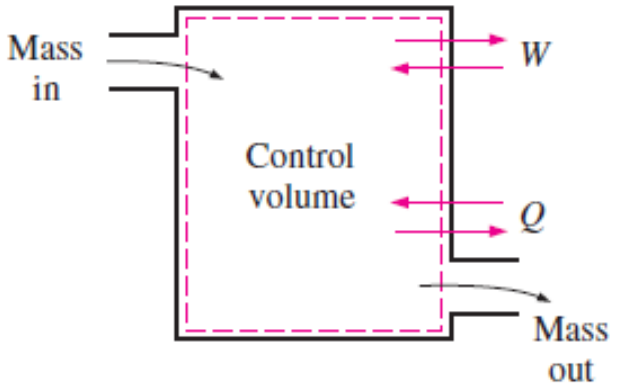


# ENERGY BALANCE FOR THE OPEN SYSTEM

- **Energy forms of the fluid entering the system**
  - Internal energy $= U_1$
  - Displacement energy $= P_1 V_1$
  - Kinetic energy $= KE_1$
  - Potential energy $= PE_1$
- **Energy forms of the fluid leaving the system**
  - Internal energy $= U_2$
  - Displacement energy $= P_2 V_2$
  - Kinetic energy $= KE_2$
  - Potential energy $= PE_2$
- W is work done by system or on system
- Q is heat supplied or rejected from system.
- $E_1$ = Initial Energy of the system.
- $E_2$ = Final Energy of the system.



- As per Law of conservation of energy
- Energy at input = Energy at Output

Initial energy of the system + Energy entering the system = Final energy of the system + Energy leaving the system.

$$E_1 + U_1 + P_1V_1 + KE_1 + PE_1 + Q = E_2 + U_2 + P_2V_2 + KE_2 + PE_2 + W$$

$$but \quad \text{Enthalpy} = H = U + PV$$

$$E_1 + H_1 + KE_1 + PE_1 + Q = E_2 + H_2 + KE_2 + PE_2 + W$$

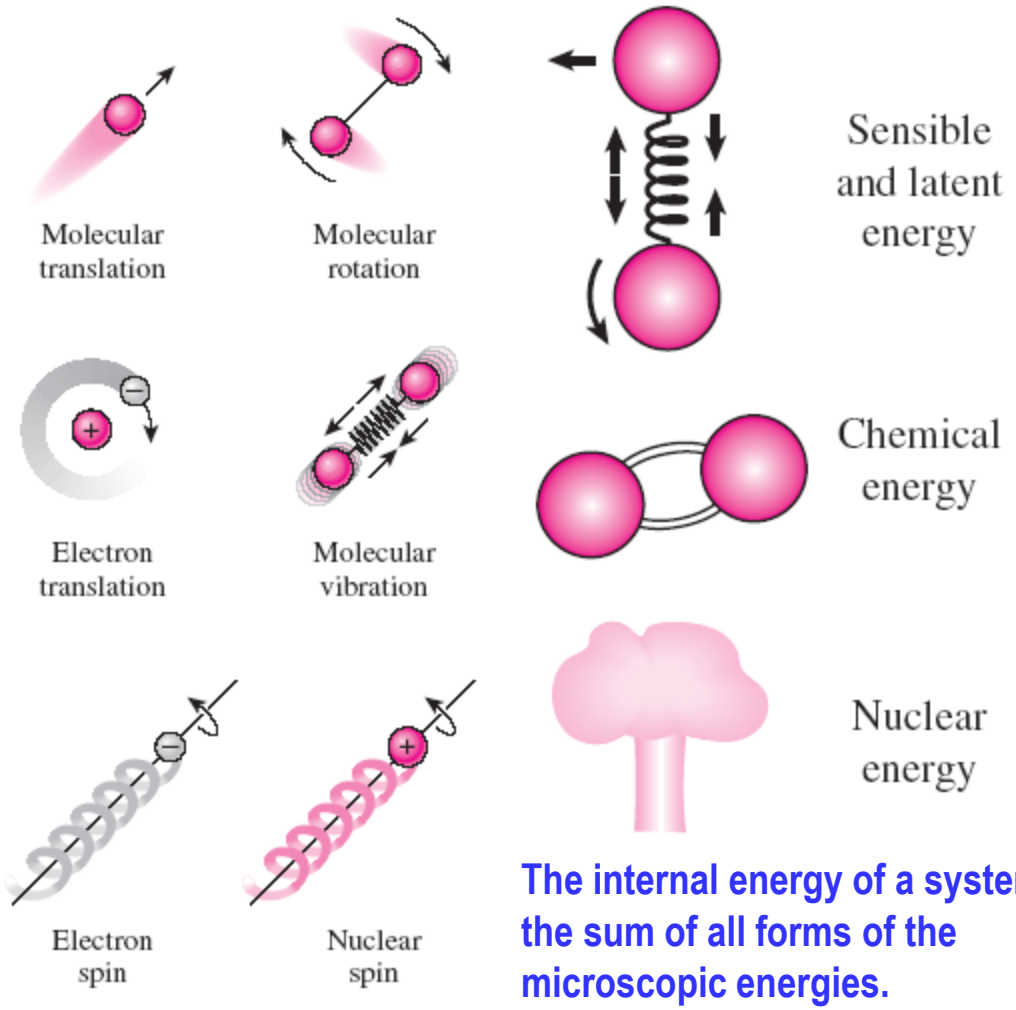
$$Q - W = (E_2 - E_1) + (H_2 - H_1) + (KE_2 - KE_1) + (PE_2 - PE_1)$$

- If mass flow rate of fluid or substance throughout the system remains constant. And total energy of the system remains constant. ---- $E_1 = E_2$
- Then above equations become

$$Q - W = (H_2 - H_1) + (KE_2 - KE_1) + (PE_2 - PE_1)$$

- This is SFEE – Steady Flow Energy Equation.

# Some Physical Insight to Internal Energy




The various forms of microscopic energies that make up *sensible* energy.

The internal energy of a system is the sum of all forms of the microscopic energies.

Sensible energy: The portion of the internal energy of a system associated with the kinetic energies of the molecules.

Latent energy: The internal energy associated with the phase of a system.

Chemical energy: The internal energy associated with the atomic bonds in a molecule.

Nuclear energy: The tremendous amount of energy associated with the strong bonds within the nucleus of the atom itself.

**Thermal = Sensible + Latent**

**Internal = Sensible + Latent + Chemical + Nuclear**

# ENERGY TRANSFER BY HEAT

Heat: The form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference.

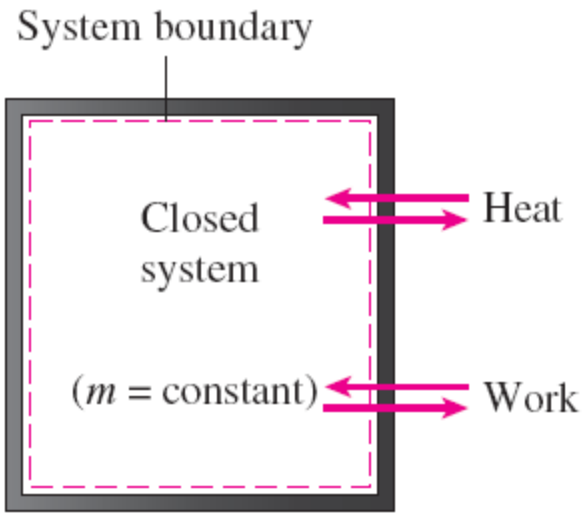



**FIGURE 2–13**
Energy can cross the boundaries of a closed system in the form of heat and work.

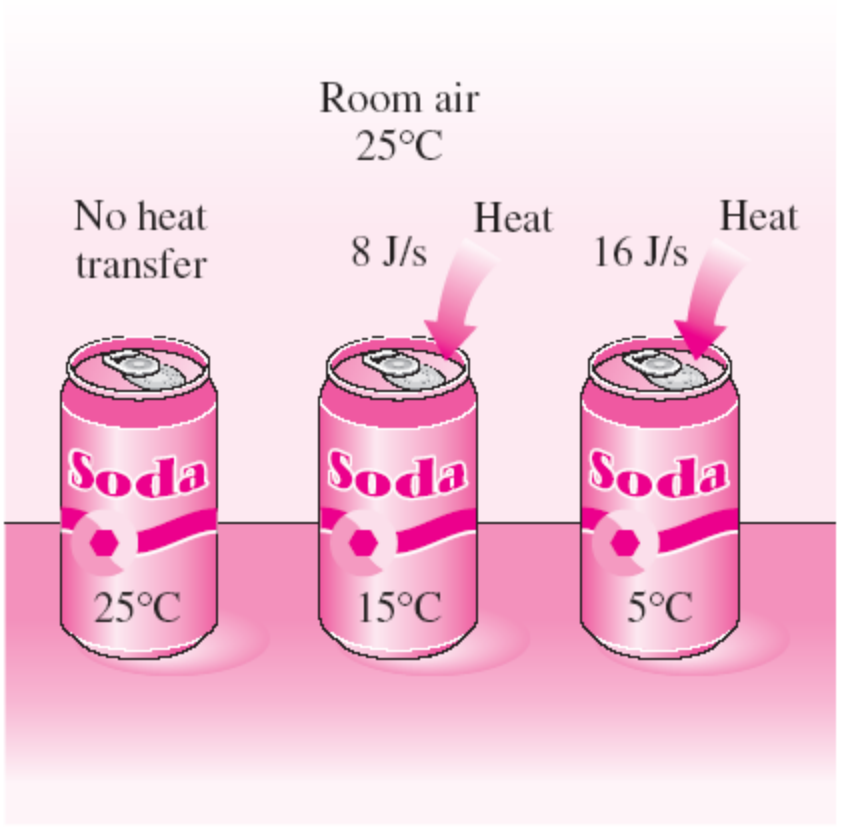



**FIGURE 2–14**
Temperature difference is the driving force for heat transfer. The larger the temperature difference, the higher is the rate of heat transfer.

# Heat vs. Work

- Both are recognized at the boundaries of a system as they cross the boundaries. That is, both heat and work are *boundary* phenomena.
- Systems possess energy, but not heat or work.
- Both are associated with a *process,* not a state.
- Unlike properties, heat or work has no meaning at a state.
- Both are *path functions* (i.e., their magnitudes depend on the path followed during a process as well as the end states).

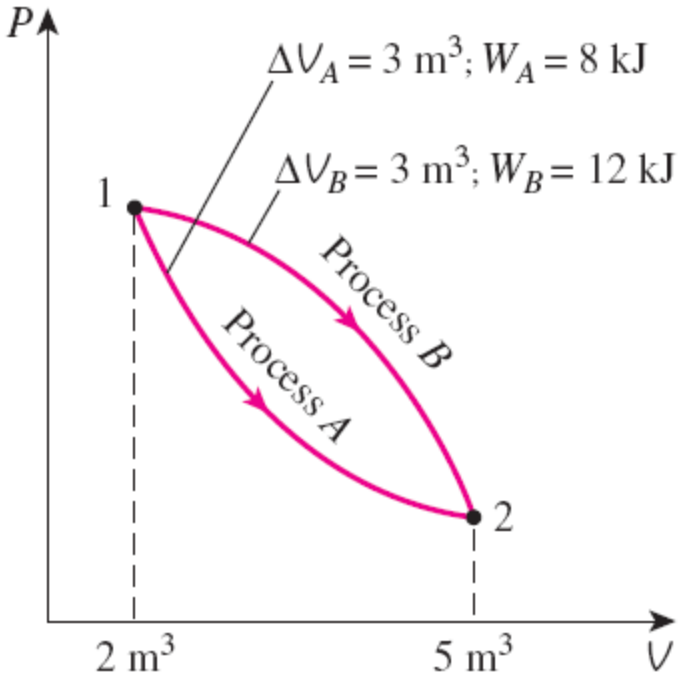



**FIGURE 2–21**
Properties are point functions; but heat and work are path functions (their magnitudes depend on the path followed).

**Properties are point functions have exact differentials (*d* ).**

$$\int_1^2 dV = V_2 - V_1 = \Delta V$$

Path functions have inexact differentials ($\delta$)

$$\int_1^2 \delta W = W_{12} \qquad (not\ \Delta W)$$

# Applied Thermodynamics: An Engineering Approach

Seventh Edition in SI Units

Yunus A. Cengel, Michael A. Boles

McGraw-Hill, 2011

MODULE

2.3

# IDEAL GASES EQUATION OF STATE

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# Ideal Equation of State (Gas equation)

The ideal gas equation in thermodynamics is **(PV = mRT)**, which links pressure, volume, temperature, and the amount of a gas.

Core Equation and Variables:

P: Absolute pressure of the gas $(kPa\ or\ Pa)$

$V$: Total volume occupied by the gas $(m^3)$

m: the amount of gas in (kg) or n is the amount of matter in (mole )

$R$: Ideal gas constant (kJ/kg.K) or R is universal gas constant = 8.314 J/K.mole

T: Absolute temperature measured in Kelvin.

M: is the molarity in mole/ $m^3$

| | | |
|---|---|---|
| $\mathbf{PV = mRT}$ | $\mathbf{P = \frac{m}{V}RT}$ , $\boldsymbol{\rho = \frac{m}{V}}$ | $\mathbf{P = \rho RT}$ |
| $\mathbf{PV = nRT}$ | $\mathbf{P = \frac{n}{V}RT}$ , | $\mathbf{P = MRT}$ |

**Validity and Assumptions:**

- ✓ Low Pressure / High Temperature: Works best when gases are far from condensation.
- ✓ Negligible Volume: Assumes gas molecules take up zero volume and have no intermolecular forces.

# Ideal gas processes and Cycles

An ideal gas is one which obeys all the gas laws and the characteristics gas equations, at all pressures and temperatures. Examples: Air, oxygen, hydrogen, nitrogen, helium etc.

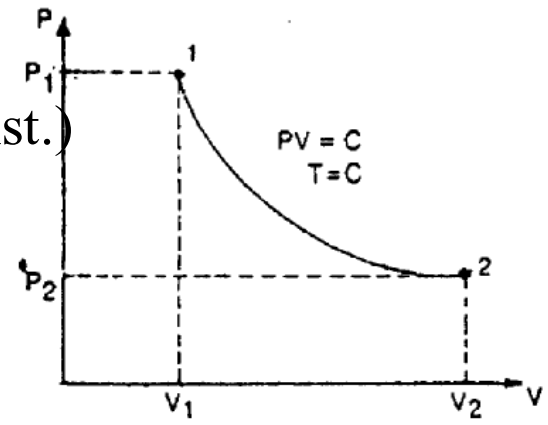
## GAS LAWS DESCRITION

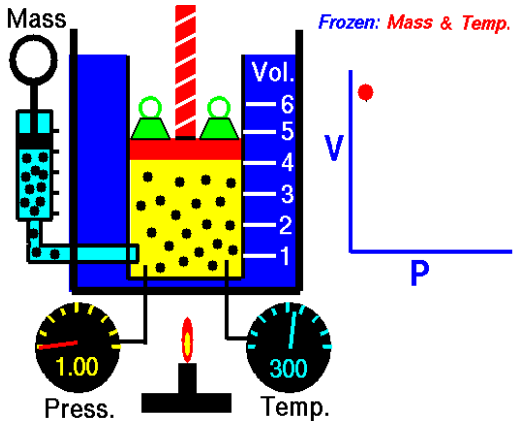
### 1. Boyle's Law

*At* contant temperature $(T = \text{const.})$

$$P \propto \frac{1}{V} \quad \text{or} \quad PV = const.$$

or $$P_1V_1 = P_2V_2 = C$$




**This equations represent rectangular hyperbola on PV plane.**

Hyperbolic process: an isothermal (constant temperature) process, where the relationship between pressure (P) and volume (V) forms a hyperbola on a property diagram. According to Boyle's law and the ideal gas equation (PV = constant) at a fixed temperature, pressure decreases as volume increases in inverse proportion.

## 2. Charles's Law:

$At$ contant pressure $(\mathrm{P} = \text{const.})$ $\quad \mathrm{V} \propto T$ or

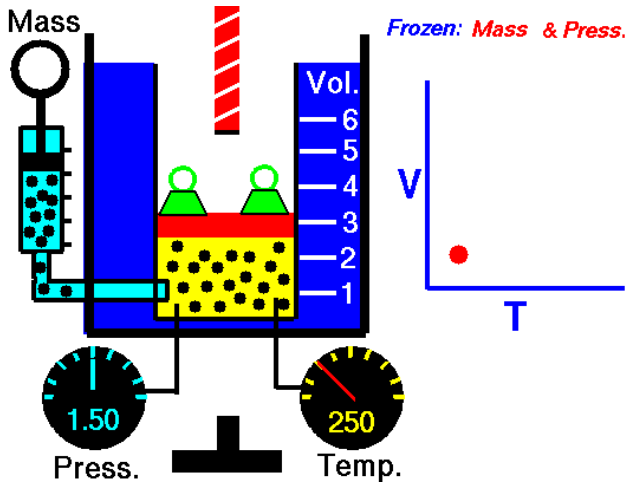
$$\frac{V}{T} = const. \quad \text{or} \quad \frac{V_1}{\mathrm{T}_1} = \frac{V_2}{\mathrm{T}_2} = C$$

from Boyle's Law $V \propto \frac{1}{P}$

from Charles's Law $V \propto T$

$combining$ two laws

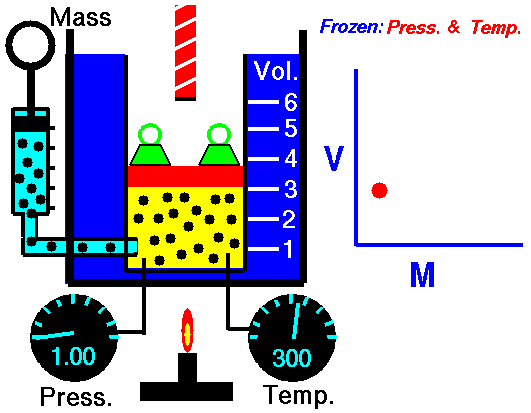
$$V \propto \frac{T}{P} \quad \text{or} \quad \frac{PV}{\mathrm{T}} = \text{const}$$




## 3. Avogadro's Law

$At$ contant pressure and Temperature $(\mathrm{P} \,\&\, \mathrm{T} = \text{const.})$

$$\mathrm{V} \propto n \quad \text{or} \quad \frac{V}{n} = const.$$




The volume and amount (moles) of the gas are directly proportional if the temperature and pressure are constant.

# Ideal Gas Law

$$\frac{P_1.V_1}{T_1.n_1} = \frac{P_2.V_2}{T_2.n_2} = C$$

$$\frac{PV}{Tn} = R = \text{constant}$$

**Ideal gas Equation** $PV = nRT$

P = pressure in Pascal or $N/m^2$
V = Volume in $m^3$
T = Temperature in Kelvin, K
n = no of moles.

$$\frac{PV}{Tn} = R = \frac{1.01325 \times 10^5 \times 22.41 \times 10^{-3}}{273.15 \times 1 mole}$$

$$R = 8.314\, J/Mole \cdot K$$

- **Characteristics gas equation**
- $P = \frac{1}{v} RT = \rho RT$

$$PV = mRT$$

$$\frac{N}{m^2} \cdot m^3 = kg. \frac{J}{kg \cdot K} K$$

$$P \cdot \frac{V}{m} = RT \quad \text{or} \quad Pv = RT$$

$$\text{where } \frac{V}{m} = v = \text{specific volume} = \frac{1}{\rho}$$

**Internal energy change** $\Delta U = mC_v \Delta T$ or $U_2 - U_1 = mC_v (T_2 - T_1)$

**Enthalpy change** $\Delta H = mC_P \Delta T$ or $H_2 - H_1 = mC_P (T_2 - T_1)$

**Specific heat ratio** $C_P / C_V = \gamma$ $\boldsymbol{\frac{C_p}{C_v} = k}$

**Gas constant** $R = C_P - C_v$

$C_P = 1.005 \text{ kJ/kg K}$ $C_v = 0.718 \text{ kJ/kg K}$

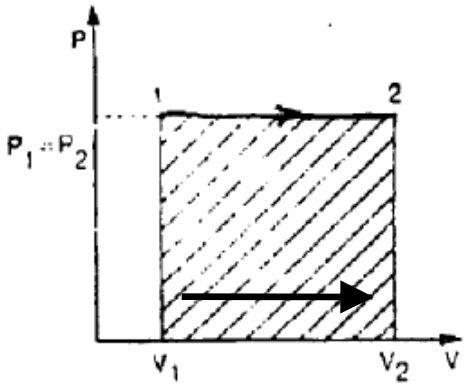
$R = 0.287 \text{ kJ/kg K}$ $\gamma = 1.4$

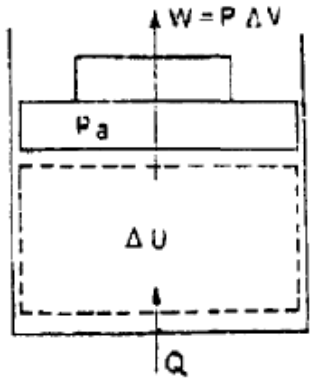
# Constant pressure process

- Apply ideal gas law from 1 to 2:

$$P_1V_1 = mRT_1 \quad \& \quad P_2V_2 = mRT_2$$

$$\frac{V_2}{V_1} = \frac{T_2}{T_1} \quad \text{as } P_1 = P_2 = P$$




$$W_{1-2} = \int_{V1}^{V2} pdV = p\int_{V1}^{V2} dV = P\cdot(V_2 - V_1) = P_2V_2 - P_1V_1 = mR(T_2 - T_1)$$

$$w_{1-2} = R(T_2 - T_1) = \text{Area under curve, for unit mass}$$

- Change in Internal Energy $\Delta U = U_2\text{-}U_1 = mC_v(T_2 - T_1)$
- Apply 1st law of thermodynamics:

$$Q_{1-2} - W_{1-2} = \Delta U$$

$$Q_{1\text{-}2} = P\cdot(V_2 - V_1) + (U_2 - U_1)$$
$$Q_{1\text{-}2} = (P_2V_2 + U_2) - (P_1V_1 + U_1)$$
$$Q_{1\text{-}2} = H_2 - H_1 = m\cdot C_P(T_2 - T_1)$$

# Constant volume process

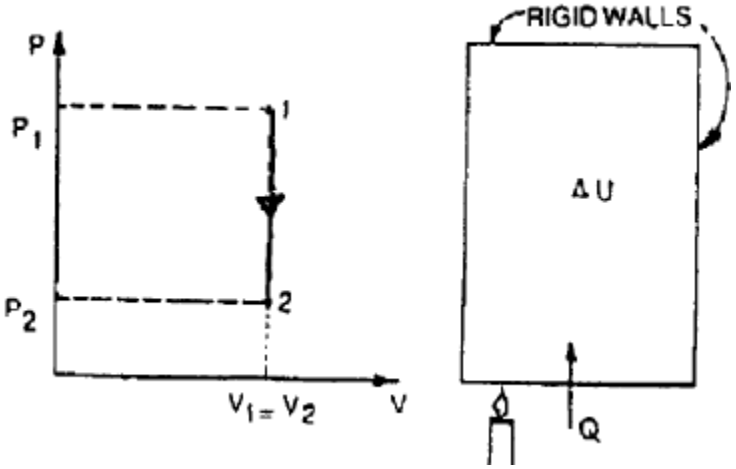
- Apply ideal gas law from 1 to 2:

$$P_1V_1 = mRT_1 \quad \& \quad P_2V_2 = mRT_2$$

$$\frac{P_2}{P_1} = \frac{T_2}{T_1} \quad \text{as } V_1 = V_2 = V = C$$

$$dV = 0$$

$$W_{1-2} = \int_1^2 PdV = 0 \qquad \text{There is no Area under curve 1 - 2}$$




$$\Delta U = U_2\text{-}U_1 = mC_v\left(T_2 - T_1\right)$$

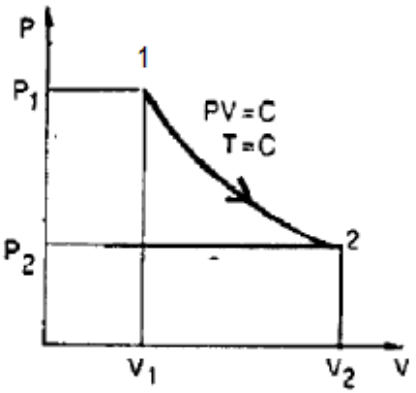
- Change in Internal Energy

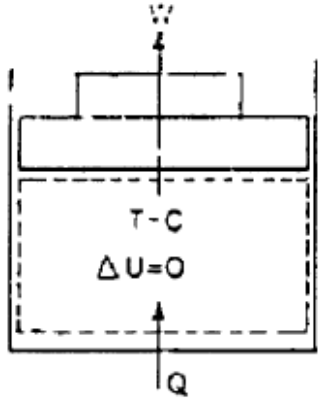
$$Q_{1-2} - W_{1-2} = \Delta U$$

Apply 1st law of thermodynamics:

$$Q_{1\text{-}2} = 0 = \Delta U = mC_v\left(T_2 - T_1\right)$$

# Constant Temperature process




- Apply ideal gas law from 1 to 2:

$$P_1V_1 = mRT_1 \quad \& \quad P_2V_2 = mRT_2$$

$$\frac{P_2}{P_1} = \frac{V_1}{V_2} \quad \text{or} \quad P_2V_2 = P_1V_1$$

$$PV = C \quad \text{or} \quad P = \frac{C}{V} \quad \text{as} \quad T_1 = T_2 = T$$

$$W_{1-2} = \int_{V1}^{V2} P\,dV = \int_{V1}^{V2} \frac{C}{V}\,dV = C \cdot \left[\ln V\right]_1^2 = C\left[\ln V_2 - \ln V_1\right]$$

$$W_{1-2} = C\left(\ln \frac{V_2}{V_1}\right) = P_1V_1\left(\ln \frac{V_2}{V_1}\right) = P_2V_2\left(\ln \frac{V_2}{V_1}\right)$$

$$W_{1-2} = mT\left(\ln \frac{V_2}{V_1}\right) = \text{Area under curve,}$$

$$Q_{1-2} - W_{1-2} = \Delta U$$

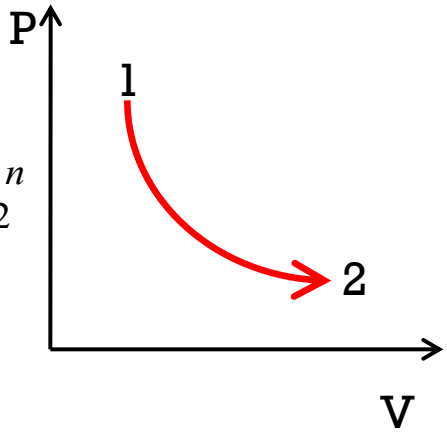
- Change in Internal Energy

$$\Delta U = U_2\text{-}U_1 = mC_v\left(T_2 - T_1\right) = 0$$

Apply 1st law of thermodynamics:

$$Q_{1\text{-}2} = W_{1-2} = P_1V_1\left(\ln \frac{V_2}{V_1}\right) = P_2V_2\left(\ln \frac{V_2}{V_1}\right)$$

- **Polytropic process**
- **What is polytropic process**
  - ✓ A general process without any restrictions.
  - ✓ The law of the process is $PV^n = C = P_1V_1^n = P_2V_2^n$




- Apply ideal gas law from 1 to 2: $P_1V_1 = mRT_1$ & $P_2V_2 = mRT_2$ or $\frac{P_2V_2}{P_1V_1} = \frac{T_2}{T_1}$

$$W_{1-2} = \int_{V1}^{V2} PdV = \int_{V1}^{V2} \frac{C}{V^n} dV = C\int_{V1}^{V2} \frac{1}{V^n} dV = C\int_{V1}^{V2} V^{-n} dV$$

$$W_{1-2} = C\left[\frac{V^{-n+1}}{-n+1}\right]_{V1}^{V2} = C\left[\frac{V_2^{1-n} - V_1^{1-n}}{1-n}\right] = P_1V_1^n\left[\frac{V_2^{1-n} - V_1^{1-n}}{1-n}\right]$$

$$W_{1-2} = \frac{P_2V_2^n \cdot V_2^{1-n} - P_1V_1^n \cdot V_1^{1-n}}{1-n} = \frac{P_2V_2 - P_1V_1}{1-n} = \frac{P_1V_1 - P_2V_2}{n-1}$$

$$W_{1-2} = \frac{mR(T_1 - T_2)}{n-1}$$

Apply 1st law of thermodynamics:

$$Q_{1-2} - W_{1-2} = \Delta U$$

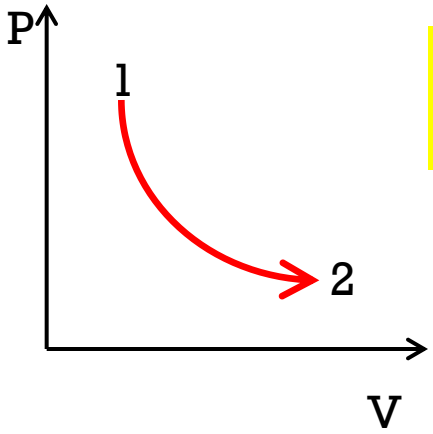
$$Q_{1-2} - \frac{mR(T_1 - T_2)}{n-1} = mR(T_2 - T_1)$$

$$Q_{1-2} = mR(T_2 - T_1) + \frac{mR(T_1 - T_2)}{n-1}$$

$$Q_{1-2} = mR(T_2 - T_1) - \frac{mR(T_2 - T_1)}{n-1}$$

$$Q_{1-2} = \left(\frac{\gamma - n}{\gamma - 1}\right) \cdot \frac{mR(T_1 - T_2)}{(n-1)}$$

$$Q_{1-2} = \left(\frac{\gamma - n}{\gamma - 1}\right) \cdot W_{1-2}$$




- **Isentropic process**
- **What is isentropic process**
  - ✓ A general process without any restrictions.
  - ✓ The law of the process is
  - ✓ Q = 0
- Apply ideal gas law from 1 to 2:

$$PV^{\gamma} = C = P_1V_1^{\gamma} = P_2V_2^{\gamma}$$

- Just replace n by γ (gamma) from all questions

$$P_1V_1 = mRT_1 \quad \& \quad P_2V_2 = mRT_2 \qquad \frac{P_2V_2}{P_1V_1} = \frac{T_2}{T_1}$$

# Example(1)

A gas whose pressure, volume and temperature are 275 kPa, 0.09 $m^3$ and 185˚C respectively. The gas state changed at constant pressure until its temperature becomes 15˚C. Determine the amount of heat transfer from the gas and the amount of work during the process. Where R=0.287 kJ/kg K, $C_v$=0.718 kJ/kg K and $C_p$=1.005 kJ/kg K.

# Example(2)

A quantity of air has a pressure of 300 kPa when its volume is 0.025$m^3$ and its temperature 37˚C. The air pressure increased to 900 kPa, while the volume remains constant. Determine the mass of the air, its final temperature and work done.

$C_p$=1.005 kJ/kg K
$C_v$=0.718 kJ/kg K
R= 0.287 kJ/kg K

# Example - 3

A quantity of gas occupies a volume of 0.4 $m^3$ at a pressure of 100 kPa and temperature of 20C. The gas is compressed isothermally to a pressure of 450 kPa. Detrmine:

(a) Mass of gas

(b) (b) Final volume

(c) (c) Heat transfer

(d) (d) Work done

$C_p$=1.005 kJ/kg K, $C_v$=0.718 kJ/kg K, R= 0.287 kJ/kg K

# Example - 4

A gas expands according to the law PV1.3=C from pressure of 1 kPa and volume 0.003 m3 to pressure of 0.1 kPa. Determine the amount if heat and work during this process. Cp=1.005 kJ/kg K , Cv=0.718 kJ/kg K, R= 0.287 kJ/kg K

# Example - 5

A gas whose original pressure and temperature were 300 kPa and 25˚C respectively is compressed through an isentropic process. The final temperature of the gas is 180˚C. Determine the new pressure of the gas and the work done.

$C_p$=1.005 kJ/kg K

$C_v$=0.718 kJ/kg K

R= 0.287 kJ/kg K

| Process | Equations | | | |
|---|---|---|---|---|
| | ΔU | (W) | (Q) | Equation of state |
| **Isothermal Process** T = constant | Zero | $P_1 V_1 \ln \frac{V_2}{V_1}$ | W | $P_1 V_1 = P_2 V_2$ |
| **Isochoric Process** V = constant | ΔU | Zero | ΔU | $\frac{P_1}{T_1} = \frac{P_2}{T_2}$ |
| **Isentropic / Adiabatic Process** $PV^{\gamma}$ = constant | -W | $\frac{(P_2 V_2 - P_1 V_1)}{\gamma - 1}$<br>$\frac{mR(T_1 - T_2)}{\gamma - 1}$ | Zero | $P_1 V_1^{\gamma} = P_2 V_2^{\gamma}$<br>$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma - 1}$<br>$= \left(\frac{P_1}{P_2}\right)^{\frac{\gamma - 1}{\gamma}}$ |
| **Isobaric Process** P = constant | ΔU | $P(V_2 - V_1)$<br>$mR\,(T_2 - T_1)$ | ΔH | $\frac{V_1}{T_1} = \frac{V_2}{T_2}$ |
| **Polytropic process** $PV^n$ = constant | ΔU | $\frac{(P_1 V_1 - P_2 V_2)}{n - 1}$<br>$\frac{mR\,(T_1 - T_2)}{n - 1}$ | $\left(\frac{\gamma - n}{\gamma - 1}\right) \frac{mR}{1 - n} (T_2 - T_1)$<br>$\left(\frac{\gamma - n}{\gamma - 1}\right) \frac{(P_1 V_1 - P_2 V_2)}{n - 1}$ | $P_1 V_1^{n} = P_2 V_2^{n}$<br>$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{n - 1}$<br>$= \left(\frac{P_1}{P_2}\right)^{\frac{n - 1}{n}}$ |

Applied Thermodynamics: An Engineering Approach
Seventh Edition in SI Units
Yunus A. Cengel, Michael A. Boles
McGraw-Hill, 2011

MODULE 2.4

# The 2nd Law of Thermodynamics

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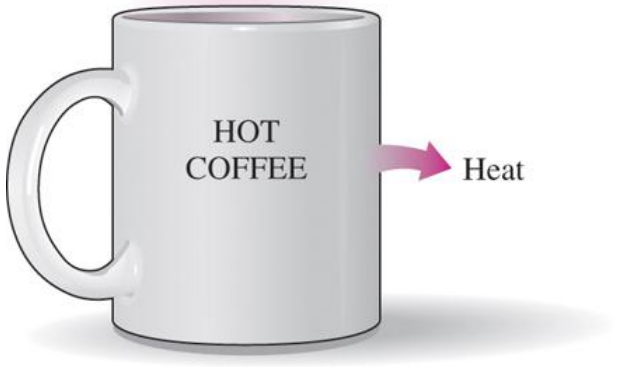
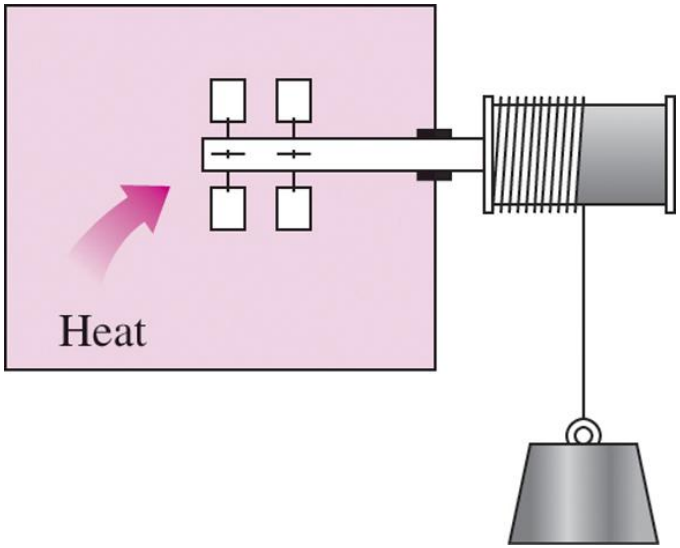
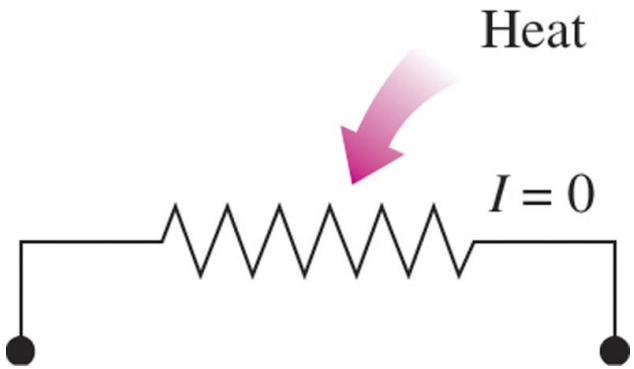
# INTRODUCTION TO THE SECOND LAW

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




Transferring heat to a paddle wheel will not cause it to rotate.

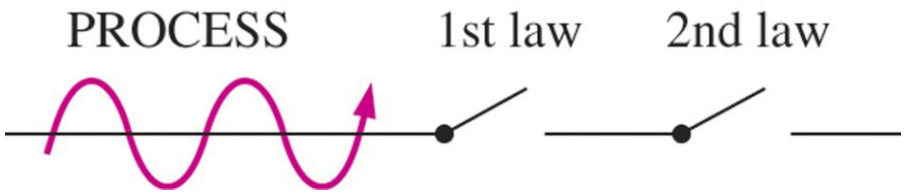



Transferring heat to a wire will not generate electricity.

These processes cannot occur even though they are not in violation of the first law.




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

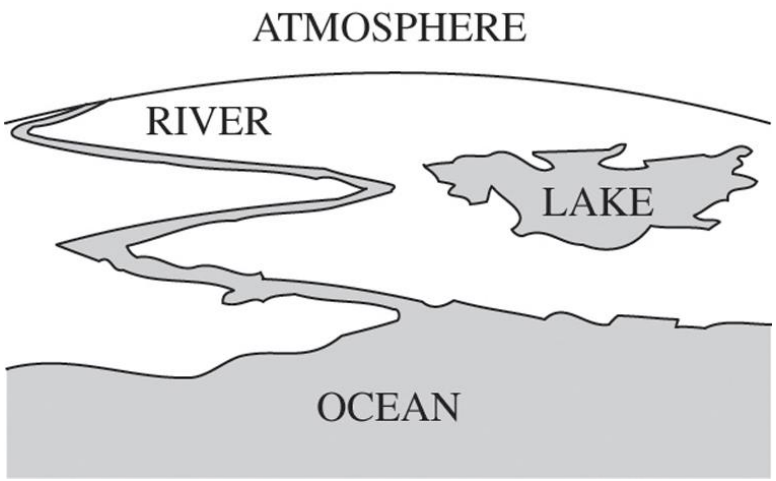



A process must satisfy both the first and second laws of thermodynamics to proceed.

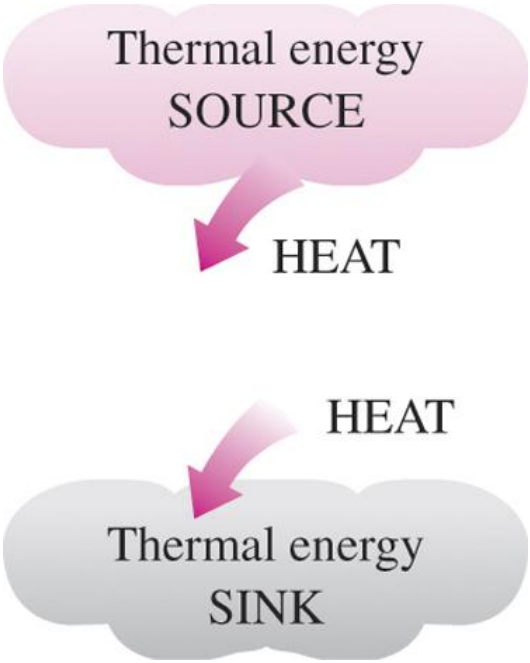
## MAJOR USES OF THE SECOND LAW

1. The second law may be used to identify the direction of processes.
2. 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. The second law provides the necessary means to determine the quality as well as the degree of degradation of energy during a process.
3. The second law of thermodynamics is also used in determining the *theoretical limits* for the performance of commonly used engineering systems, such as heat engines and refrigerators, as well as predicting the *degree of completion* of chemical reactions.

# THERMAL ENERGY RESERVOIRS



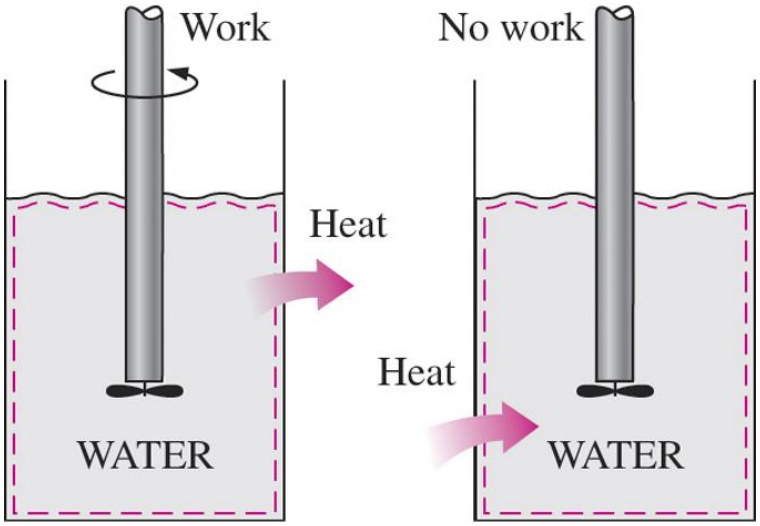

Bodies with relatively large thermal masses can be modeled as thermal energy reservoirs.

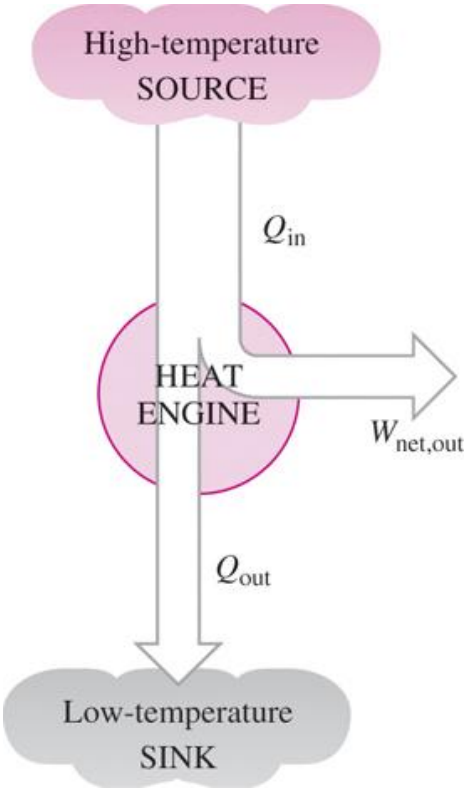



A source supplies energy in the form of heat, and a sink absorbs it.

- **A hypothetical body with a relatively large *thermal energy capacity* (mass x specific heat) that can supply or absorb finite amounts of heat without undergoing any change in temperature is called a thermal energy reservoir, or just a reservoir.**
- **In practice, large bodies of water such as oceans, lakes, and rivers as well as the atmospheric air can be modeled accurately as thermal energy reservoirs because of their large thermal energy storage capabilities or thermal masses.**

# HEAT ENGINES




Work can always be converted to heat directly and completely, but the reverse is not true.

Part of the heat received by a heat engine is converted to work, while the rest is rejected to a sink.

**The devices that convert heat to work.**

1. **They receive heat from a high-temperature source (solar energy, oil furnace, nuclear reactor, etc.).**
2. **They convert part of this heat to work (usually in the form of a rotating shaft.)**
3. **They reject the remaining waste heat to a low-temperature sink (the atmosphere, rivers, etc.).**
4. **They operate on a cycle.**

**Heat engines and other cyclic devices usually involve a fluid to and from which heat is transferred while undergoing a cycle. This fluid is called the working fluid.**

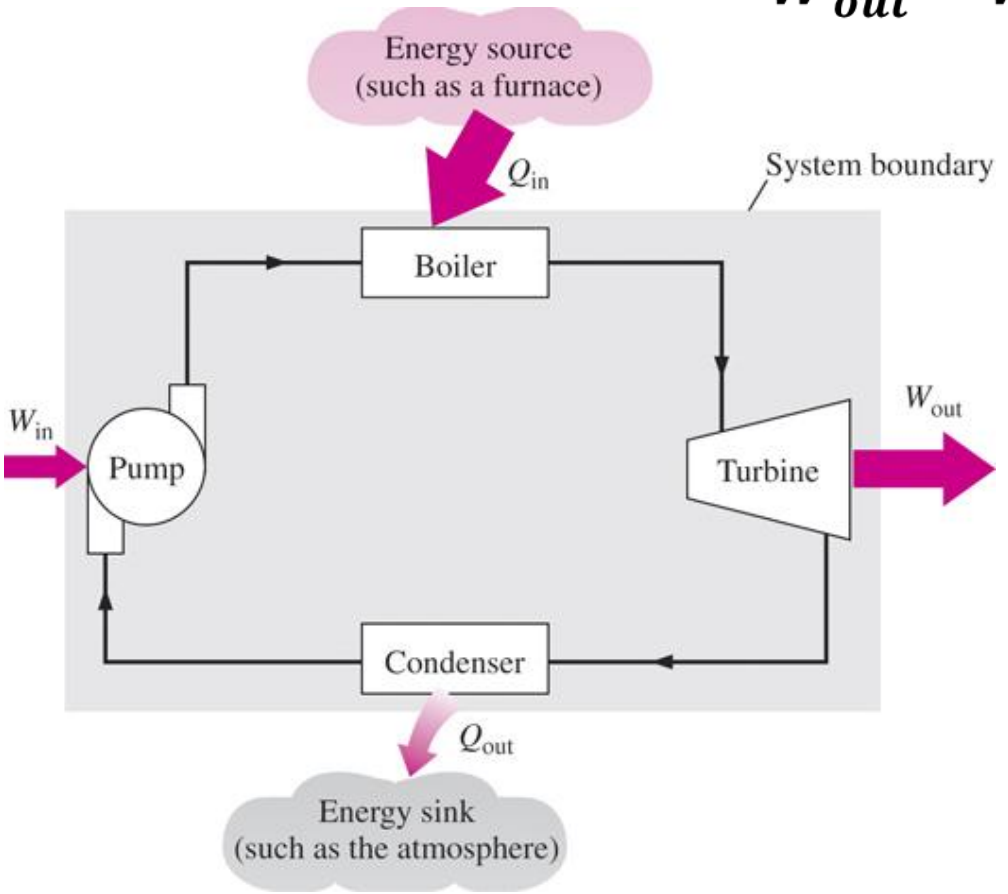
$$E_{in} = E_{out} \rightarrow Q_{in} = W_{net} + Q_{out}$$

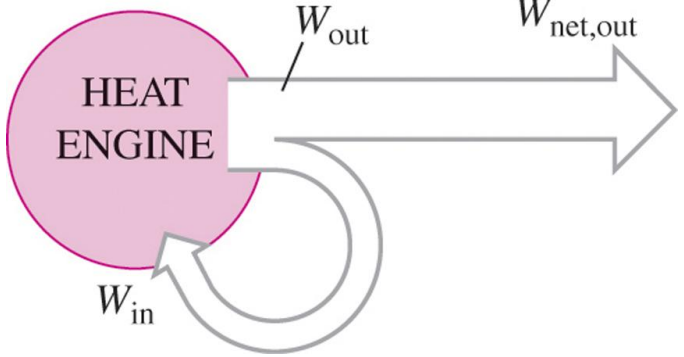
$$Q_{in} - Q_{out} = W_{net}$$

# A steam power plant

$$E_{in} = E_{out} \rightarrow Q_{in} + W_{in} = W_{out} + Q_{out}$$

$$W_{out} - W_{in} = Q_{in} - Q_{out} = W_{net}$$




**A portion of the work output of a heat engine is consumed internally to maintain continuous operation.**

$$W_{net,out} = W_{out} - W_{in} \quad \text{(kJ)}$$

$$W_{net,out} = Q_{in} - Q_{out} \quad \text{(kJ)}$$

$Q_{in}$ = amount of heat supplied to steam in boiler from a high-temperature source (furnace)

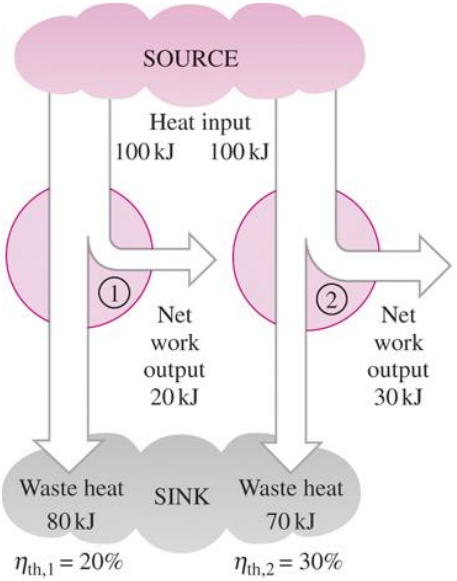
$Q_{out}$ = amount of heat rejected from steam in condenser to a low-temperature sink (the atmosphere, a river, etc.)

$W_{out}$ = amount of work delivered by steam as it expands in turbine

$W_{in}$ = amount of work required to compress water to boiler pressure

# Thermal efficiency

$E_{in} = E_{out}$




**System1:**

$Q_{in1} = W_{net1} + Q_{out}1$

$W_{net1} = Q_{in1}$

$-\ Q_{out1}$=100-80= 20 kJ

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{20}{100}$$

$$= 0.2 \rightarrow 20\%$$

**System2:**

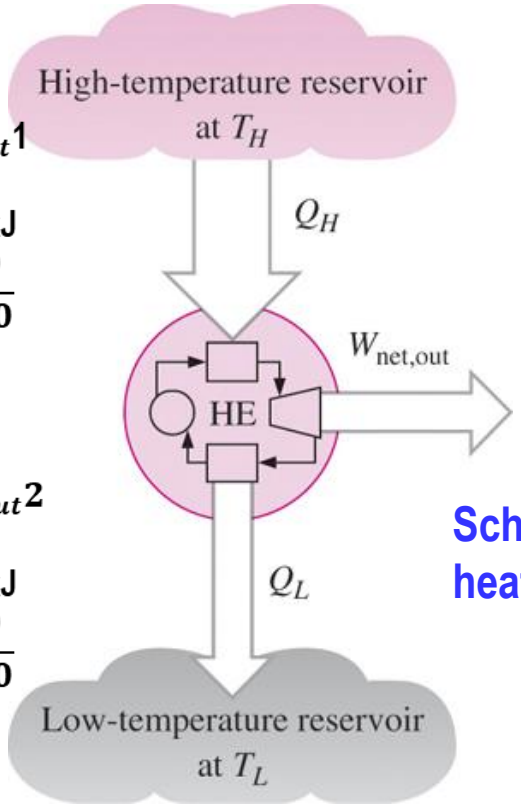
$Q_{in2} = W_{net2} + Q_{out}2$

$W_{net1} = Q_{in1}$

$-\ Q_{out1}$=100-70= 30 kJ

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{30}{100}$$

$$= 0.3 \rightarrow 30\%$$




$$W_{net,out} = Q_H - Q_L$$

$$\eta_{th} = \frac{W_{net,out}}{Q_H}$$

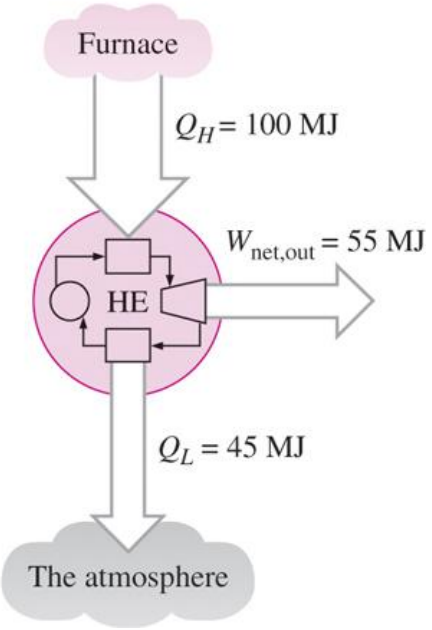
$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

**Schematic of a heat engine.**

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = \frac{Q_{in}}{Q_{in}} - \frac{Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

**Some heat engines perform better than others (convert more of the heat they receive to work).**

**Even the most efficient heat engines reject almost one-half of the energy they receive as waste heat.**

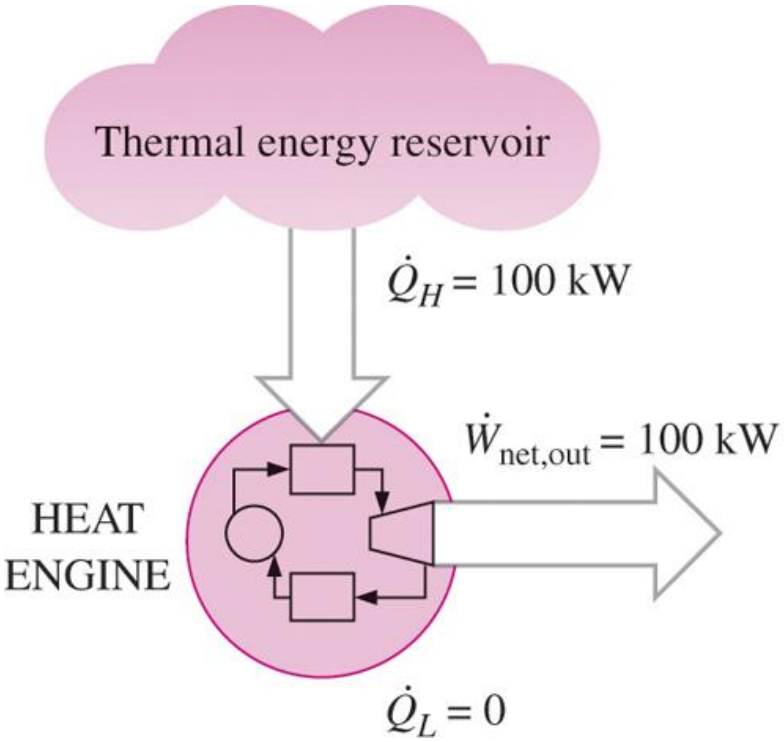



$$\text{Thermal efficiency} = \frac{\text{Net work output}}{\text{Total heat input}}$$

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}} \qquad \eta_{th} = 1 - \frac{Q_{out}}{Q_{in}} \qquad W_{net,out} = Q_{in} - Q_{out}$$

# The Second 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.**

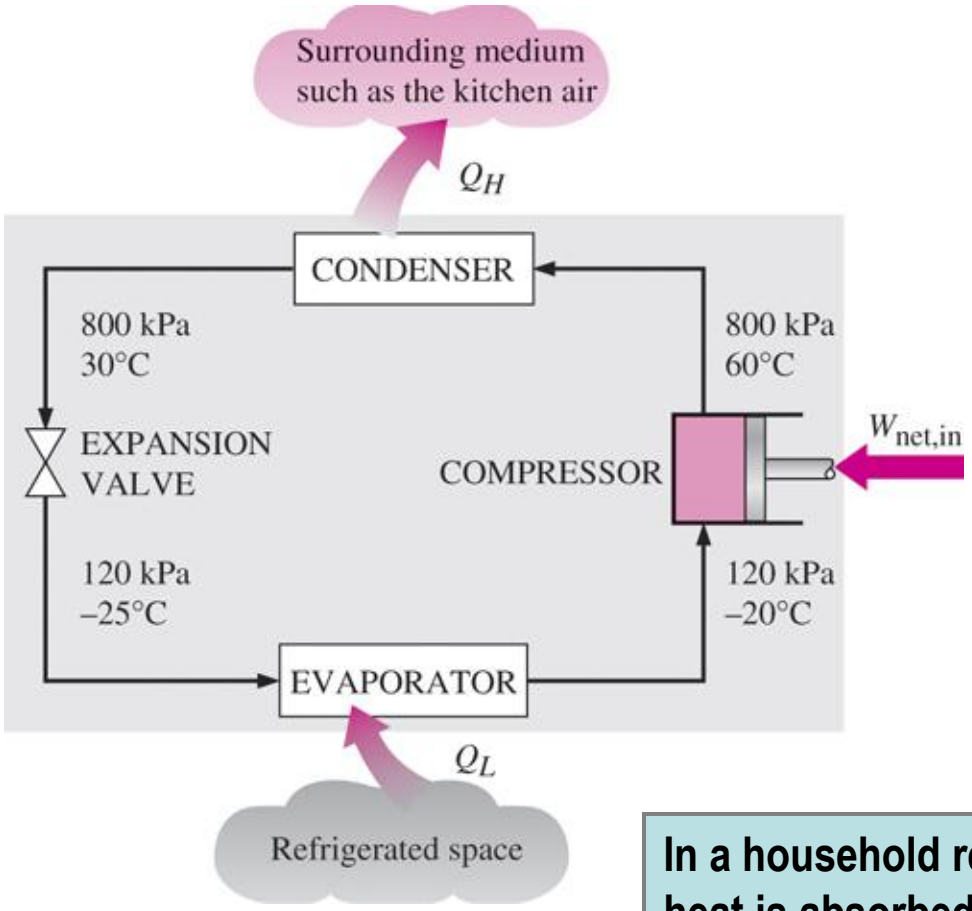



A heat engine that violates the Kelvin–Planck statement of the second law.

*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.*

The impossibility of having a 100% efficient heat engine is not due to friction or other dissipative effects. It is a limitation that applies to both the idealized and the actual heat engines.

# REFRIGERATORS AND HEAT PUMPS

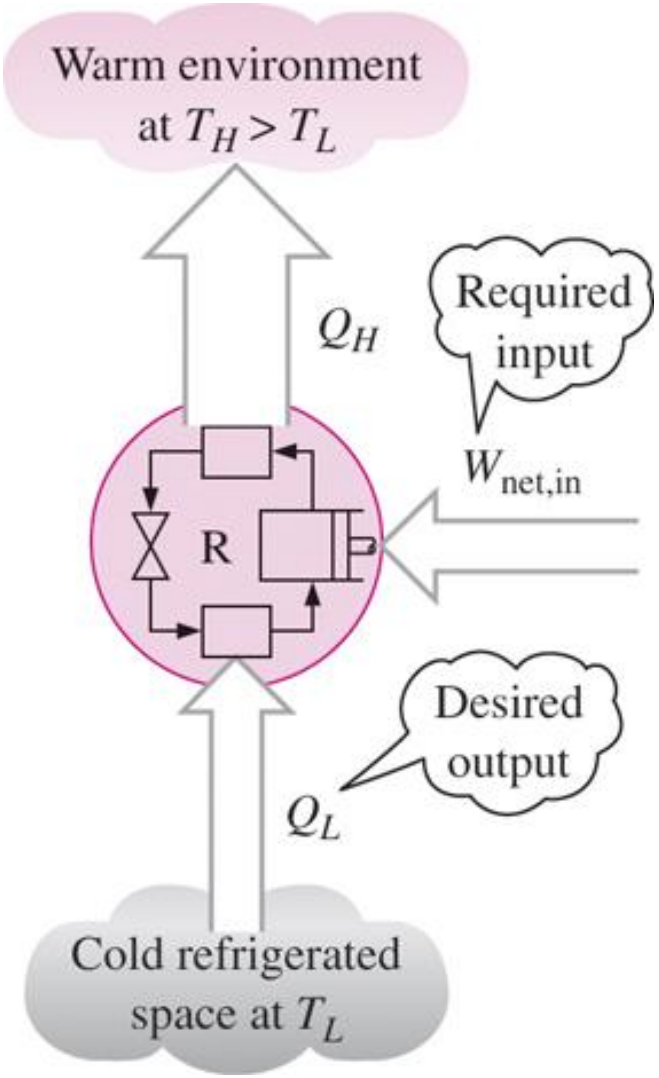



Basic components of a refrigeration system and typical operating conditions.

- The transfer of heat from a low-temperature medium to a high-temperature one requires special devices called refrigerators.
- Refrigerators, like heat engines, are cyclic devices.
- The working fluid used in the refrigeration cycle is called a refrigerant.
- The most frequently used refrigeration cycle is the *vapor-compression refrigeration cycle*.

**In a household refrigerator, the freezer compartment where heat is absorbed by the refrigerant serves as the evaporator, and the coils usually behind the refrigerator where heat is dissipated to the kitchen air serve as the condenser.**

# Coefficient of Performance




The objective of a refrigerator is to remove $Q_L$ from the cooled space.

**The *efficiency* of a refrigerator is expressed in terms of the coefficient of performance (COP).**

**The objective of a refrigerator is to remove heat ($Q_L$) from the refrigerated space.**

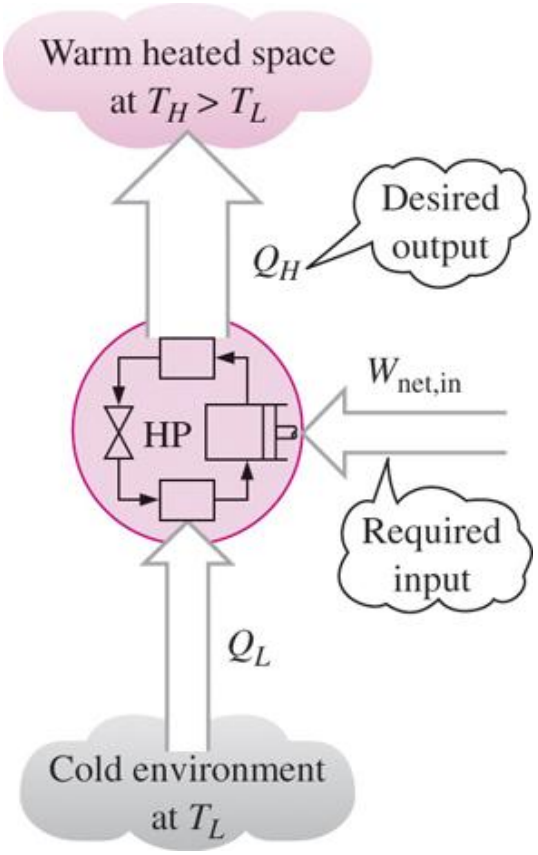
$$\text{COP}_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_L}{W_{net,in}}$$

$$W_{net,in} = Q_H - Q_L \qquad \text{(kJ)}$$

$$\text{COP}_R = \frac{Q_L}{Q_H - Q_L} = \frac{1}{Q_H/Q_L - 1}$$

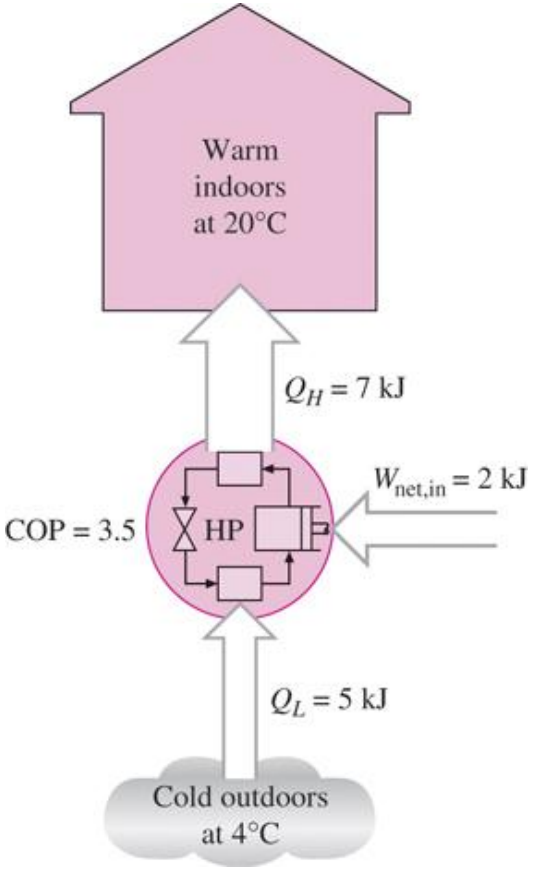
**Can the value of $\text{COP}_R$ be greater than unity?**

# Heat Pumps




The objective of a heat pump is to supply heat $Q_H$ into the warmer space.

The work supplied to a heat pump is used to extract energy from the cold outdoors and carry it into the warm indoors.




$$\text{COP}_{\text{HP}} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_H}{W_{\text{net,in}}}$$

$$\text{COP}_{\text{HP}} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - Q_L/Q_H}$$

$$\text{COP}_{\text{HP}} = \text{COP}_{\text{R}} + 1$$ for fixed values of $Q_L$ and $Q_H$

Can the value of $\text{COP}_{\text{HP}}$ be lower than unity?

What does $\text{COP}_{\text{HP}}=1$ represent?




When installed backward, an air conditioner functions as a heat pump.

- Most heat pumps in operation today have a seasonally averaged COP of 2 to 3.
- Most existing heat pumps use the cold outside air as the heat source in winter (*air-source* HP).
- In cold climates their efficiency drops considerably when temperatures are below the freezing point.
- In such cases, *geothermal* (*ground-source*) HP that use the ground as the heat source can be used.
- Such heat pumps are more expensive to install, but they are also more efficient.
- Air conditioners are basically refrigerators whose refrigerated space is a room or a building instead of the food compartment.
- The COP of a refrigerator decreases with decreasing refrigeration temperature.
- Therefore, it is not economical to refrigerate to a lower temperature than needed.

$$\text{EER} = 3.412\,\text{COP}_R$$

Energy efficiency rating (EER): The amount of heat removed from the cooled space in Btu's for 1 Wh (watthour) of electricity consumed.

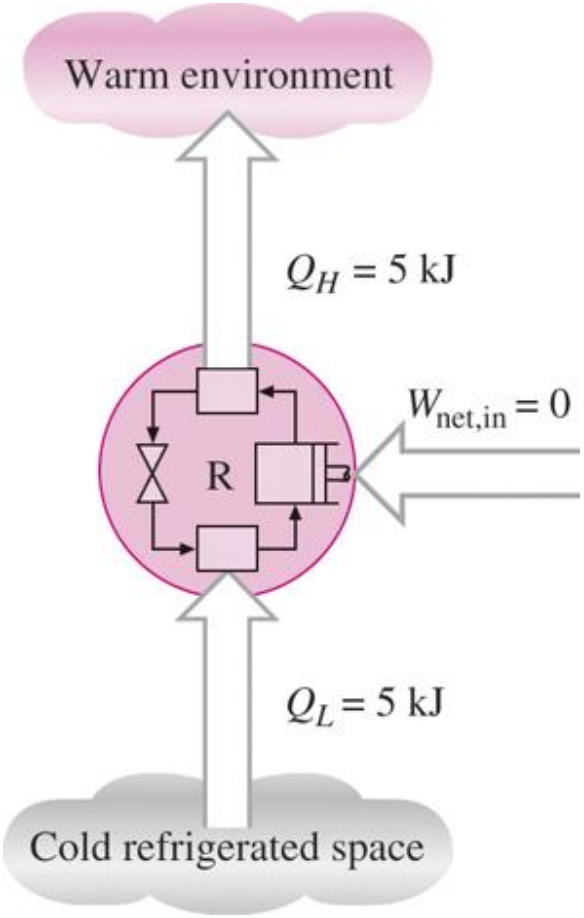
# The Second Law of Thermodynamics: Clasius Statement

**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.**

*It states that a refrigerator cannot operate unless its compressor is driven by an external power source, such as an electric motor.*

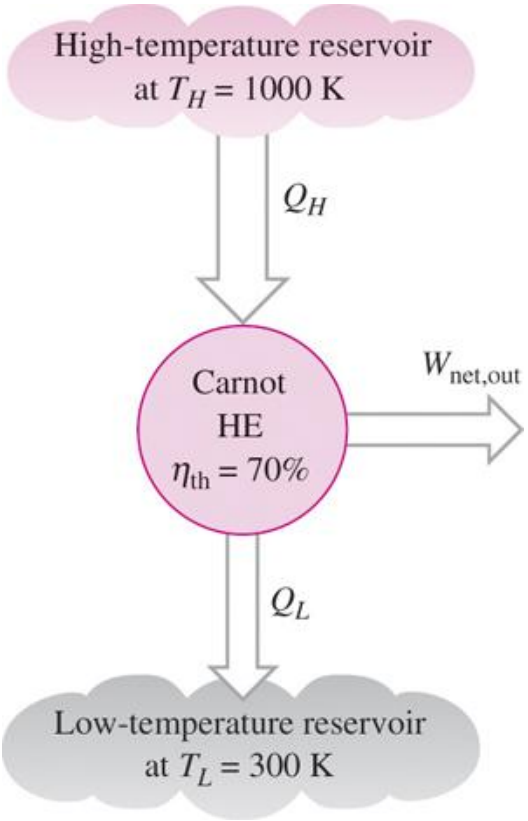
This way, the net effect on the surroundings involves the consumption of some energy in the form of work, in addition to the transfer of heat from a colder body to a warmer one.

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

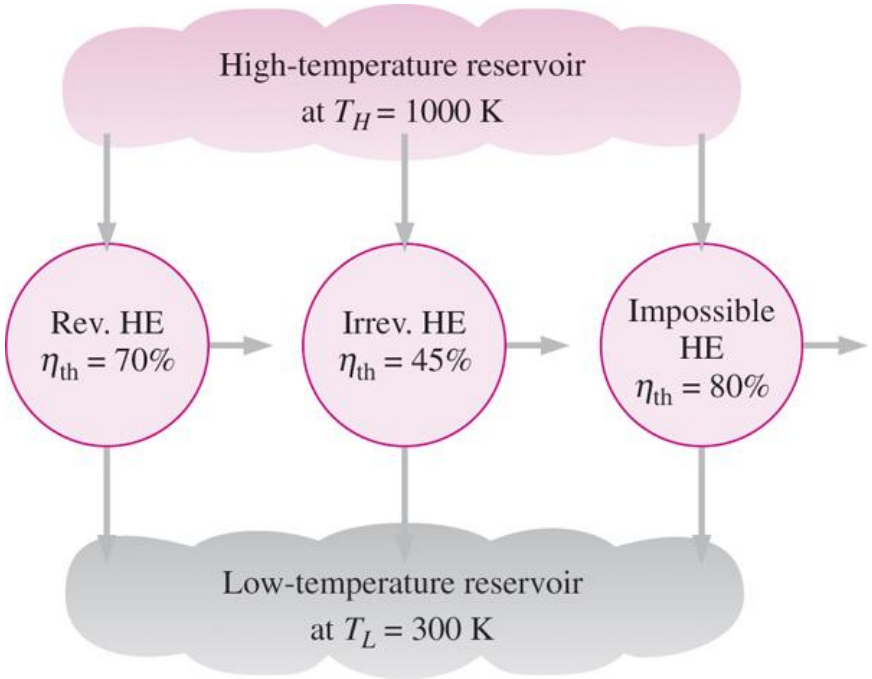



A refrigerator that violates the Clausius statement of the second law.

# THE CARNOT HEAT ENGINE




The Carnot heat engine is the most efficient of all heat engines operating between the same high- and low-temperature reservoirs.




No heat engine can have a higher efficiency than a reversible heat engine operating between the same high- and low-temperature reservoirs.

**Any** heat **engine**

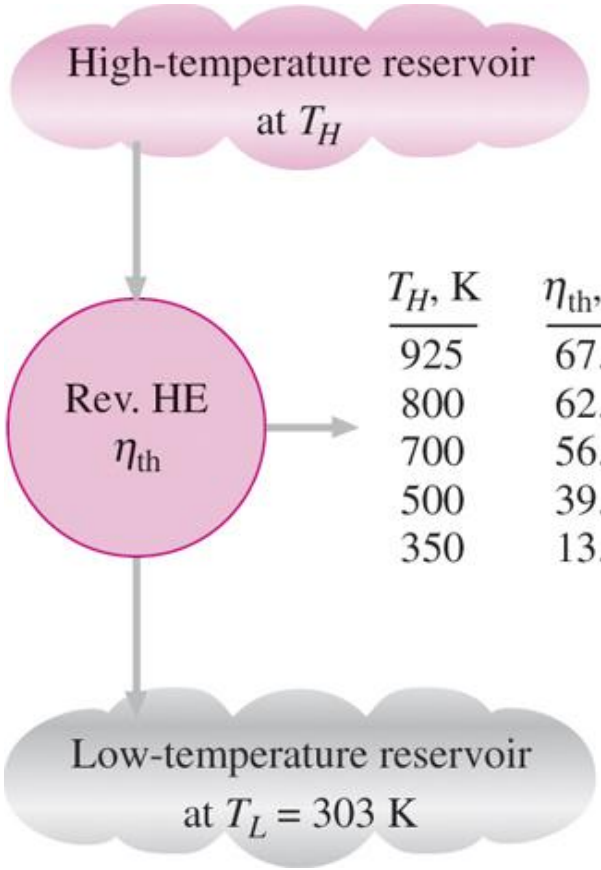
$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

Carnot heat engine

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

$$\eta_{th} \begin{cases} < \eta_{th,rev} & \text{irreversible heat engine} \\ = \eta_{th,rev} & \text{reversible heat engine} \\ > \eta_{th,rev} & \text{impossible heat engine} \end{cases}$$

# The Quality of Energy

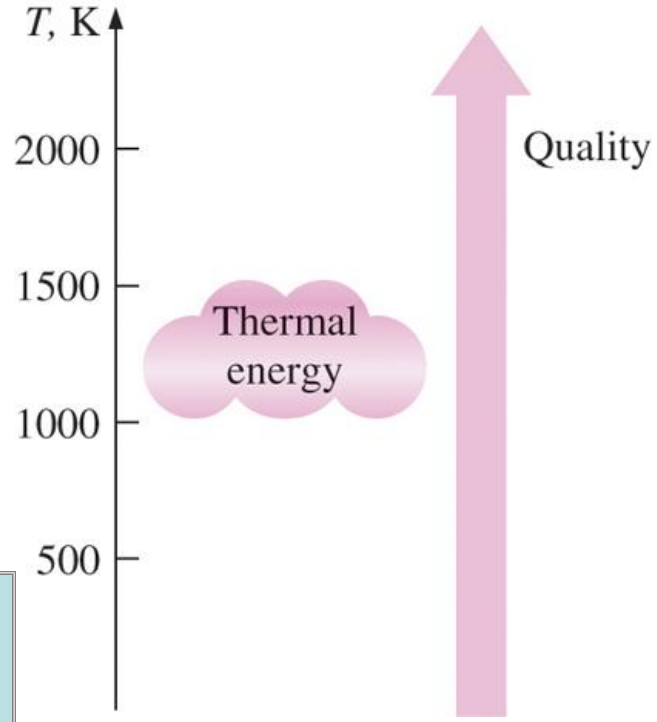



| $T_H$, K | $\eta_{th}$, % |
|---|---|
| 925 | 67.2 |
| 800 | 62.1 |
| 700 | 56.7 |
| 500 | 39.4 |
| 350 | 13.4 |

The fraction of heat that can be converted to work as a function of source temperature.

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

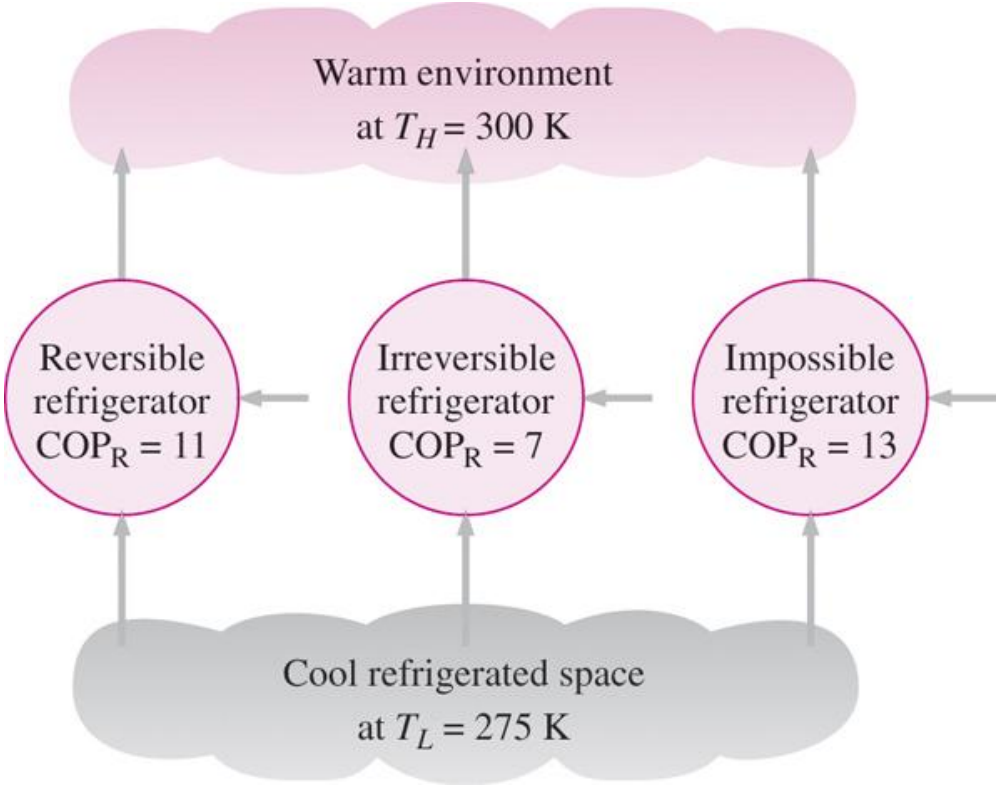
**Can we use °C unit for temperature here?!!**




The higher the temperature of the thermal energy, the higher its quality.

**How do you increase the thermal efficiency of a Carnot heat engine? How about for actual heat engines?**

# THE CARNOT REFRIGERATOR AND HEAT PUMP




**No refrigerator can have a higher COP than a reversible refrigerator operating between the same temperature limits.**

**Any refrigerator or heat pump**

$$COP_R = \frac{1}{Q_H/Q_L - 1}$$

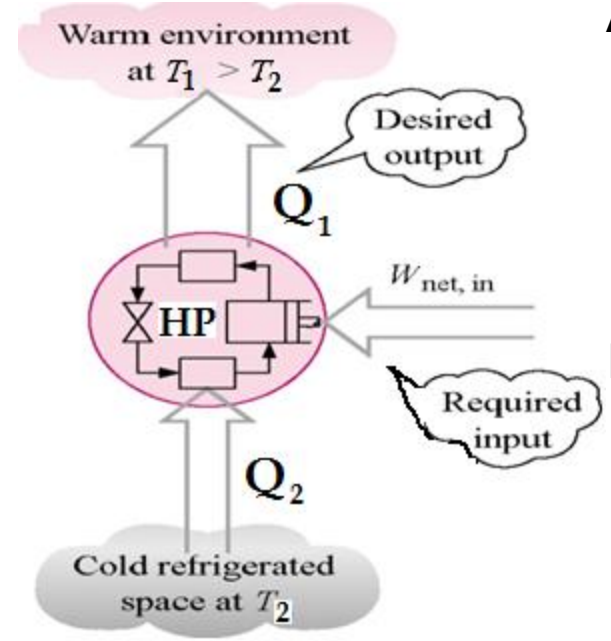
$$COP_{HP} = \frac{1}{1 - Q_L/Q_H}$$

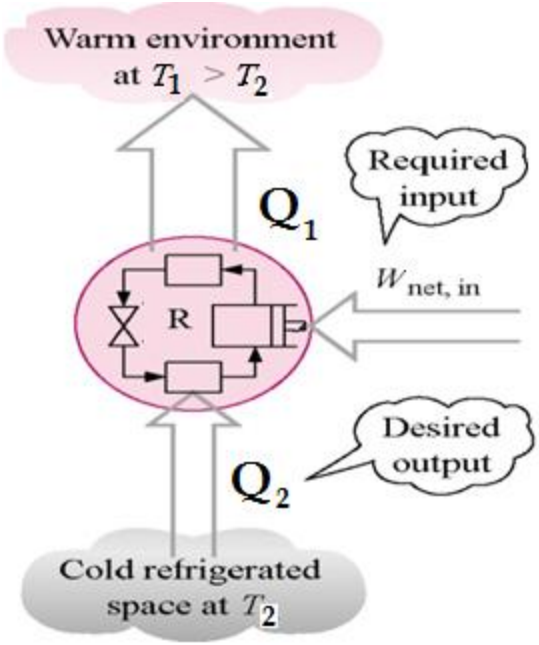
**Carnot refrigerator or heat pump**

$$COP_{HP,rev} = \frac{1}{1 - T_L/T_H}$$

$$COP_{R,rev} = \frac{1}{T_H/T_L - 1}$$

**How do you increase the COP of a Carnot refrigerator or heat pump? How about for actual ones?**




## A reverse heat engine

It is a system which operates in a cycle with the object of transferring heat from a low temperature reservoir to high temperature one.

There are two reverse engine, according to the purpose for its use.

## Heat Pump

A heat pump is a thermodynamic system operating in a thermodynamic cycle that removes heat from a low-temperature body and delivers heat to a high-temperature body. To accomplish this energy transfer, the heat pump receives external energy in the form of work or heat from the surroundings.

## Refrigerator

A refrigerator is a device that operates on a thermodynamic cycle and extracts heat from a low-temperature medium.

The heat pump also operates on a thermodynamic cycle but rejects heat to the high-temperature medium.

$$\eta_{th} = \frac{\text{Net Work Output}}{\text{Total Heat Input}} = \text{is a + ve value.}$$

## Example 1

**A steam power plant produces 50 MW of net work while burning fuel to produce 150 MW of heat energy at the high temperature. Determine the cycle thermal efficiency and the heat rejected by the cycle to the surroundings.**

$$\eta_{th} = \frac{W_{net,\,out}}{Q_H}$$

$$= \frac{50\ MW}{150\ MW} = 0.333 \quad \text{or} \quad 33.3\%$$

$$W_{net,\,out} = Q_H - Q_L$$

$$Q_L = Q_H - W_{net,\,out}$$

$$= 150\ MW - 50\ MW$$

$$= 100\ MW$$

Thermodynamics: An Engineering Approach

Seventh Edition in SI Units

Yunus A. Cengel, Michael A. Boles

McGraw-Hill, 2011

MODULE 3.1

# PROPERTIES OF PURE SUBSTANCES

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# PURE SUBSTANCE

- **Pure substance**: A substance that has a fixed chemical composition throughout.
- Air is a mixture of several gases, but it is considered to be a pure substance.

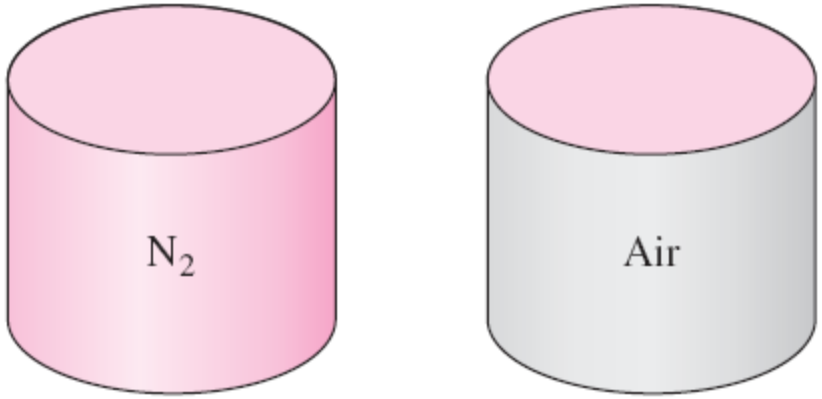
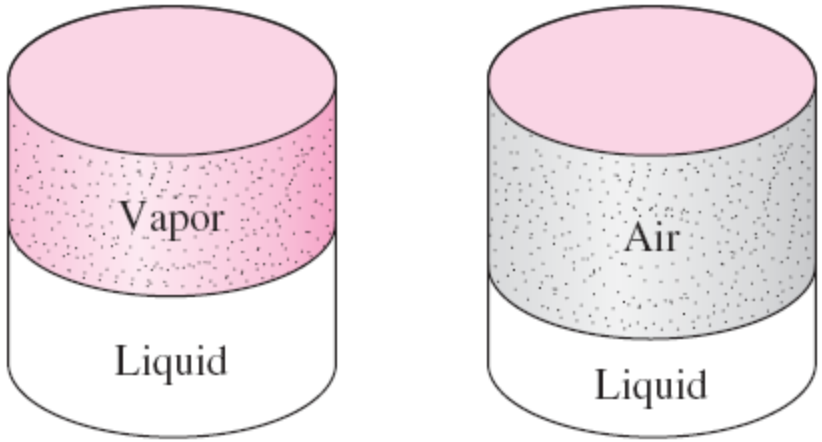


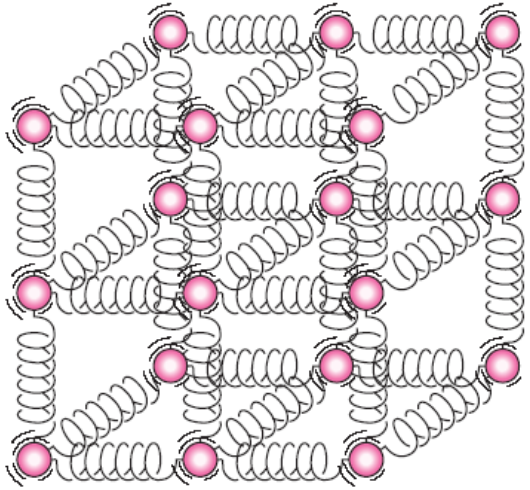

**FIGURE 3–1**
Nitrogen and gaseous air are pure substances.



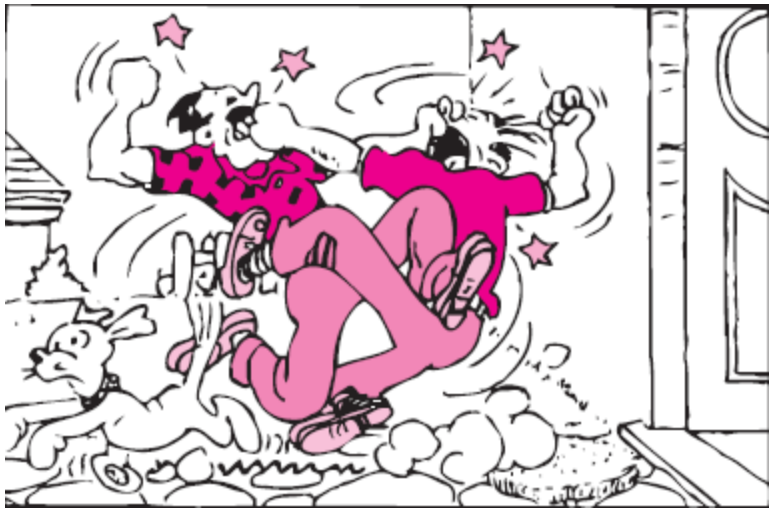

(*a*) $H_2O$ (*b*) Air

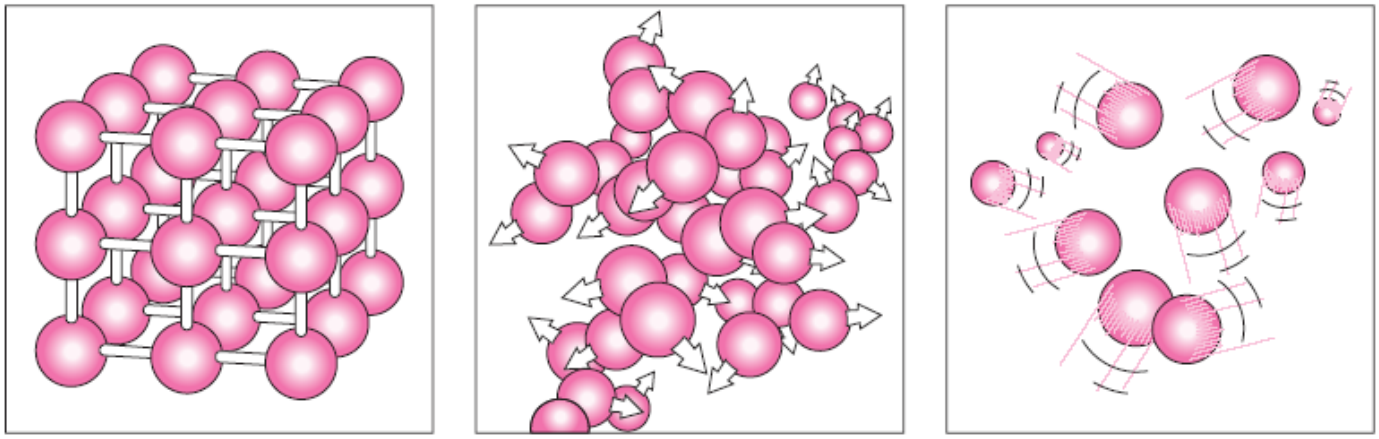
**FIGURE 3–2**
A mixture of liquid and gaseous water is a pure substance, but a mixture of liquid and gaseous air is not.

# PHASES OF A PURE SUBSTANCE



The molecules in a solid are kept at their positions by the large springlike inter-molecular forces.





(a) (b) (c)

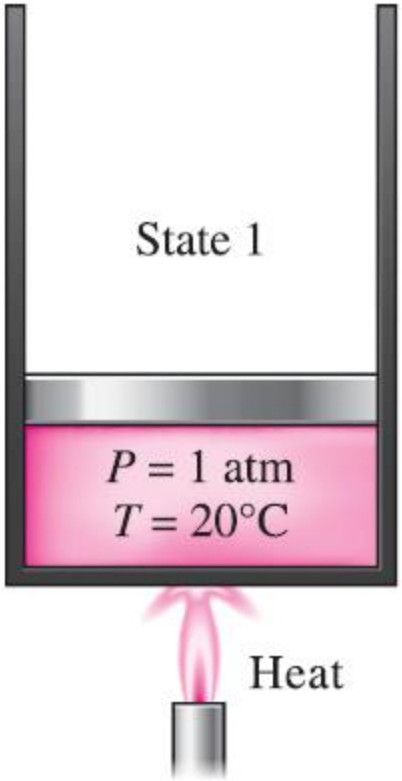
**FIGURE 3–5**

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.

In a solid, the attractive and repulsive forces between the molecules tend to maintain them at relatively constant distances from each other.

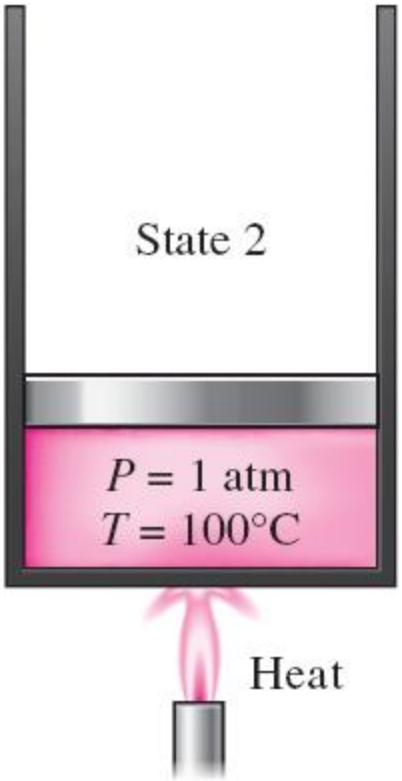
# PHASE-CHANGE PROCESSES OF PURE SUBSTANCES

- **Compressed liquid (subcooled liquid)**: A substance that it is *not about to vaporize.*
- **Saturated liquid**: A liquid that is *about to vaporize.*

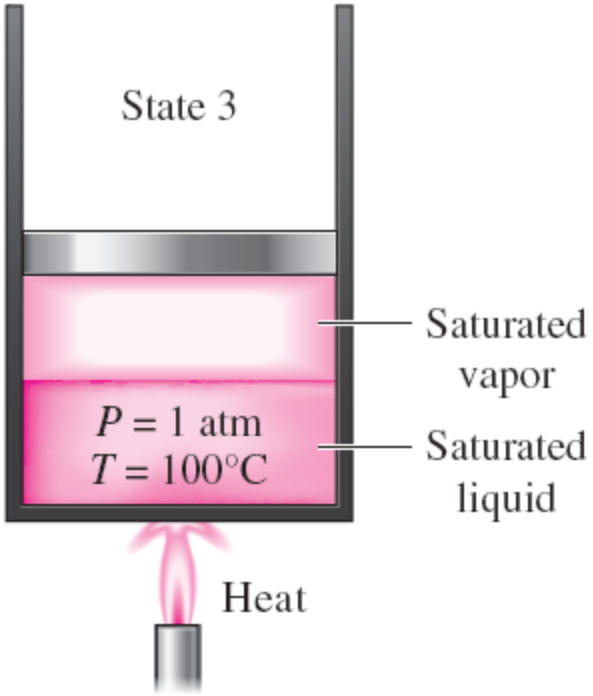



At 1 atm and 20°C, water exists in the liquid phase (***compressed liquid***).

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



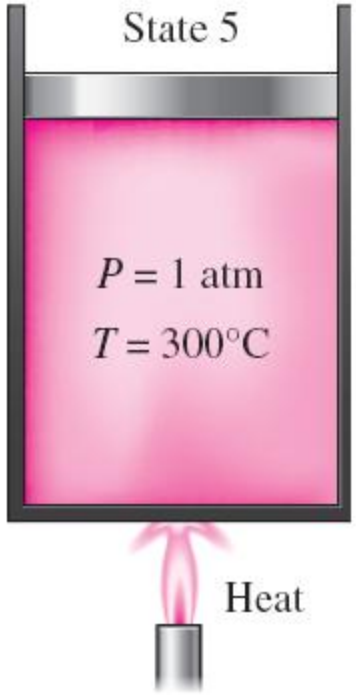
- **Saturated vapor**: A vapor that is *about to condense.*
- **Saturated liquid–vapor mixture**: The state at which the *liquid and vapor phases coexist* in equilibrium.
- **Superheated vapor**: A vapor that is *not about to condense* (i.e., not a saturated vapor).




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

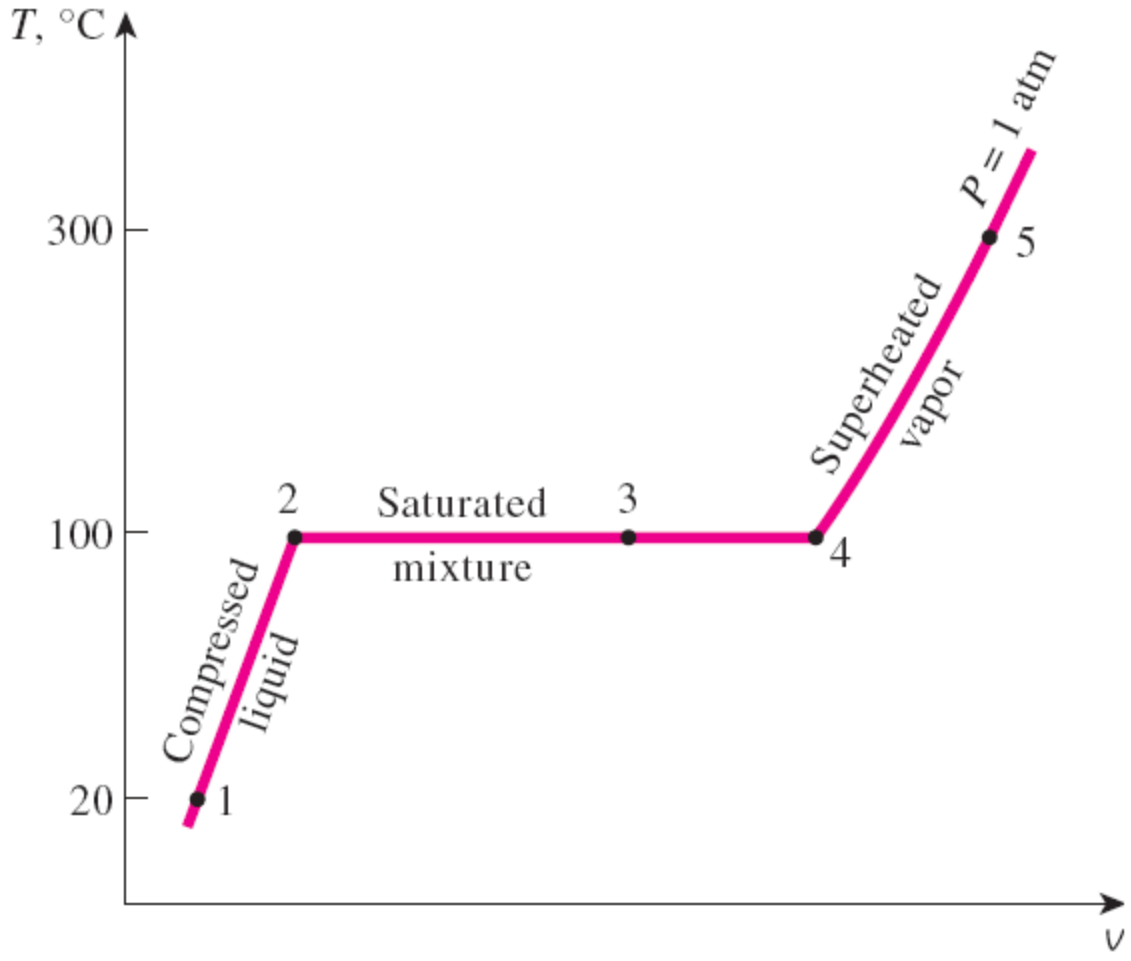



At 1 atm pressure, the temperature remains constant at 100°C until the last drop of liquid is vaporized (***saturated vapor***).




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

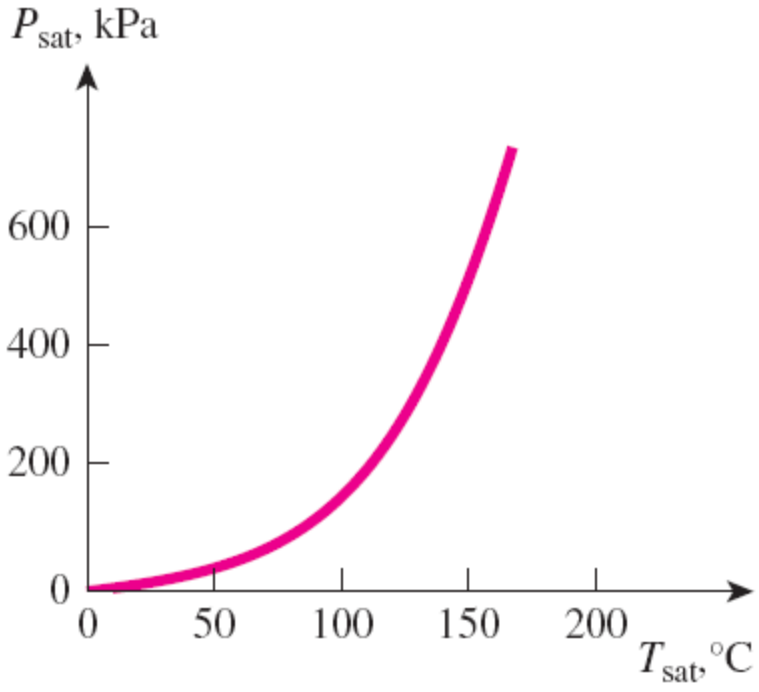
If the entire process between state 1 and 5 described in the figure is reversed by cooling the water while maintaining the pressure at the same value, the water will go back to state 1, retracing the same path, and in so doing, the amount of heat released will exactly match the amount of heat added during the heating process.




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

# Saturation Temperature and Saturation Pressure

- The temperature at which water starts boiling depends on the pressure; therefore, if the pressure is fixed, so is the boiling temperature.
- Water boils at 100°C at 1 atm pressure.
- **Saturation temperature $T_{sat}$**: The temperature at which a pure substance changes phase at a given pressure.
- **Saturation pressure $P_{sat}$**: The pressure at which a pure substance changes phase at a given temperature.




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

**TABLE 3–1**

Saturation (boiling) pressure of water at various temperatures

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

- **Latent heat**: The amount of energy absorbed or released during a phase-change process.
- **Latent heat of fusion**: The amount of energy absorbed during melting. It is equivalent to the amount of energy released during freezing.
- **Latent heat of vaporization:** The amount of energy absorbed during vaporization and it is equivalent to the energy released during condensation.
- 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.
- The atmospheric pressure, and thus the boiling temperature of water, decreases with elevation.

**TABLE 3–2**

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 |

# Some Consequences of $T_{sat}$ and $P_{sat}$ Dependence

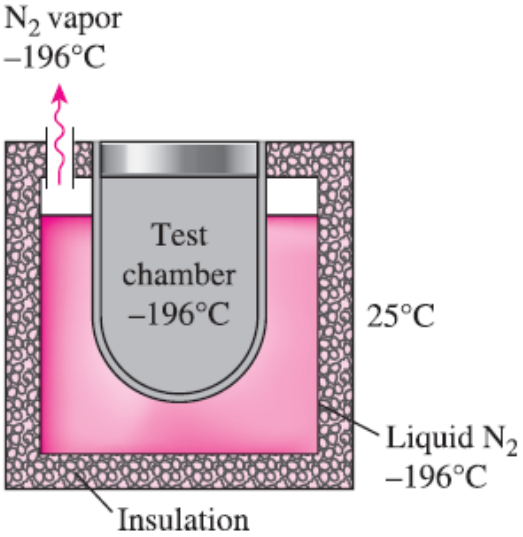
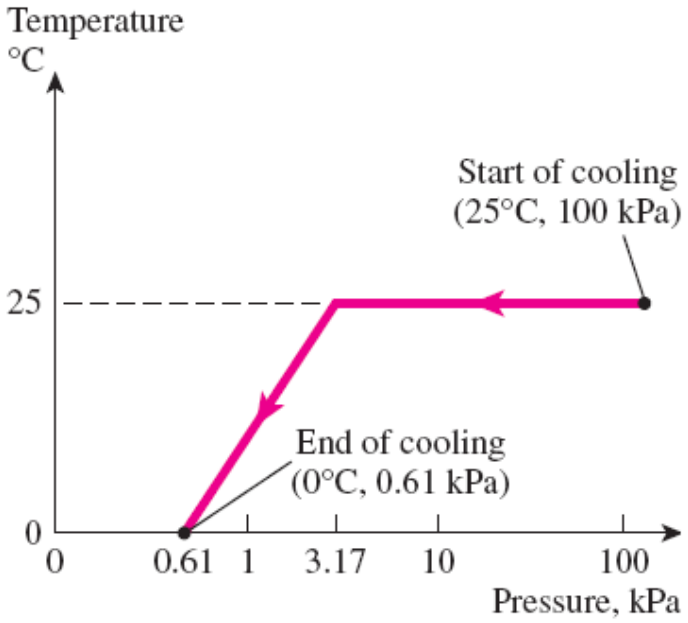
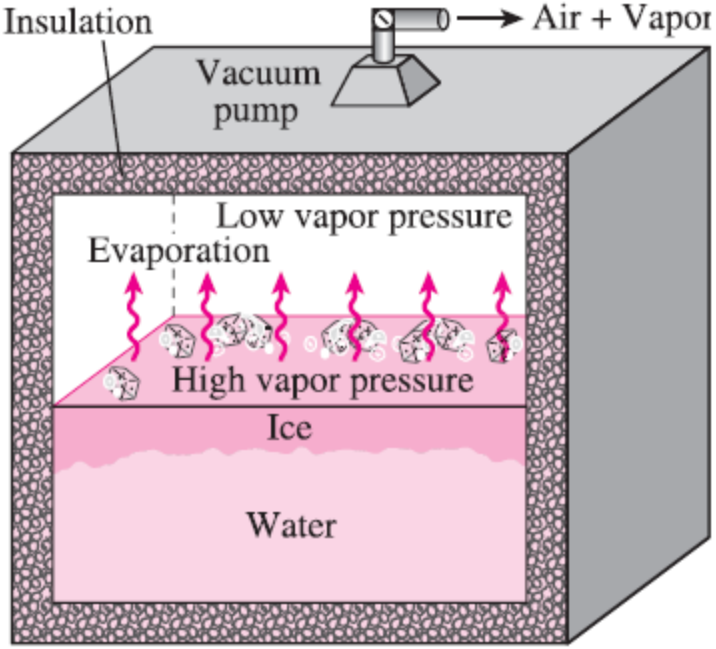



**FIGURE 3–13**
The temperature of liquid nitrogen exposed to the atmosphere remains constant at −196°C, and thus it maintains the test chamber at −196°C.

The variation of the temperature of fruits and vegetables with pressure during vacuum cooling from 25°C to 0°C.

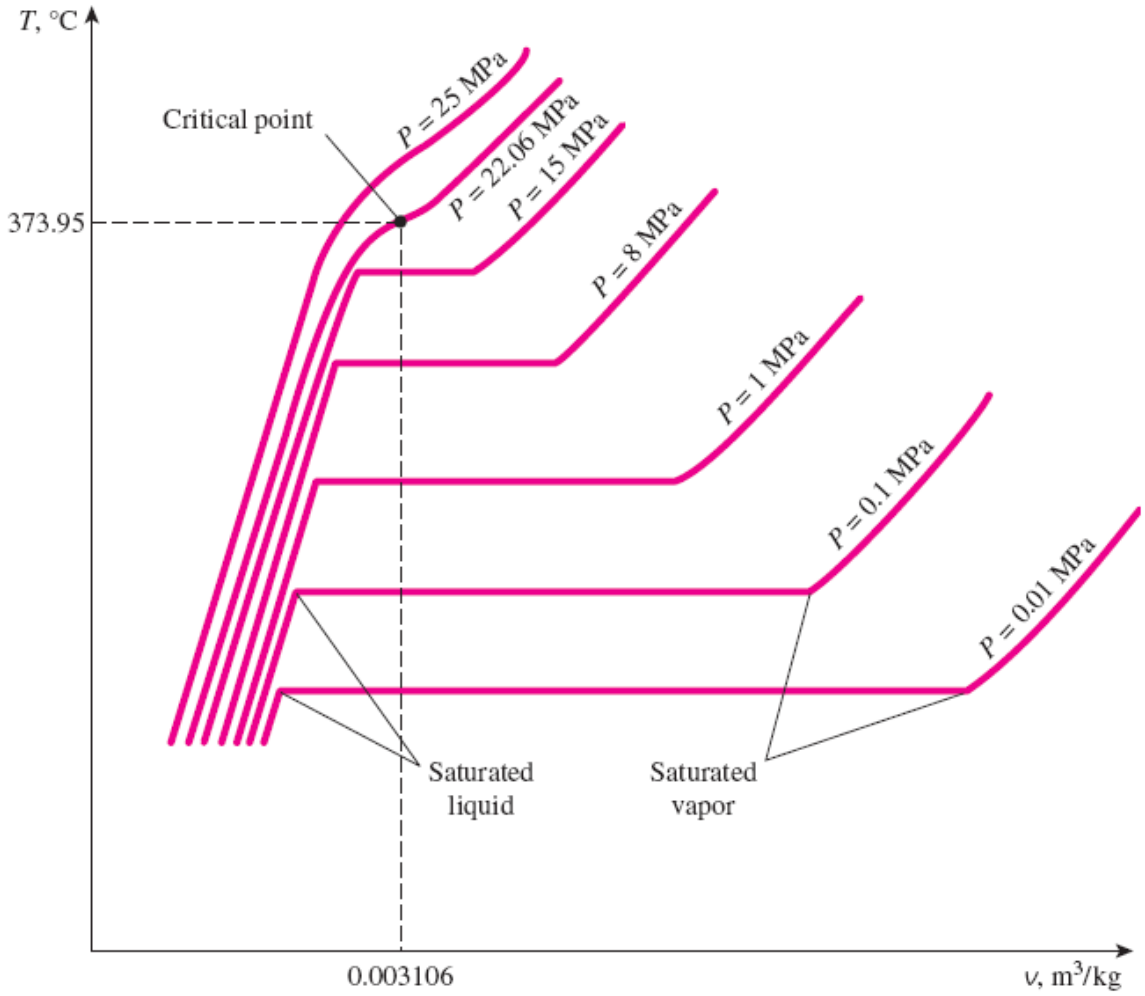



In 1775, ice was made by evacuating the air space in a water tank.

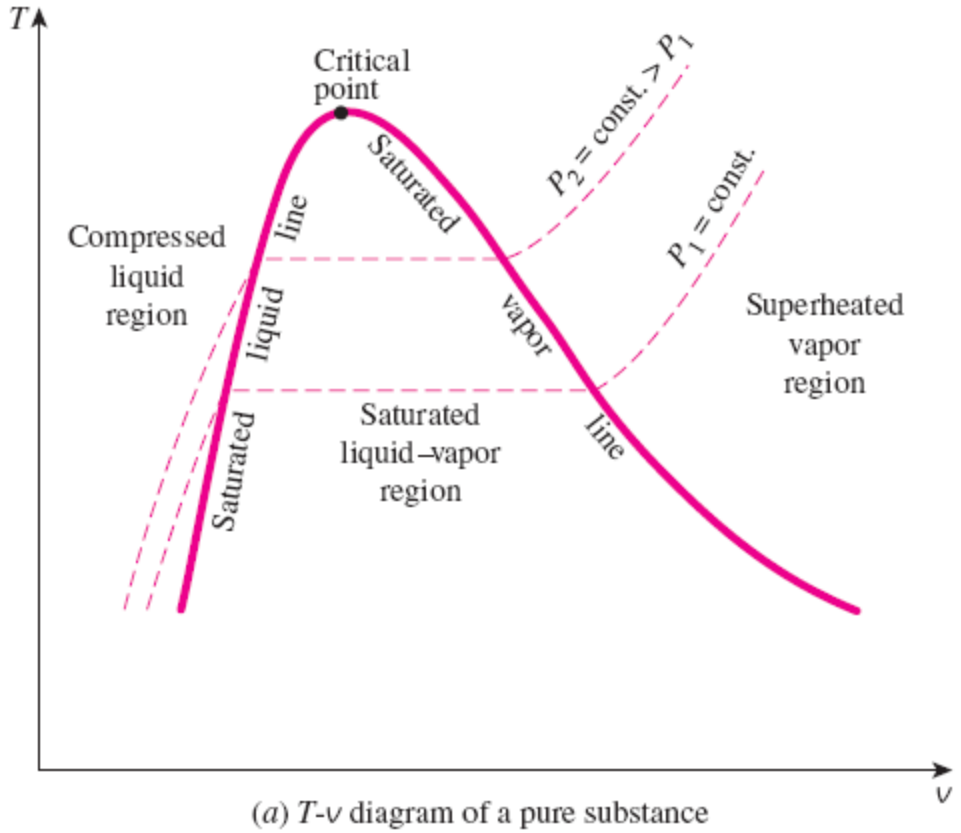
# PROPERTY DIAGRAMS FOR PHASE-CHANGE PROCESSES

The variations of properties during phase-change processes are best studied and understood with the help of property diagrams such as the *T*-*v*, *P*-*v*, and *P*-*T* diagrams for pure substances.




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

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




(*a*) *T*-*v* diagram of a pure substance

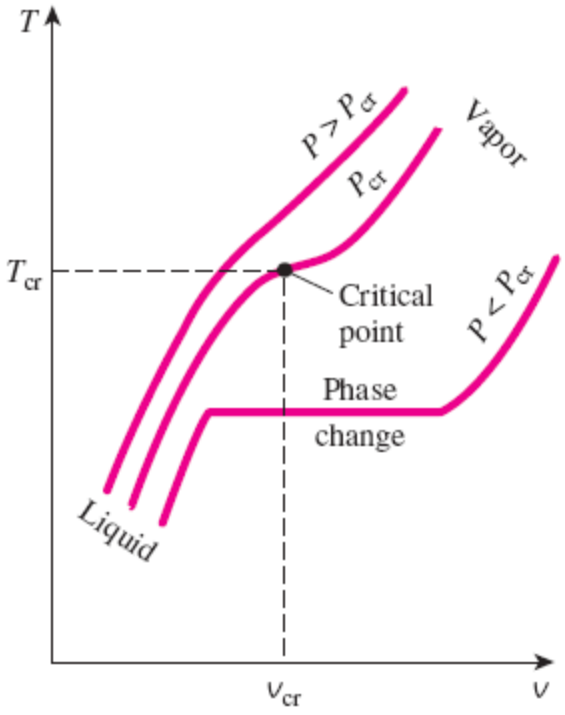
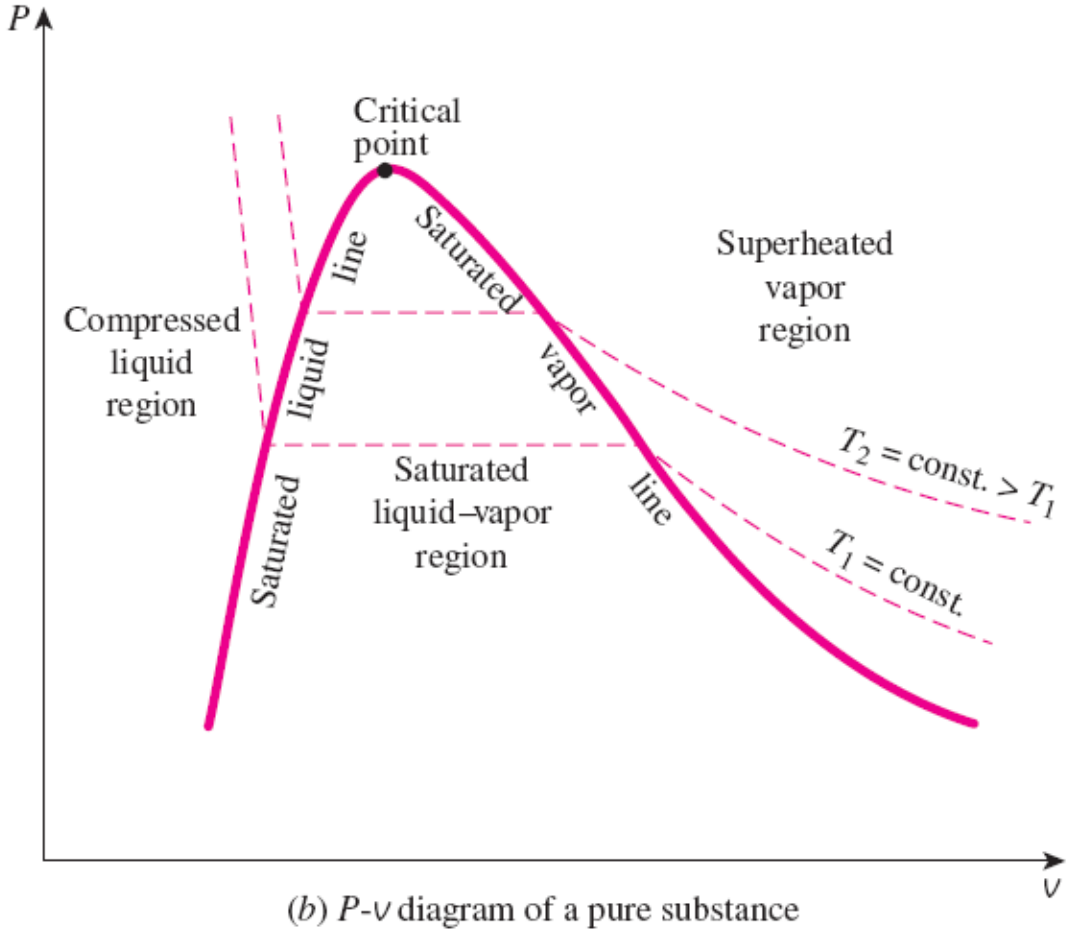



**FIGURE 3–18**
Property diagrams of a pure substance.

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

**Critical point**: The point at which the saturated liquid and saturated vapor states are identical.




(*b*) *P*-*v* diagram of a pure substance

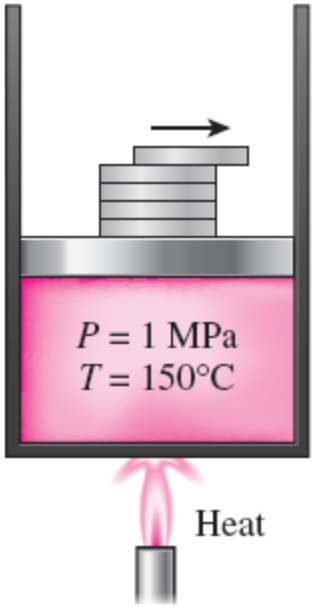
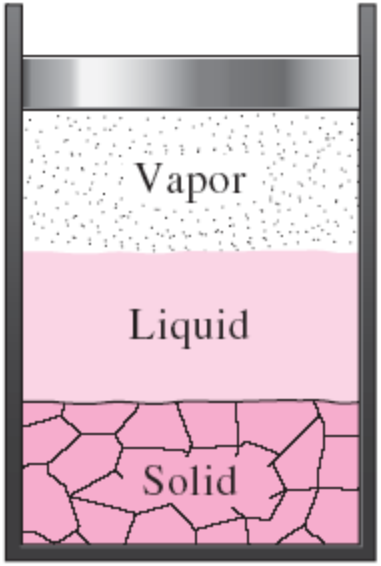



**FIGURE 3–19**

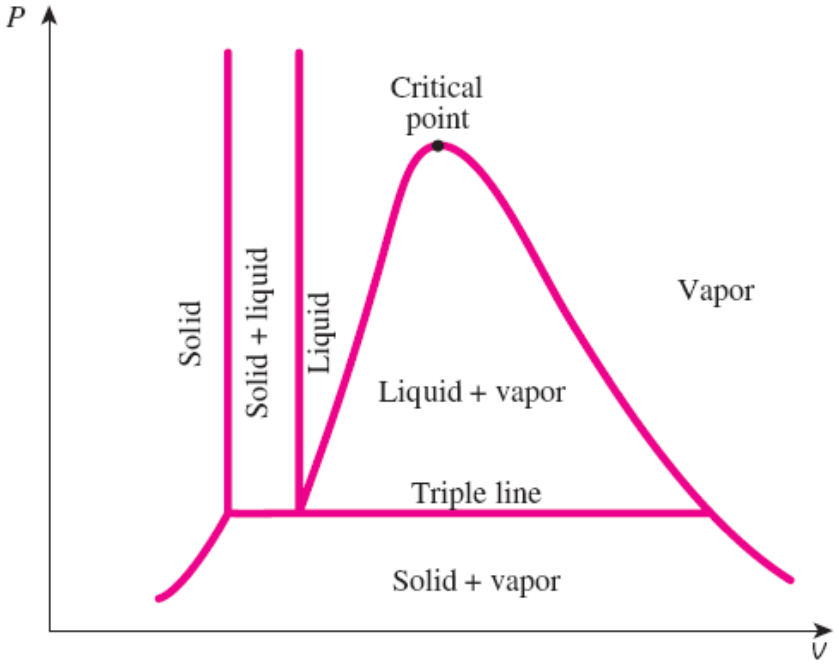
The pressure in a piston–cylinder device can be reduced by reducing the weight of the piston.

# Extending the Diagrams to Include the Solid Phase

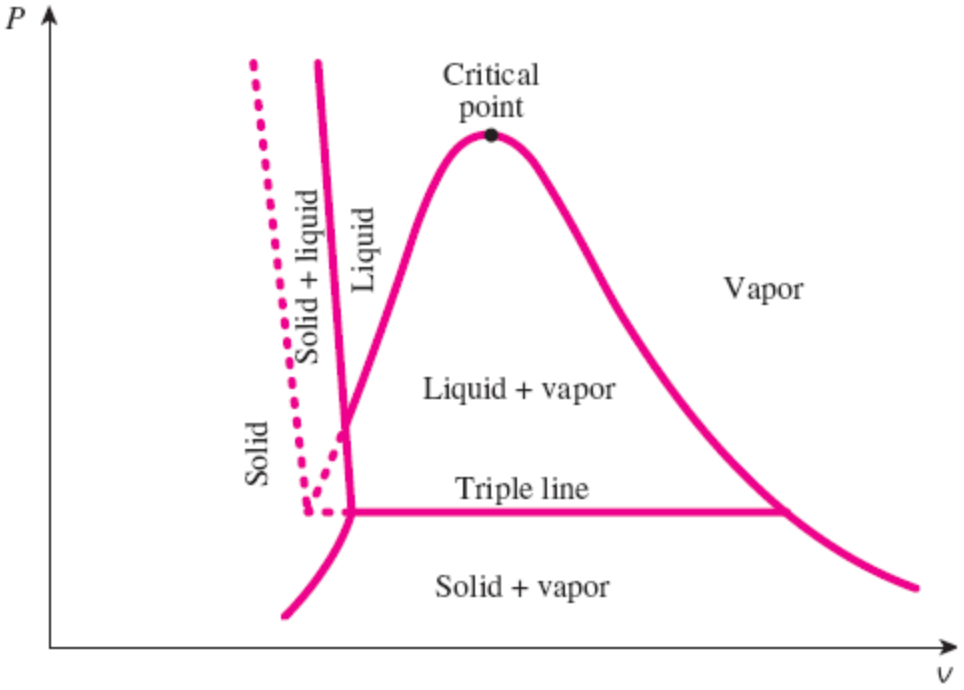
For water,
$T_{tp}$ = 0.01°C
$P_{tp}$ = 0.6117 kPa




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




(*a*) *P*-*v* diagram of a substance that contracts on freezing



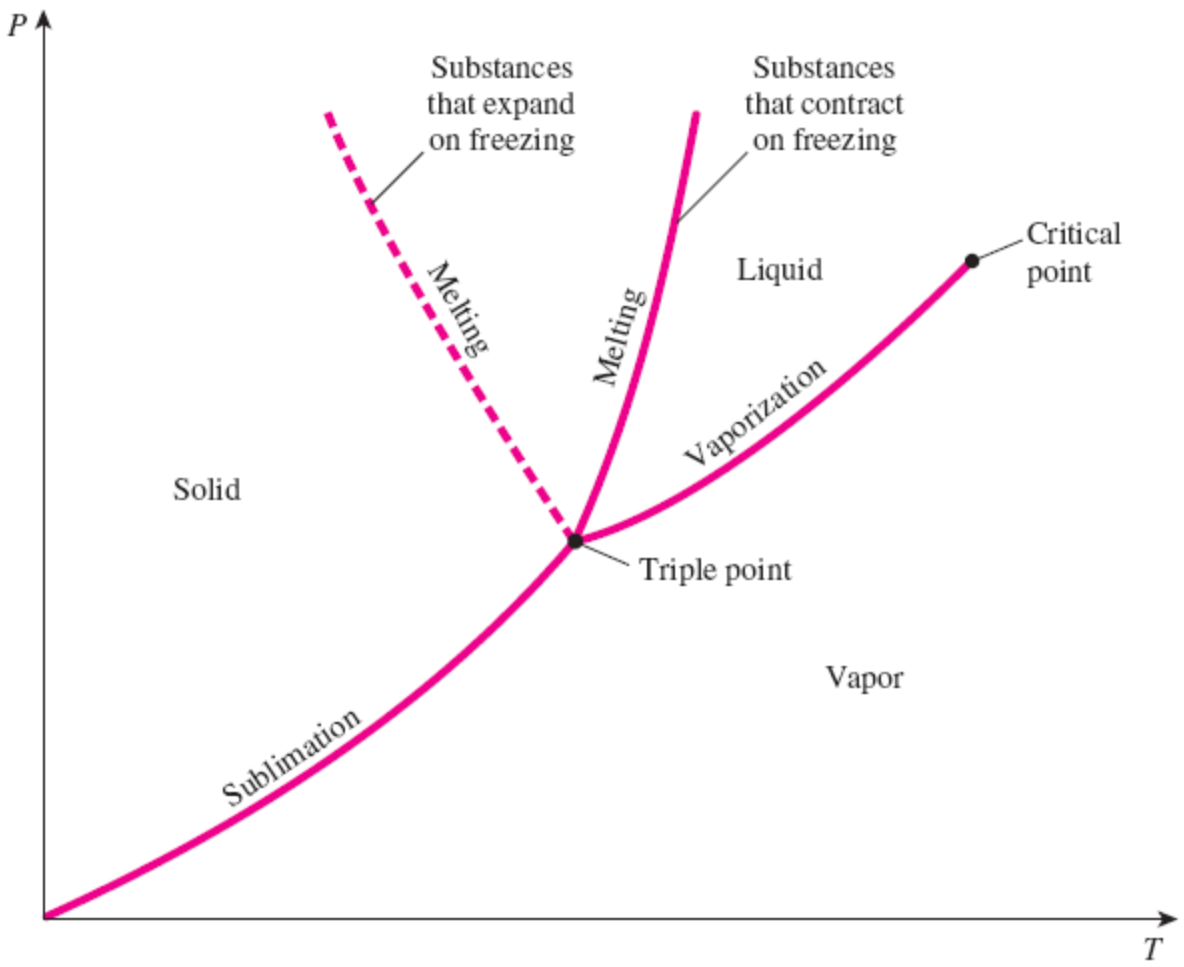

(*b*) *P*-*v* diagram of a substance that expands on freezing (such as water)

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




At low pressures (below the triple-point value), solids evaporate without melting first (*sublimation*).

## Phase Diagram




*P-T* diagram of pure substances.

The *P-v-T* surfaces present a great deal of information at once, but in a thermodynamic analysis it is more convenient to work with two-dimensional diagrams, such as the *P-v* and *T-v* diagrams.

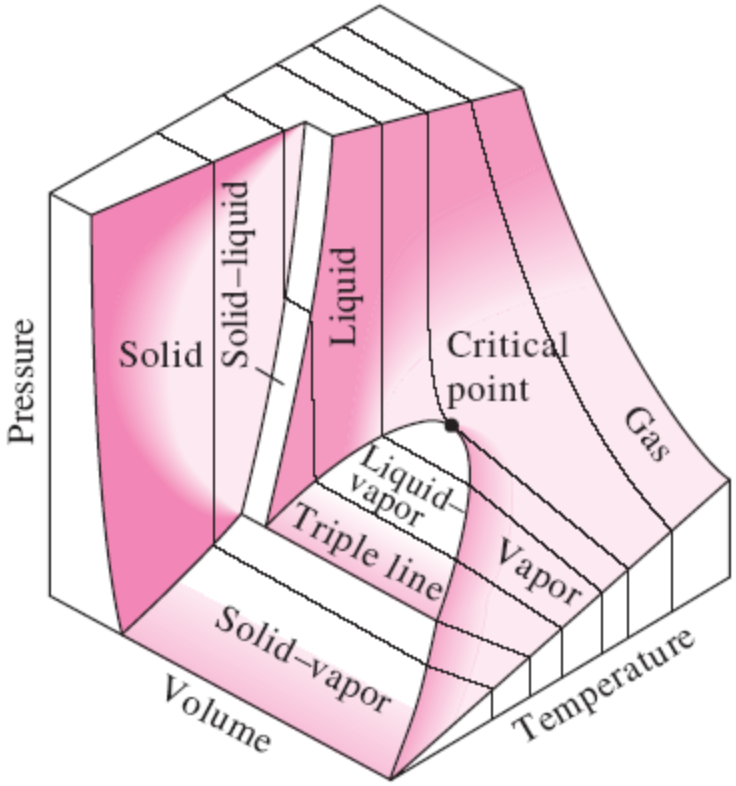



**FIGURE 3–24**
*P-v-T* surface of a substance that *contracts* on freezing.

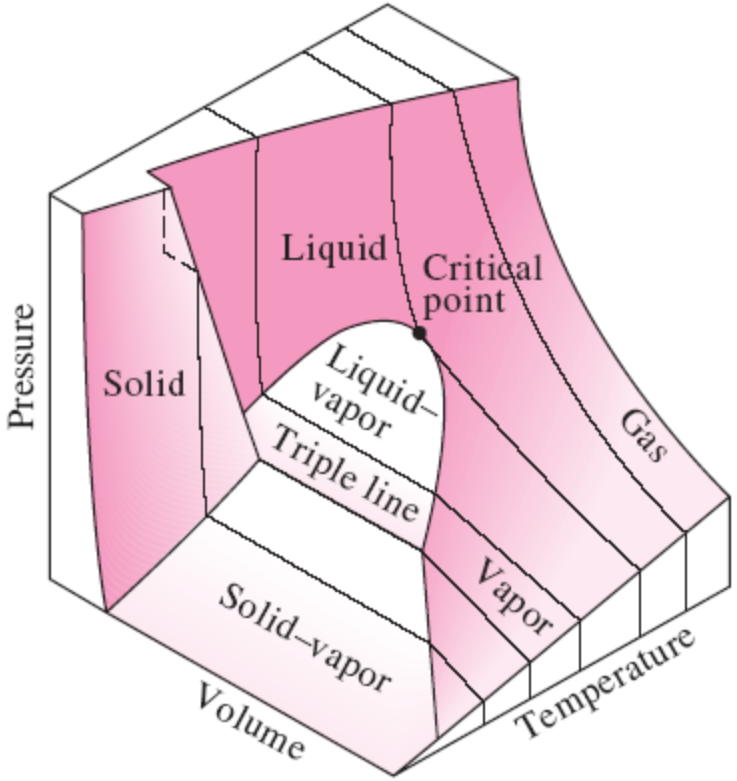



**FIGURE 3–25**
*P-v-T* surface of a substance that *expands* on freezing (like water).

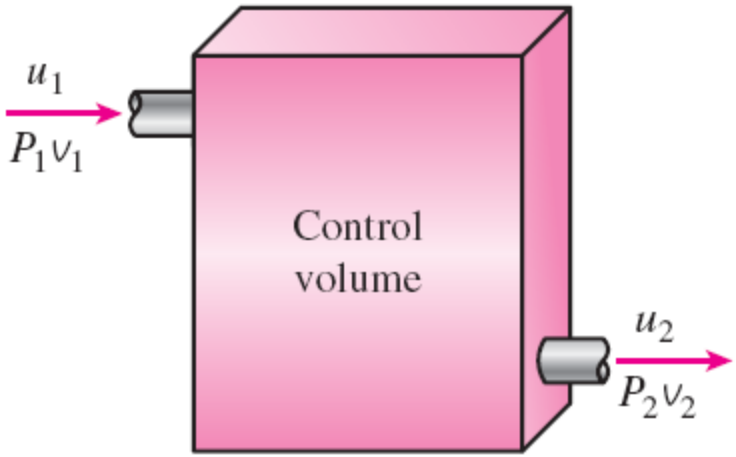
# PROPERTY TABLES

- For most substances, the relationships among thermodynamic properties are too complex to be expressed by simple equations.
- Therefore, properties are frequently presented in the form of tables.
- Some thermodynamic properties can be measured easily, but others cannot and are calculated by using the relations between them and measurable properties.
- The results of these measurements and calculations are presented in tables in a convenient format.

## Enthalpy—A Combination Property

$$h = u + Pv \qquad (\text{kJ/kg})$$

$$H = U + PV \qquad (\text{kJ})$$




The combination $u + Pv$ is frequently encountered in the analysis of control volumes.

$\text{kPa}\cdot\text{m}^3 \equiv \text{kJ}$
$\text{kPa}\cdot\text{m}^3/\text{kg} \equiv \text{kJ/kg}$
$\text{bar}\cdot\text{m}^3 \equiv 100\ \text{kJ}$
$\text{MPa}\cdot\text{m}^3 \equiv 1000\ \text{kJ}$
$\text{psi}\cdot\text{ft}^3 \equiv 0.18505\ \text{Btu}$

The product *pressure* × *volume* has energy units.

# Saturated Liquid and Saturated Vapor States

- **Table A–4**: Saturation properties of water under temperature.
- **Table A–5**: Saturation properties of water under pressure.

A partial list of Table A–4.

| Temp. °C $T$ | Sat. press. kPa $P_{sat}$ | Specific volume $m^3/kg$ Sat. liquid $v_f$ | Specific volume $m^3/kg$ 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 |

Specific temperature

Corresponding saturation pressure

Specific volume of saturated liquid

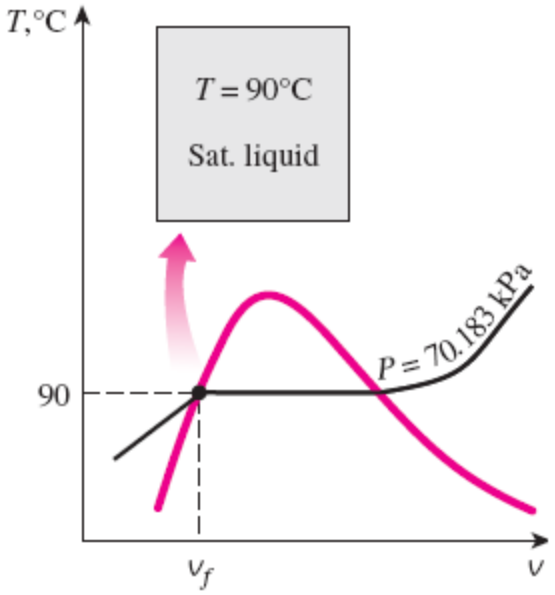
Specific volume of saturated vapor

$v_f$ = specific volume of saturated liquid

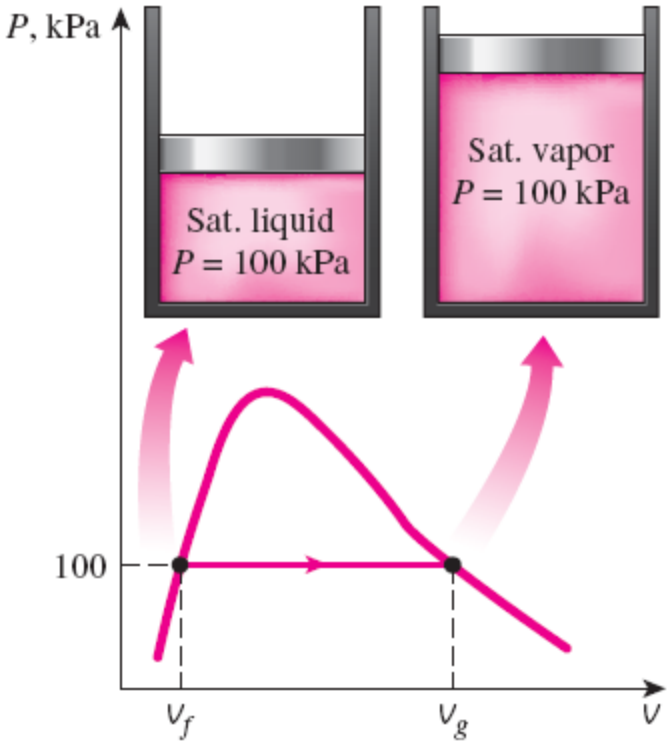
$v_g$ = specific volume of saturated vapor

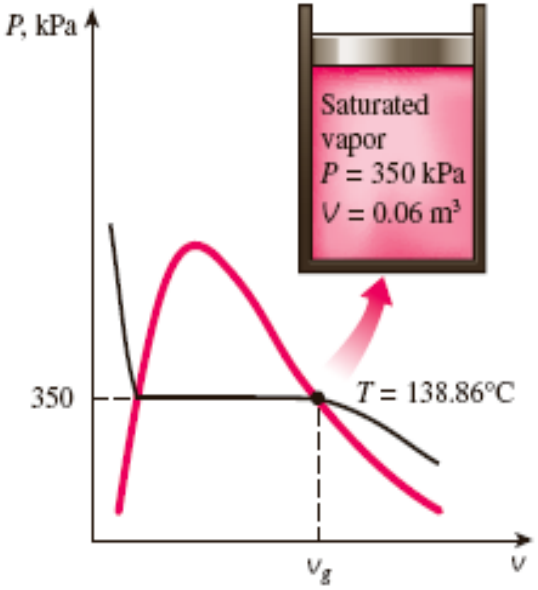
$v_{fg}$ = difference between $v_g$ and $v_f$ (that is, $v_{fg} = v_g - v_f$)

**Enthalpy of vaporization, $h_{fg}$ (Latent heat of vaporization):** The amount of energy needed to vaporize a unit mass of saturated liquid at a given temperature or pressure.




**Examples**:
Saturated liquid and saturated vapor states of water on *T-v* and *P-v* diagrams.



# Saturated Liquid–Vapor Mixture

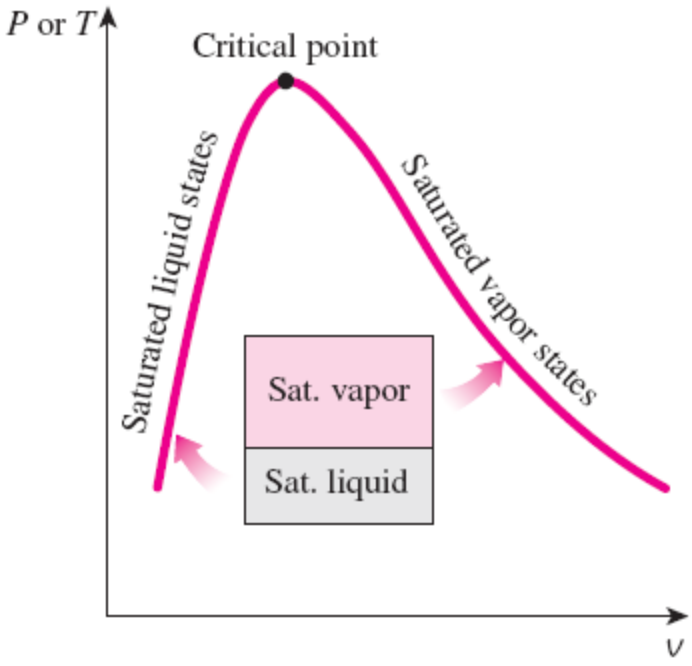
**Quality, *x*** : The ratio of the mass of vapor to the total mass of the mixture.

**Quality is between 0 and 1 → 0: sat. liquid, 1: sat. vapor.**

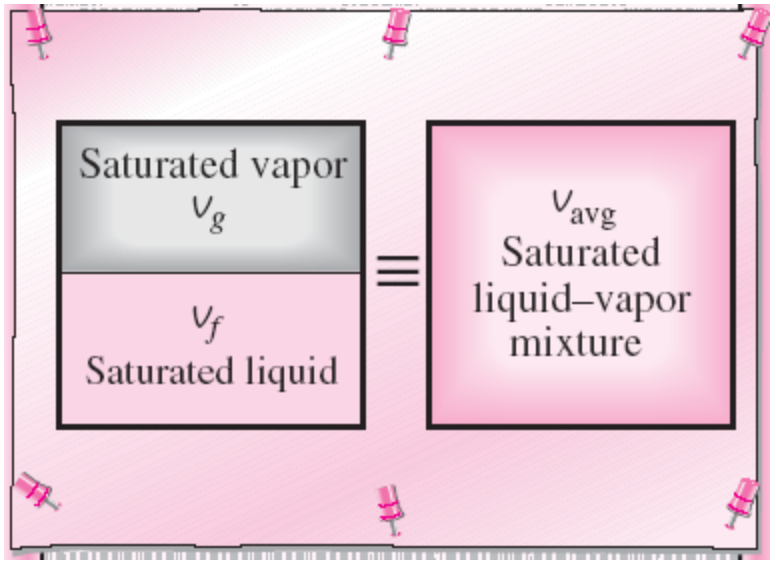
*The properties of the saturated liquid are the same whether it exists alone or in a mixture with saturated vapor.*

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

Temperature and pressure are dependent properties for a mixture.




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




A two-phase system can be treated as a homogeneous mixture for convenience.

$$v_{avg} = v_f + x v_{fg} \qquad (m^3/kg)$$

$$x = m_g/m_t \qquad x = \frac{v_{avg} - v_f}{v_{fg}}$$

$$u_{avg} = u_f + x u_{fg} \qquad (kJ/kg)$$

$$h_{avg} = h_f + x h_{fg} \qquad (kJ/kg)$$

**y** → *v*, *u*, or *h*.

$$y_{avg} = y_f + x y_{fg}$$

$$y_f \le y_{avg} \le y_g$$

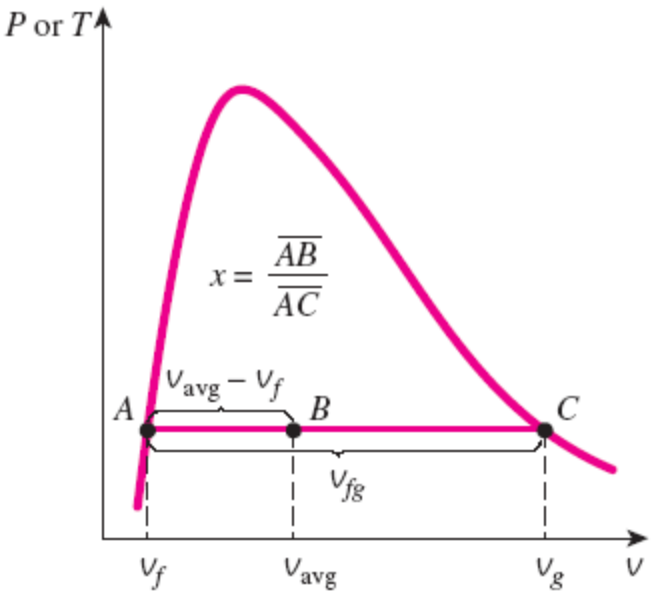



**FIGURE 3–34**
Quality is related to the horizontal distances on *P*-*v* and *T*-*v* diagrams.

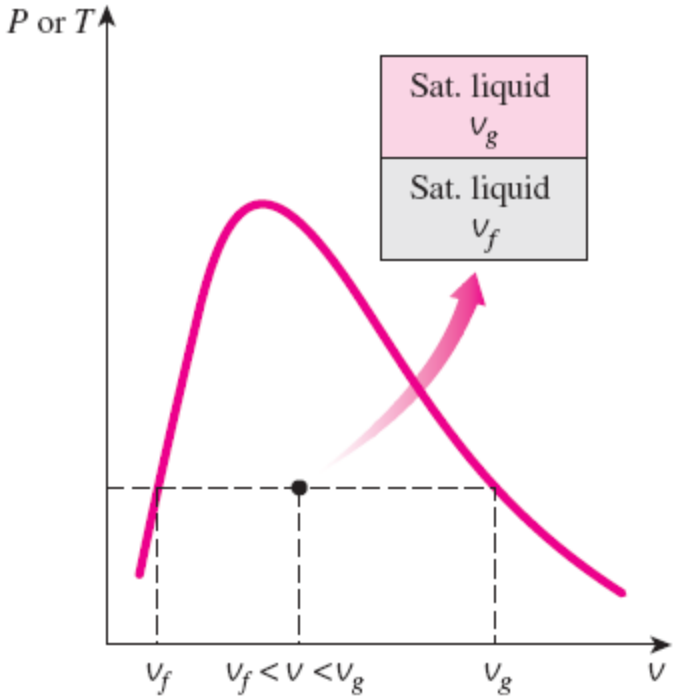
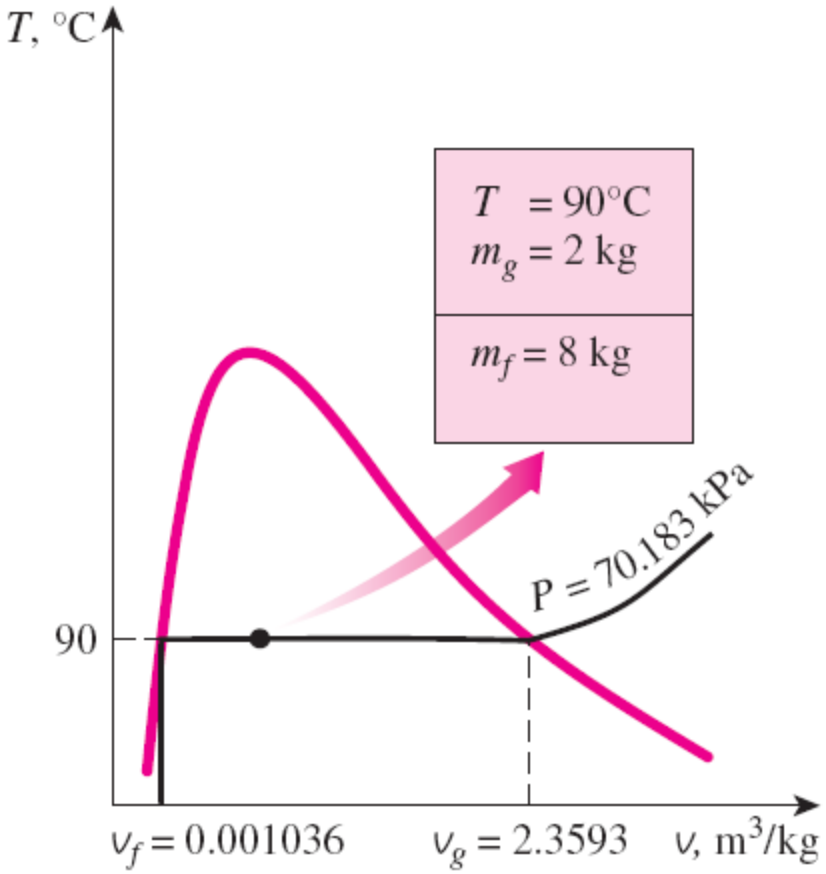
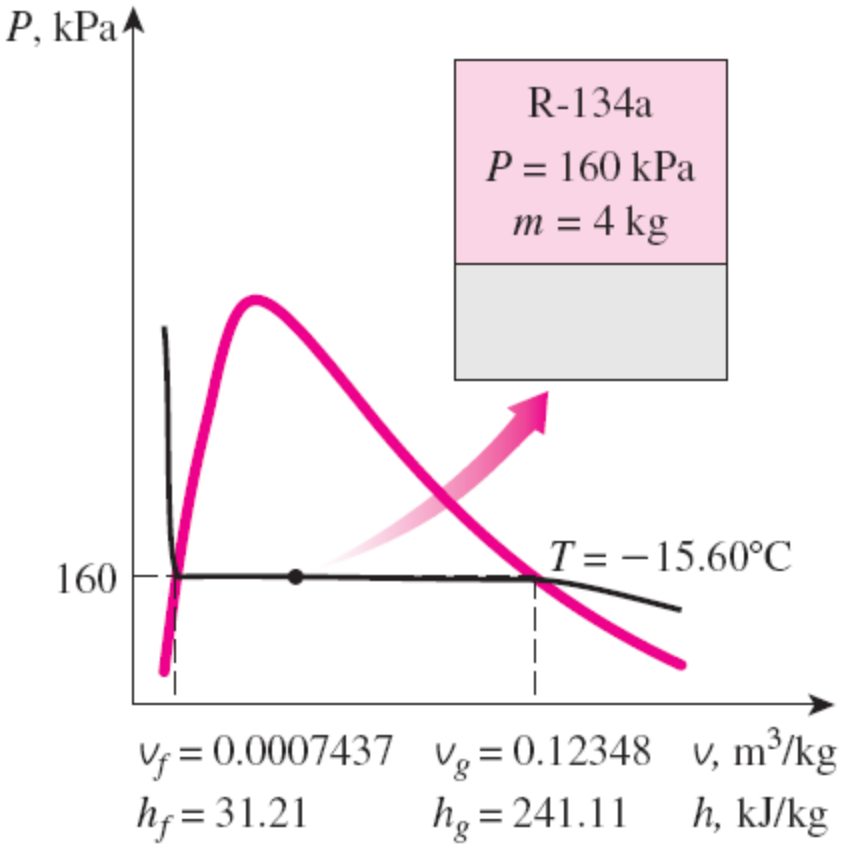



**FIGURE 3–35**
The *v* value of a saturated liquid–vapor mixture lies between the $v_f$ and $v_g$ values at the specified *T* or *P*.

**Examples**: Saturated liquid-vapor mixture states on *T-v* and *P-v* diagrams.



# Superheated Vapor

In the region to the right of the saturated vapor line and at temperatures above the critical point temperature, a substance exists as superheated vapor. In this region, temperature and pressure are independent properties.

Compared to saturated vapor, superheated vapor is characterized by

Lower pressures ($P < P_{sat}$ at a given $T$)

Higher tempreatures ($T > T_{sat}$ at a given $P$)

Higher specific volumes ($v > v_g$ at a given $P$ or $T$)

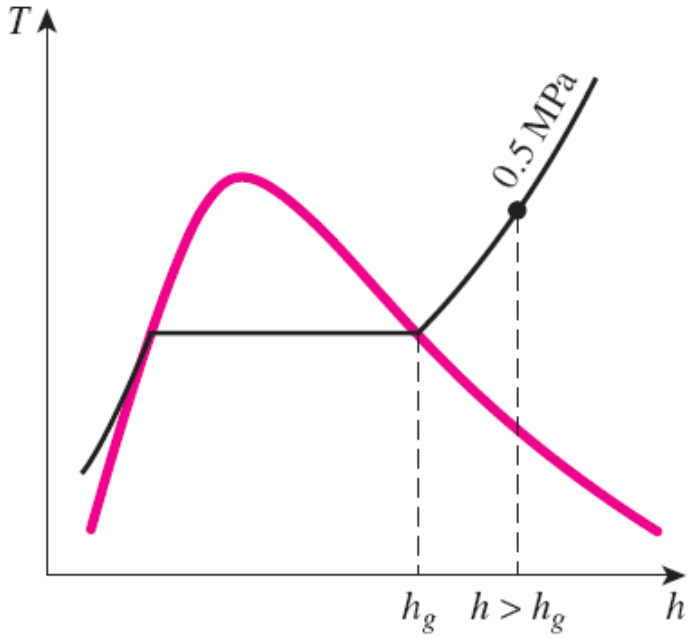
Higher internal energies ($u > u_g$ at a given $P$ or $T$)

Higher enthalpies ($h > h_g$ at a given $P$ or $T$)

| $T$, °C | $v$ m³/kg | $u$ kJ/kg | $h$ kJ/kg |
|---|---|---|---|
| | $P$ = 0.1 MPa (99.61°C) | | |
| Sat. | 1.6941 | 2505.6 | 2675.0 |
| 100 | 1.6959 | 2506.2 | 2675.8 |
| 150 | 1.9367 | 2582.9 | 2776.6 |
| ⋮ | ⋮ | ⋮ | ⋮ |
| 1300 | 7.2605 | 4687.2 | 5413.3 |
| | $P$ = 0.5 MPa (151.83°C) | | |
| Sat. | 0.37483 | 2560.7 | 2748.1 |
| 200 | 0.42503 | 2643.3 | 2855.8 |
| 250 | 0.47443 | 2723.8 | 2961.0 |

A partial listing of Table A–6.

At a specified $P$, superheated vapor exists at a higher $h$ than the saturated vapor.



# Compressed Liquid

The compressed liquid properties depend on temperature much more strongly than they do on pressure.

$y \cong y_{f\,@\,T}$ **y** → *v*, *u*, or *h*

A more accurate relation for *h*

$$h \cong h_{f\,@\,T} + v_{f\,@\,T}(P - P_{\text{sat}\,@T})$$

**Given: *P* and *T***

$$v \cong v_{f\,@T}$$
$$u \cong u_{f\,@T}$$
$$h \cong h_{f\,@T}$$

A compressed liquid may be approximated as a saturated liquid at the given temperature.

Compressed liquid is characterized by

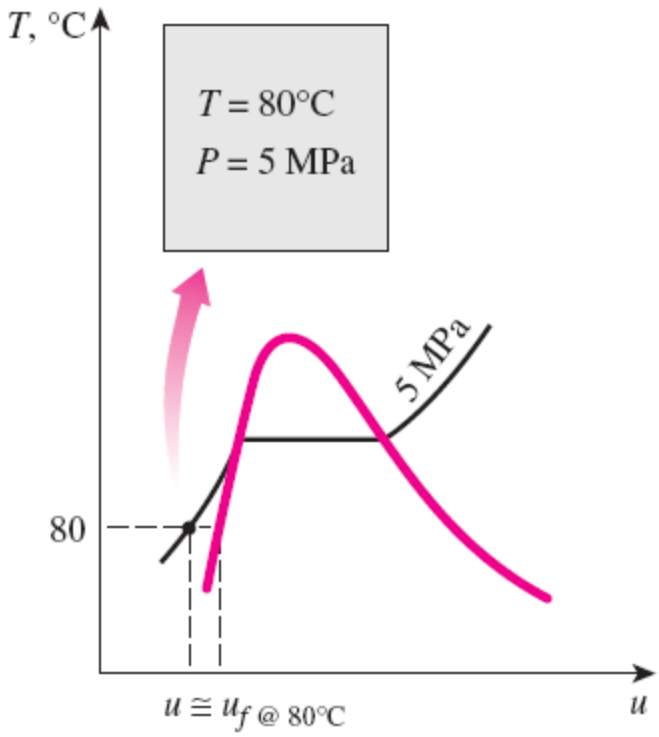
Higher pressures ($P > P_{\text{sat}}$ at a given $T$)

Lower tempreatures ($T < T_{\text{sat}}$ at a given $P$)

Lower specific volumes ($v < v_f$ at a given $P$ or $T$)

Lower internal energies ($u < u_f$ at a given $P$ or $T$)

Lower enthalpies ($h < h_f$ at a given $P$ or $T$)



1. Compressed liquid:

In general, a compressed liquid is characterized by:

| Given | Properties Comparison | Tables |
|---|---|---|
| T, P | $P > P_{sat.}$ or $T_{given} < T_{sat.}$ | From saturated Table or compressed Table. |
| T, or P, and *v* | $v_{given} < v_f$ | From saturated Table or compressed Table. |
| T, or P, and u | $u_{given} < u_f$ | From saturated Table or compressed Table. |
| T, or P, and s | $s_{given} < s_f$ | From saturated Table or compressed Table. |
| T, or P, and h | $h_{given} < h_f$ | From saturated Table or compressed Table. |

2. Superheated vapor:

*In general, a superheated is characterized by:*

| Given | Properties Comparison | Tables |
|---|---|---|
| T, P | $P < P_{sat.}$ or $T_{given} > T_{sat.}$ | From superheated Table. |
| T, or P, and *v* | $v_{given} > v_g$ | From superheated Table. |
| T, or P, and u | $u_{given} > u_g$ | From superheated Table. |
| T, or P, and s | $s_{given} > s_g$ | From superheated Table. |
| T, or P, and h | $h_{given} > h_g$ | From superheated Table. |

3. Saturated liquid (x=0 , $v = v_f$, $u = u_f$, $h = h_f$, and $s = s_f$ at a given saturated temperature or pressure)
4. Saturated vapor (x=1 , $v = v_g$, $u = u_g$, $h = h_g$, and $s = s_g$ at a given saturated temperature or pressure).
5. Saturated liquid-vapor mixture ($0 < x < 1$) all the properties are between saturated liquid properties and saturated vapor properties: $v_f < v_{given} < v_g, u_f < u_{gievn} < u_g, h_f < h_{given} < h_g, and\ s_f < s_{given} > s_g$.

# Applied Thermodynamics: An Engineering Approach

Seventh Edition in SI Units

Yunus A. Cengel, Michael A. Boles

McGraw-Hill, 2011

# Modules 4,5,6: Gas Power cycles

# (Otto Cycle, Diesel Cycle, and Brayton Cycle)

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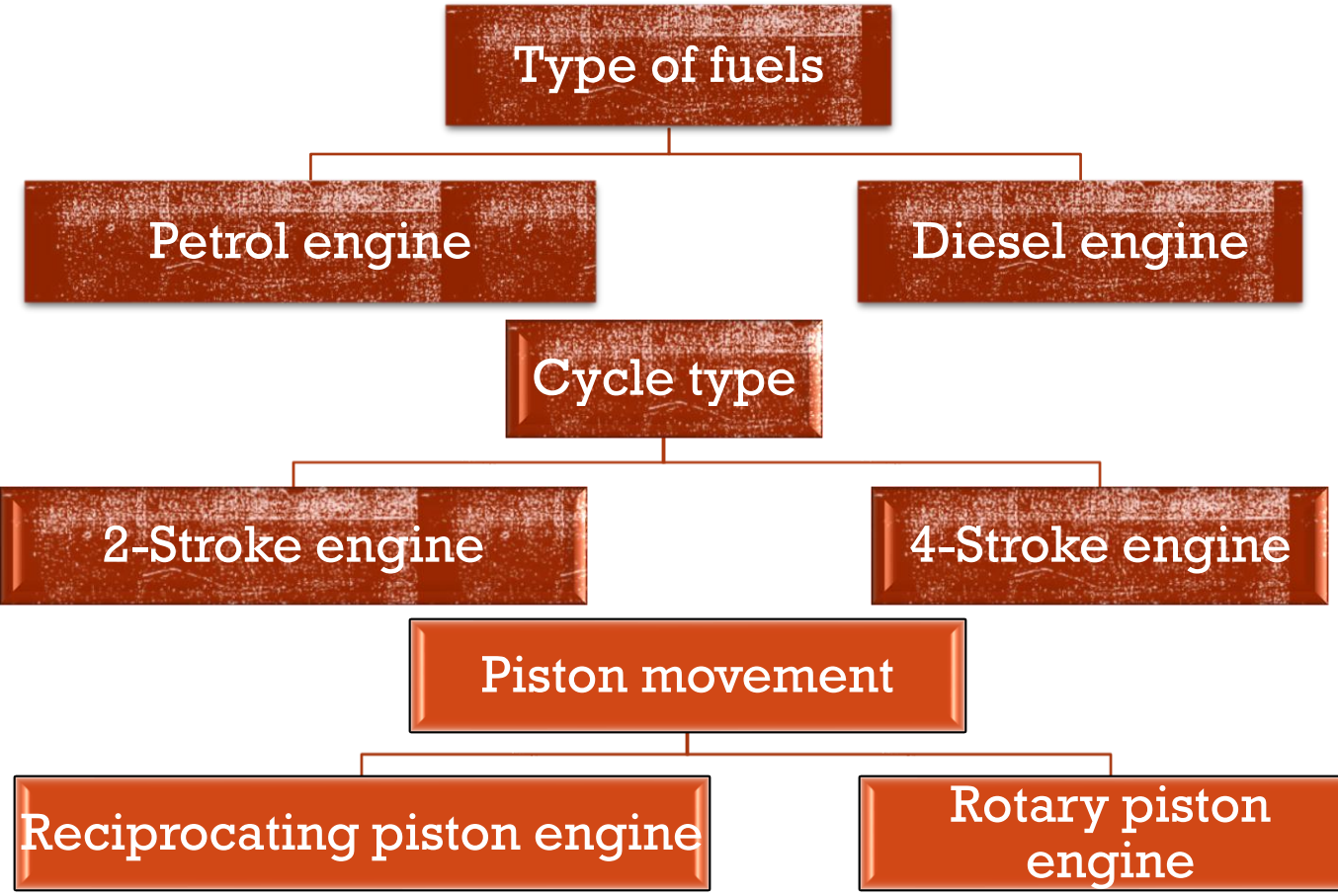
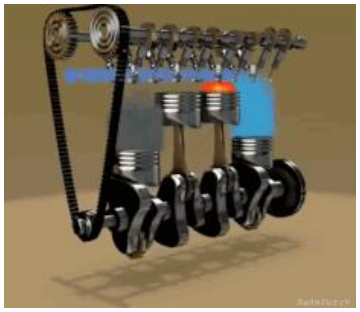
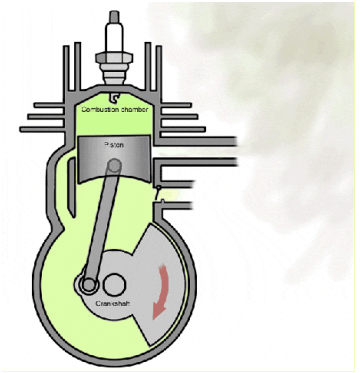
# INTERNAL COMBUSTION ENGINES

- **Internal combustion engines (ICE)** are a type of heat engine where the combustion of fuel occurs with an oxidizer (usually air) in a combustion chamber that is an integral part of the working fluid flow circuit, such as automobiles, ships, tractors, power generation and many more applications.

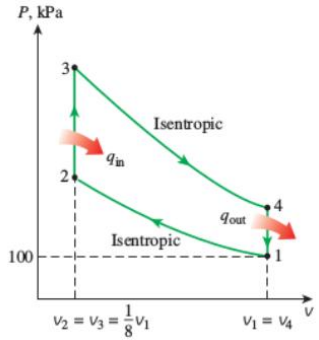


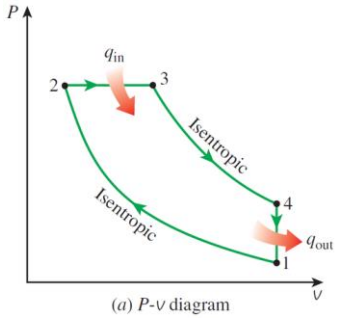





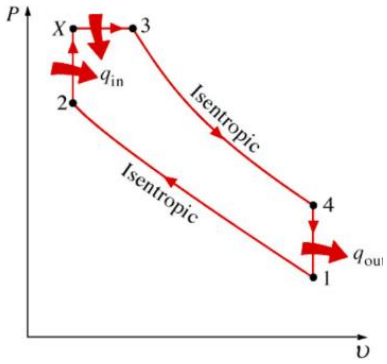
# POWER CYCLE CLASSIFICATION

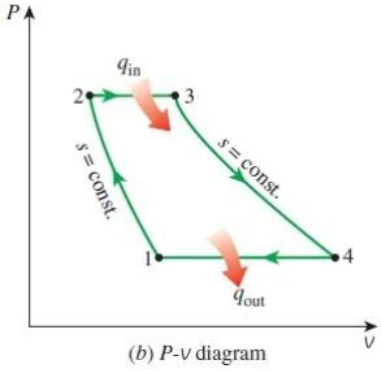
- Gas Power Cycle
  - Otto Cycle
  - Diesel Cycle
  - Dual Cycle
  - Brayton Cycle



(a) P-v diagram

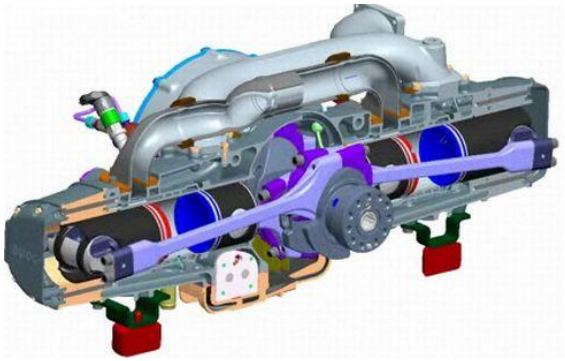


(b) P-v diagram

- Cooling method
  - Air cooled engine
  - Water cooled engine
- Ignition method
  - Spark ignition
  - Compression ignition

# CLASSIFICATION OF INTERNAL COMBUSTION ENGINES





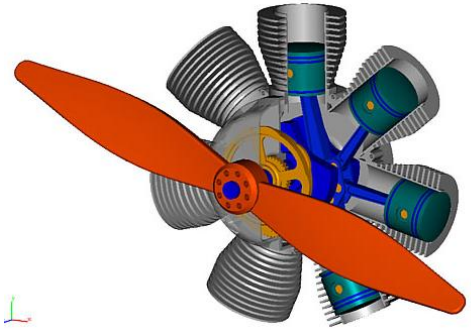
**Cylinders arrangement**

- Radial engine
- Opposed piston engine
- Opposed cylinder engine
- V-Engine
- Vertical engine
- Horizontal engine

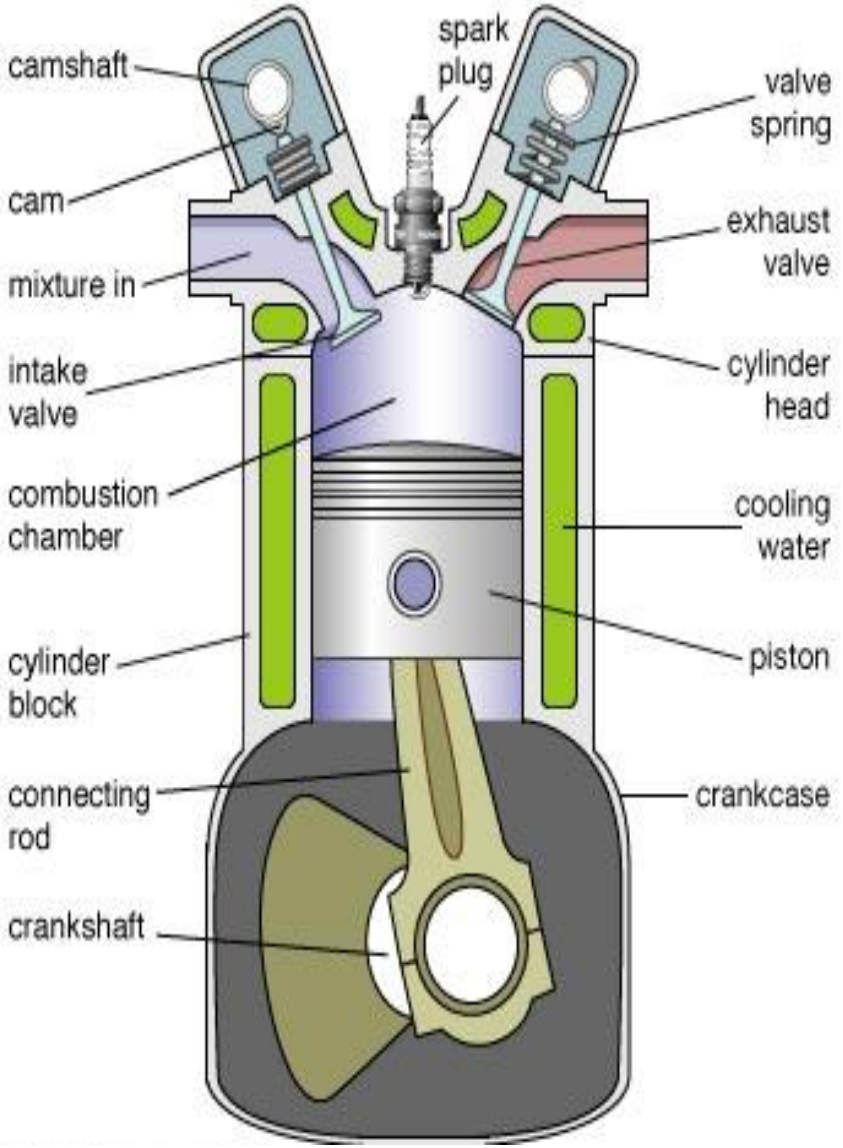


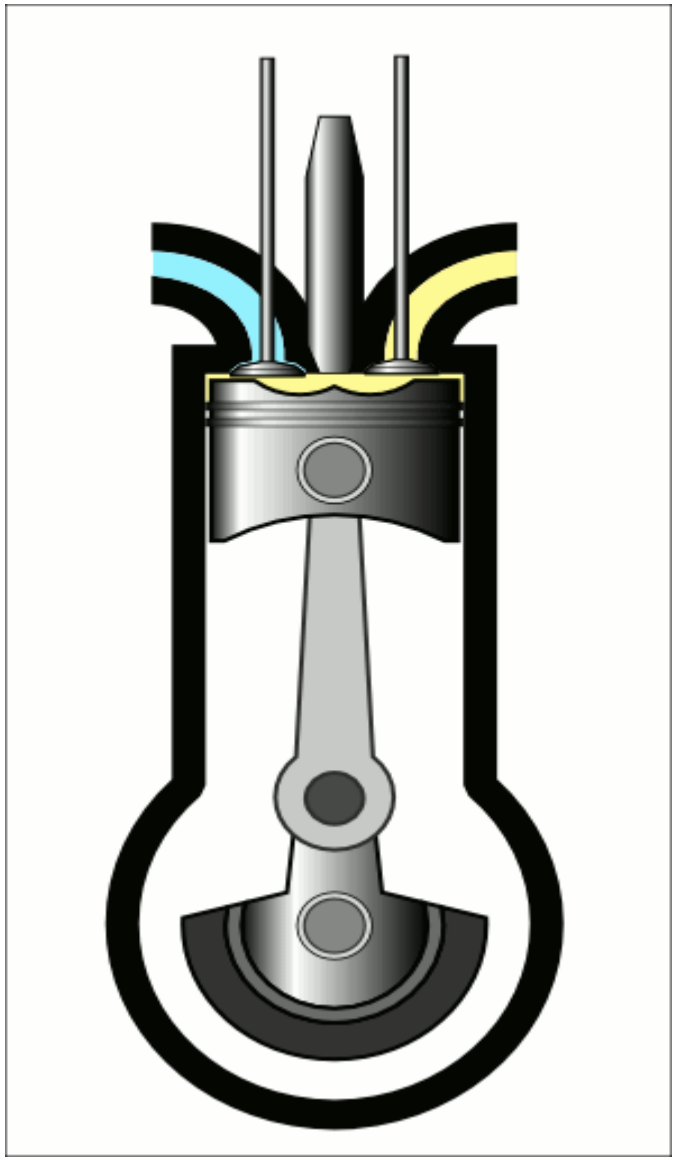






# RECIPROCATING ENGINE DETAILS

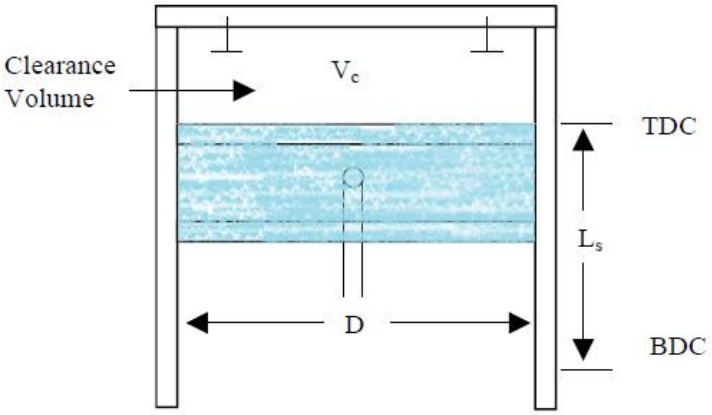


# ENGINE NOMENCLATURE

- **Stroke ($L_s$):**
  - The distance between two the dead centers (TDC and BDC) of the engine.
  - Distance travelled by the piston
- **Displacement volume / Swept Volume / Stroke Volume ($V_s$):**

  It is the volume results from the piston motion through the stroke.




$$V_s = \frac{\pi D^2}{4} \times L_s$$

- **Clearance volume ($V_c$):** The volume between TDC and the cylinder head.
- **Cylinder volume (V):** It is the sum of the piston displacement volume and clearance volume. $V = V_s + V_c$
- **Compression ratio (R):** The ratio between the cylinder volume $V_s$ and clearance volume $V_c$. $CR = V / V_c$
- Size of Engine = no. of cylinder x total volume of cylinder

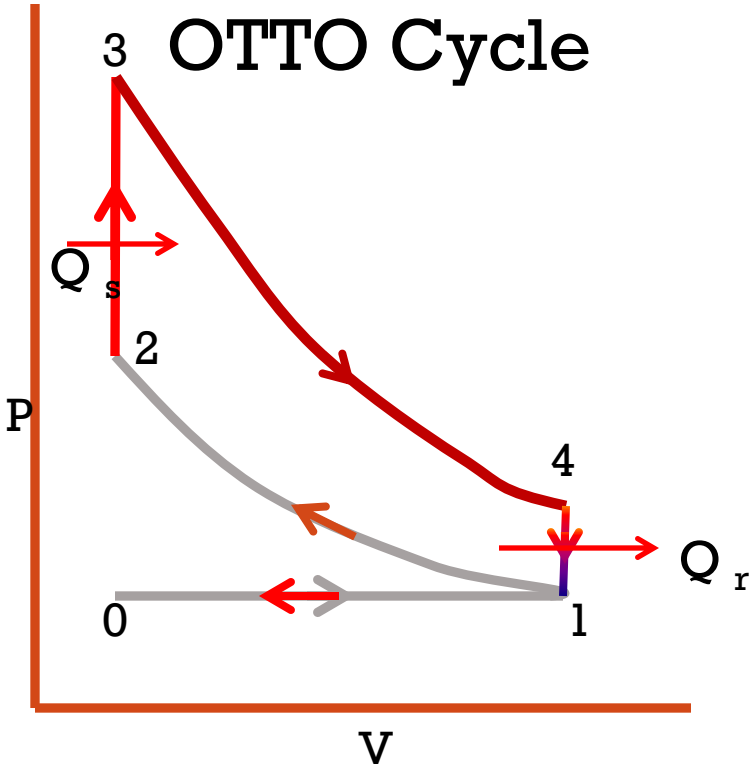
# FOUR STROKE ENGINES

- The following is a comparison between petrol and diesel engines

| Point of comparison | Petrol engine | Diesel engine |
|---|---|---|
| **Intake charge** | Air / petrol mixture | Air only |
| **Combustion achieved** | Using spark plug | Using diesel fuel injector |
| **Rotation speed** | Much faster than diesel | Lower than petrol engine |
| **Distance per gallon** | Lower than diesel engine | 30% more than petrol engine |
| **Engine price** | Lower than diesel engine | Higher than petrol engine |
| **Noise wise** | Quite | More noisy |
| **Service required** | Less service required | More service required |
| **Service cost** | Cheaper to service | More costly to service |
| **Electric / fuel system** | More complex electric system | More complex fuel system |
| **Fuel quality sensitivity** | More sensitive to fuel quality | Less sensitive to fuel quality |

# PETROL ENGINE CYCLE (OTTO CYCLE)

| Stroke # | Stroke name | Operation | Valves position | |
|---|---|---|---|---|
| | | | Intake | Exhaust |
| 1 | Intake stroke | Air / petrol mixture is admitted through the inlet valve into engine cylinder. | Open | Close |
| 2 | Compression stroke | The mixture is compressed. Before the end of stroke a spark plug creates spark to ignite the mixture. | Close | Close |
| 3 | Power stroke | The ignited mixture at high temperature and pressure drives the piston downwards. | Close | Close |
| 4 | Exhaust stroke | The combustion product (Exhaust) is removed from the engine cylinder. | Close | Open |




Process 0 – 1: Suction Stroke

Process 1 – 2: Compression Stroke
Isentropic Compression Process

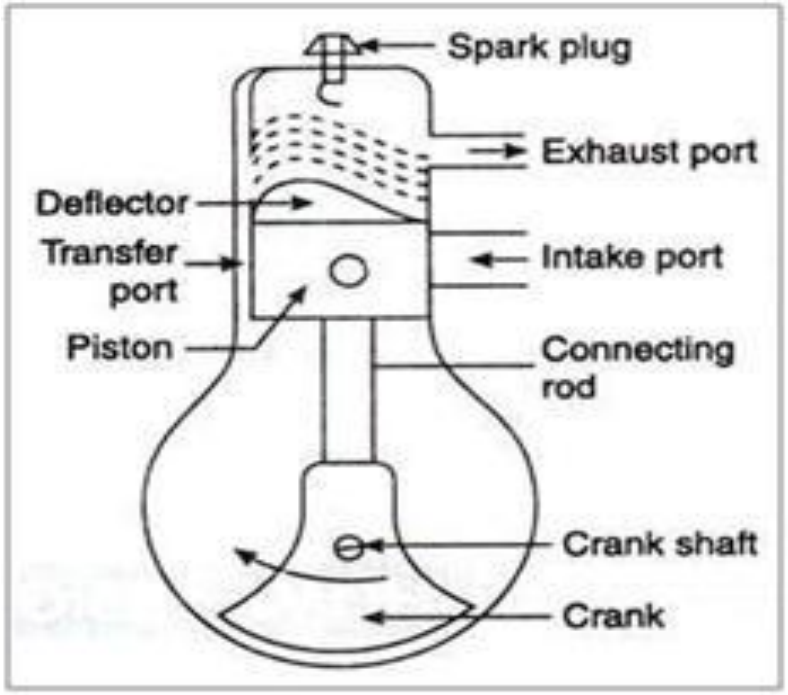
Process 2 – 3: Constant volume heat addition Process

Process 3 – 4: Power Stroke
Isentropic Expansion Process

Process 4 – 1: Constant volume heat rejection Process

Process 1 – 0: Exhaust Stroke

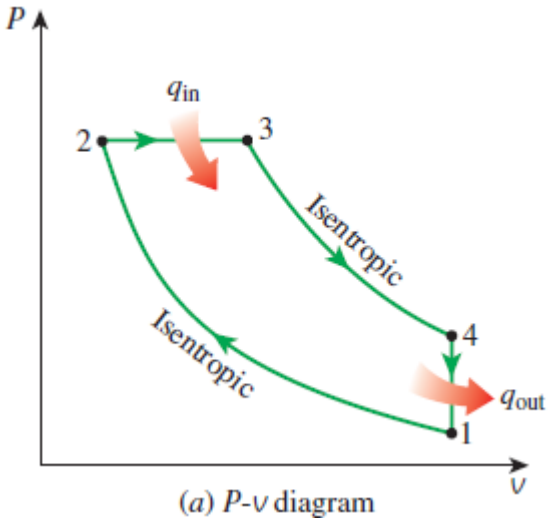
# 2-Stroke Petrol Engine



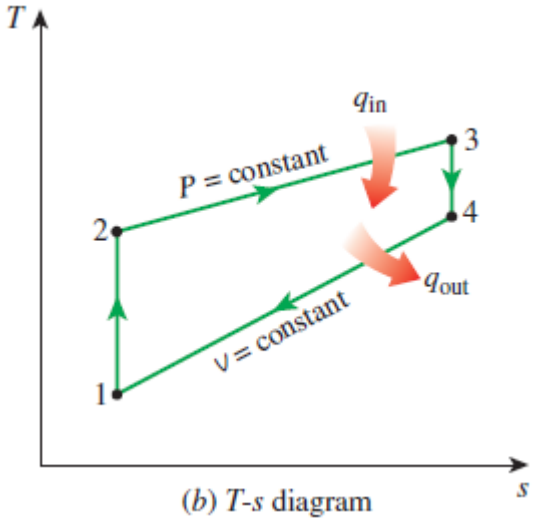
# DIESEL ENGINE CYCLE

| Stroke # | Stroke name | Operation | Valves position | |
|---|---|---|---|---|
| | | | Intake | Exhaust |
| 1 | Intake stroke | Air is admitted through inlet valve into engine cylinder. | Open | Close |
| 2 | Compression stroke | Air is compressed. Before the end of compression stroke fuel is injected into the combustion chamber to be ignited by means of high temp. | Close | Close |
| 3 | Power stroke | The ignited mixture at high temperature and pressure drives the piston downwards. | Close | Close |
| 4 | Exhaust stroke | The combustion product (Exhaust) is removed from the engine cylinder. | Close | Open |

# Diesel Cycle



(a) P-v diagram



(b) T-s diagram

Process 0 – 1: Suction Stroke

Process 1 – 2: Compression Stroke
Isentropic Compression Process

Process 2 – 3: Constant Pressure heat addition Process

Process 3 – 4: Power Stroke
Isentropic Expansion Process

Process 4 – 1: Constant volume heat rejection Process

Process 1 – 0: Exhaust Stroke

# The Ideal Diesel Cycle

Process 1-2 ( Isentropic Compression of an ideal gas )

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} \qquad \frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\gamma} \qquad P_1 V_1 = mRT_1$$

Process 2-3( Constant pressure heat addition of an ideal gas)

$$P_3 = P_2$$

$$\frac{P_2 V_2}{T_2} = \frac{P_3 V_3}{T_3} \qquad Q_{in} = m\,(h_3 - h_2) = m\,C_p\,(T_3 - T_2)$$

Process 3-4 ( Isentropic Expansion of an ideal gas )

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{\gamma-1} \qquad \frac{P_4}{P_3} = \left(\frac{V_3}{V_4}\right)^{\gamma}$$

Process 4-1( Constant Volume heat rejection of an ideal gas)

$$Q_{out} = m\,C_v\,(T_4 - T_1)$$

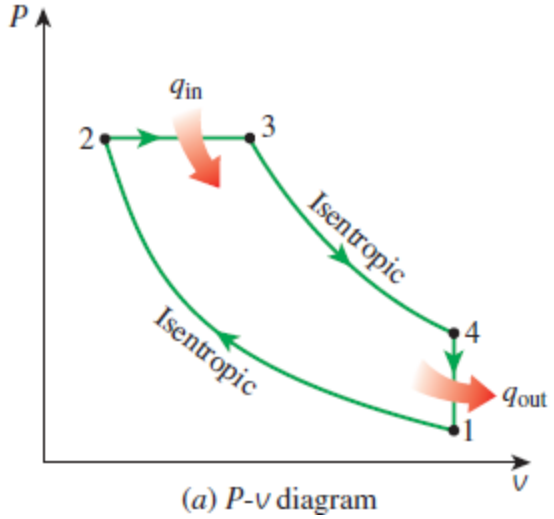
$$W_{net} = Q_{in} - Q_{out}$$

$$\eta = \frac{W_{net}}{Q_{in}}$$

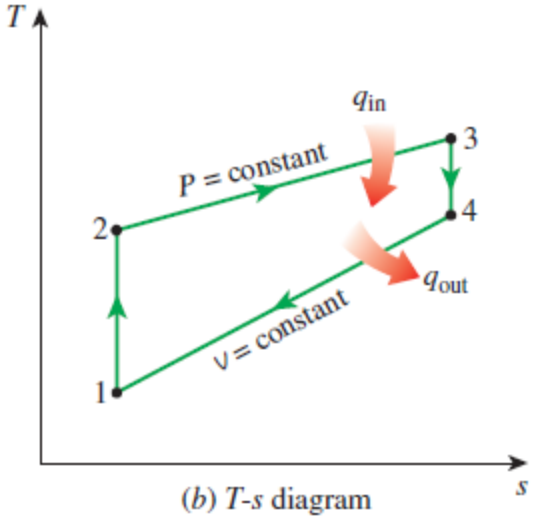
$$MEP = \frac{W_{net}}{V_{max} - V_{min}} = \frac{W_{net}}{V_1 - V_2}$$

R = °F + 459.67

$$\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^{\gamma} = \left(\frac{T_1}{T_2}\right)^{\frac{\gamma}{\gamma-1}}$$



(a) P-v diagram



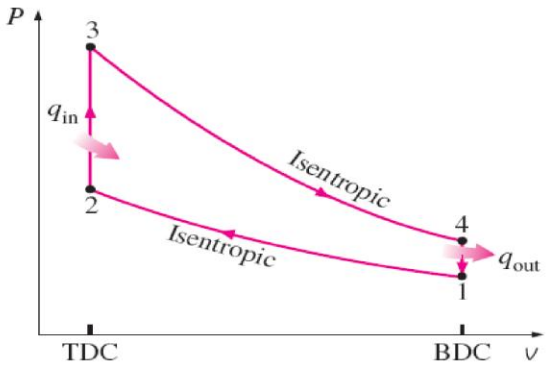
(b) T-s diagram

# Example : Ideal Otto CYCLE

**Example :** Otto cycle with compression ratio of 9.5. The air is at 100 kPa, 17 °C, and 600 cm³ prior to the compression stroke. Temperature at the end of isentropic expansion is 800 K.

Find: a) Highest temperature and pressure in the cycle, b) amount of heat transferred, c) thermal efficiency, and d) mean effective pressure. Use constant specific heat.

Properties of air at room temperature: cp = 1.005 kJ/kgK, cv = 0.718 kJ/kgK, $\gamma$ = 1.4, R = 0.287 kJ/kgK




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

$$a) \quad m = \frac{P_1 \times V_1}{T_1 \times R} = \frac{(100 \times 600 \times 10^{-6})}{290 \times .287} = 7.209 \times 10^{-4} \text{ Kg}$$

$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma-1} \qquad T_3 = (9.5)^{1.4-1} \times 800 = 1968.7\ K$$

$$V_4 = V_1 = V_{max}$$

$$V_3 = V_2 = V_{min}$$

$$V_{min} = V_3 = \frac{600}{9.5} = 63.16\ cm^3$$

$$r = \frac{V_{max}}{V_{min}}$$

$$P_3 = \frac{mRT_3}{V_3} = \frac{(7.209 \times 10^{-4} \times 0.287 \times 1968.7)}{63.16 \times 10^{-6}} = 6449\ Kpa$$

# Example : Ideal Otto CYCLE (contd)

b) The heat transfer occurs between states 2 and 3. Using the First Law

$$Q_{in} = m\, C_V (T_3 - T_2)$$

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} \qquad T_2 = (9.5\ )^{1.4-1} \times 290 = 713.65\ K$$

$$Q_{in} = 7.209 \times 10^{-4} \times 0.718\ (1968.7 - 713.65) = 0.650\ kJ$$

c) Thermal efficiency for an Otto cycle is given by

$$\eta_{th} = 1 - \frac{1}{r^{\gamma-1}} = 1 - \frac{1}{9.5^{1.4-1}} = 0.594\ (59.4\%)$$

d) The mean effective pressure is defined as

$$W_{net} = \eta_{th} Q_{th} = 0.65 \times 0.594 = 0.3856\ kJ$$

$$MEP = \frac{0.3856}{(600 - 63.16) \times 10^{-6}} = 718.3\ Kpa$$

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

# Engine Testing

There are two types of tests performed:

1. Commercial tests.
2. Thermodynamics tests.

## Commercial tests.

**The majority of tests on internal combustion engines are carried out for commercial purposes in order to check the following:**

To determine rated power output w.r.t the fuel consumption in kg/B.P. hr.
To determine the quantity of lubricating oil required per B.P. hour.
To determine the quantity of cooling water required per B.P. hour.
To check the steadiness of the engine under different loads.
To determine the overload carrying capacity of the engine.

## Thermodynamics tests.

**This test is carried out to comparing actual results with the theoretical of ideal performance.**

1. Indicated power
2. Brake power
3. Rate of fuel consumption
4. Calorific value of fuel
5. Heat carried away by the exhaust gases
6. Engine room temperature and pressure
7. Thermal efficiency
8. Volumetric efficiency

## Indicated power:

Power developed inside the cylinder of engine, denoted by IP and is given by

$$IP = \frac{P_m LANn}{60} \quad \forall \quad P_m = \text{Mean effective pressure, N/m}^2,$$

$L = \text{Length of the stroke, m}, \quad A = \text{Area of the piston, m}^2,$

$N = \text{RPM (It is N/2 for four stroke engine)}, \quad n = \text{Number of cylinders.}$

## Brake power:

The power developed by an engine and measured at the output shaft is called the brake power (BP) and is given by,

$$BP = \frac{2\pi NT}{60} \quad \forall \quad T = \text{Torque in } N\text{-}m$$

## Specific fuel consumption:

## Brake Specific fuel consumption:

It is defined as the amount of fuel consumed for each unit of brake power per hour it indicates the efficiency with which the engine develops the power from fuel. it is used to compare performance of different engines.

$$BSFC = \frac{m_f}{BP} \quad \text{in} \quad {}^{\text{kg}}/_{\text{W.s}} \quad \forall \quad m_f \text{ is fuel mass flow rate in } {}^{\text{kg}}/_{\text{s}} \text{ and } BP \text{ in Watts}$$

$$BSFC = \frac{m_f \times 3600 \times 10^3}{BP} \text{ similarly } ISFC = \frac{m_f \times 3600 \times 10^3}{IP} \quad \text{in} \quad {}^{\text{kg}}/_{\text{KW - hr}}$$

**Heat Supplied or Fuel Energy to Engine (HS):** $HS = m_f \times \mathrm{CV}$ in Watts

**Frictional Power (F.P.):** There is a loss of power between the cylinder and the crankshaft due to friction between the moving parts. $FP = IP - BP$ in Watts

**Heat carried away by Cooling Water:** $Q_w = m_w \mathrm{C_p}\left(\mathrm{T_o} - T_i\right)$

$\forall$ $m_\mathrm{w}$ = mass flow rate of cooling water, $T_o$ = outlet temperature of water

$T_i$ = inlet temperature of water, $C_p$ = specific heat of water

**Heat carried away by Exhaust Gases:** $Q_{Exhaust} = m_g \mathrm{C_{p\,(gas)}}\left(\mathrm{T_o} - T_i\right)$

$\forall$ $m_\mathrm{g}$ = mass flow rate of exhaust gas, $T_o$ = Exit temperature of exhaust gas,

$T_i$ = Engine room temperature, $C_p$ = specific heat of exhaust gas,

**Mechanical Efficiency ($\eta_{mech}$):** $\eta_{mech} = BP/IP$

**Indicated Thermal Efficiency ($\eta_{th,\,indicated}$):** $\eta_{th,indicated} = IP/HS$

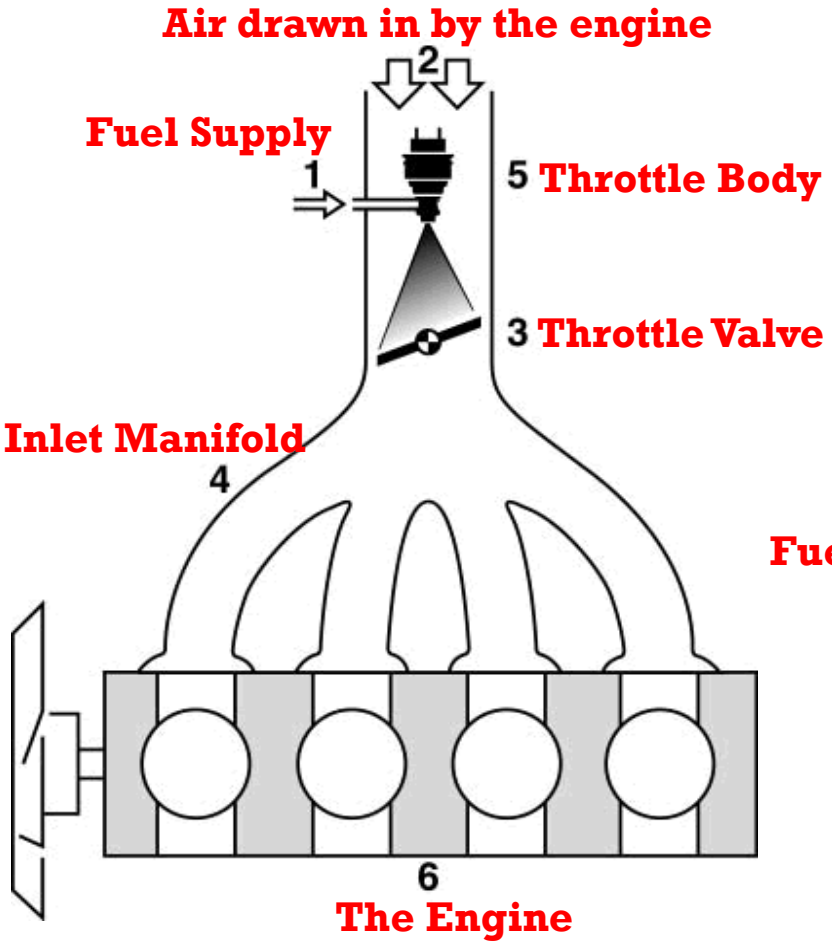
**Brake Thermal Efficiency ($\eta_{th,\,indicated}$):** $\eta_{th,brake} = BP/HS$

$\eta_{th,brake} = \eta_{th,indicated} \times \eta_{\mathrm{mech}}$

**Volumetric efficiency ($\eta_{vol.}$):**

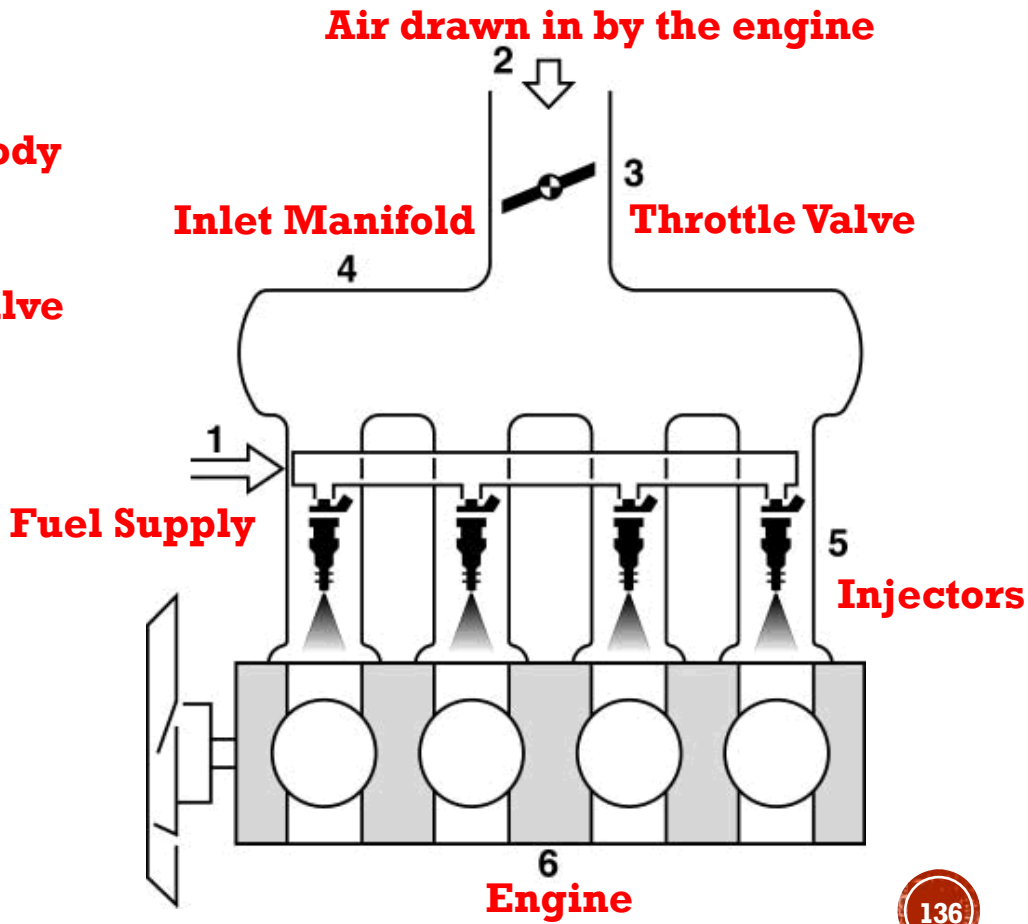
# FUEL SYSTEM

- **Petrol engine (spark ignition engine)**
  - Single point fuel injection.




**Single point fuel injection**

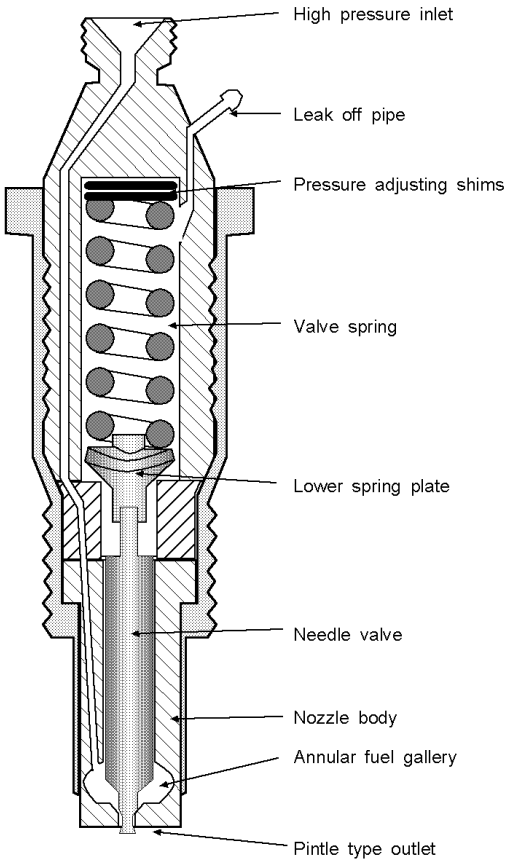
- Multipoint fuel injection.



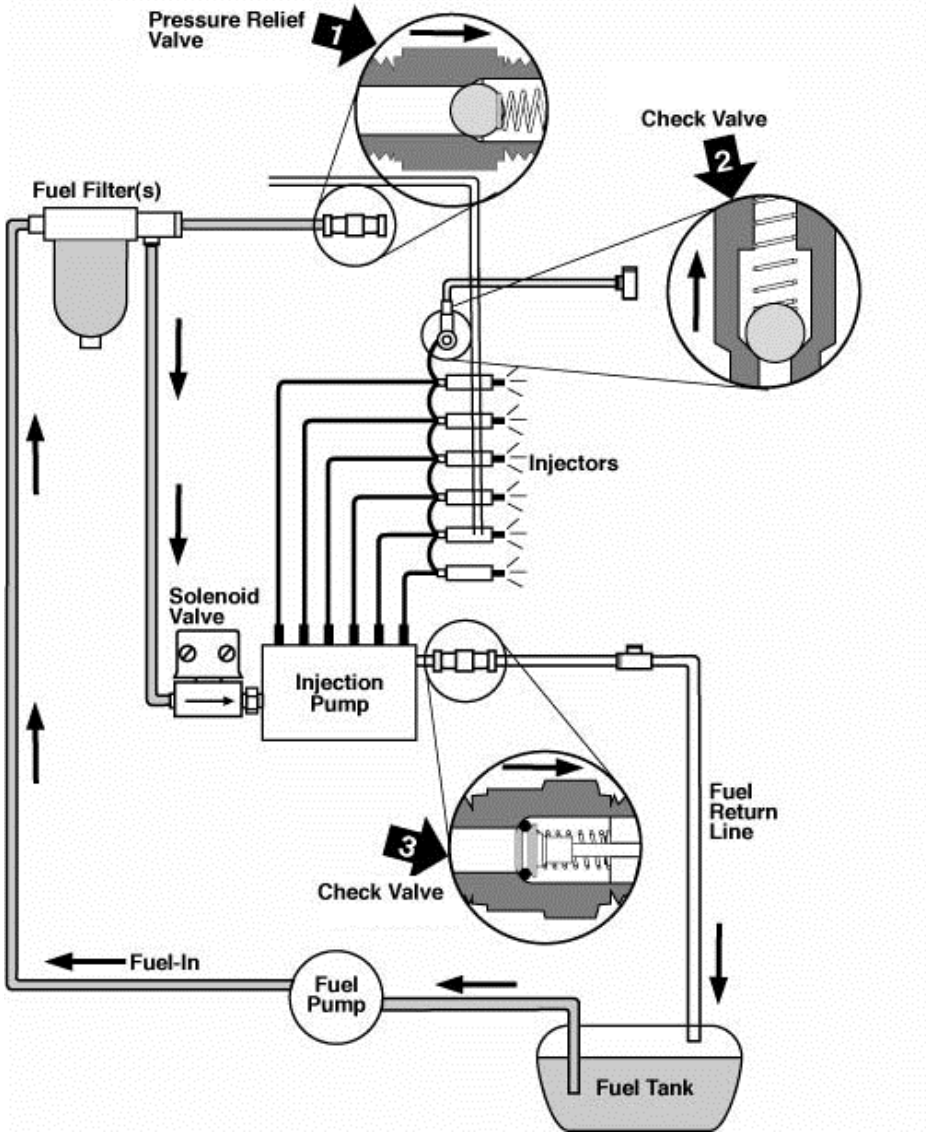

**Multipoint fuel injection**

# FUEL SYSTEM

- The following presents the fuel injection system in diesel (compression ignition) engine




Diesel fuel injector



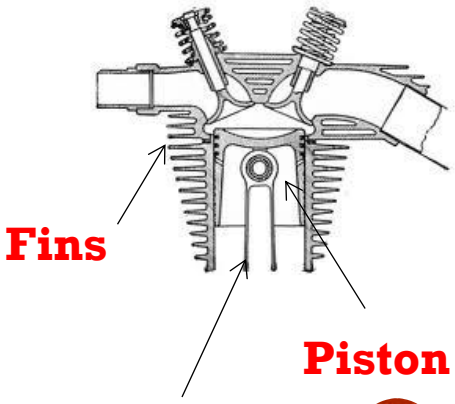
# ENGINE COOLING SYSTEMS

- **Air cooling system:** It is a direct method of cooling. In air cooled engine fins are case on the cylinder head and cylinder case to increase its exposed surface of contact with air. Air passes over fins and carries away heat with it. Air foe cooling the fins may be obtained from blower or fan driven by the engine.

- **Water cooling system:** It is indirect method of engine cooling. Water after circulating the water jackets (passes around the cylinder, combustion chamber, valves, etc.) goes through the air radiator to waste the heat to the surrounding.

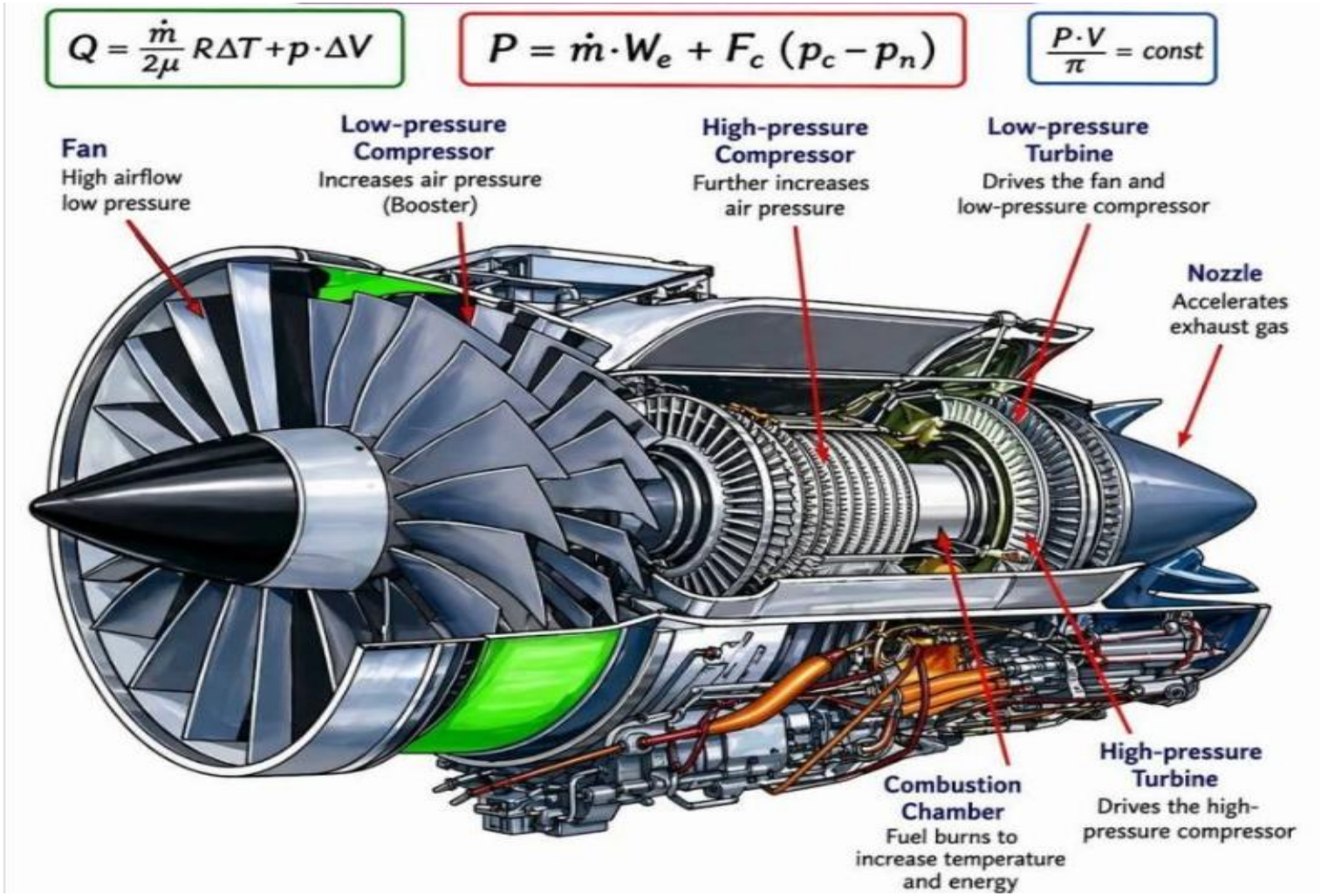






# Brayton Gas Cycle (Gas Turbine)

**Gas Turbines** are one of the most efficient equipment for converting fuel energy to mechanical energy and the gas turbines are used to drive electric generators, process gas compressors, crude oil pipeline pumps and water injection pumps.



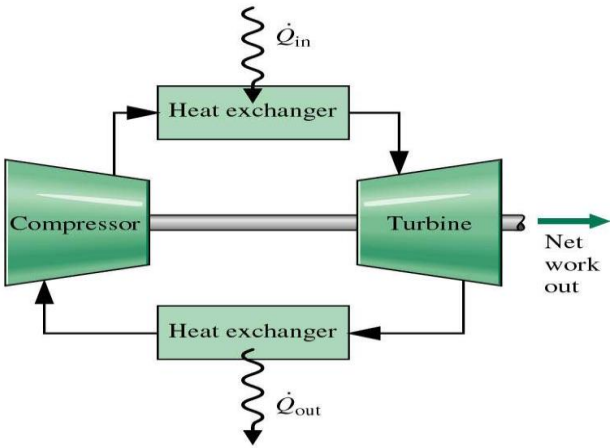
# Gas Turbine Classifications

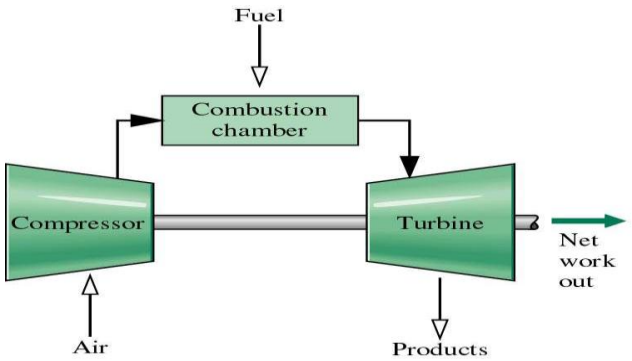
**According to process of heat absorption**

- Constant pressure gas turbines
  Joules or Brayton Cycle
- Constant volume gas turbines.
  **Atkinson Cycle**

**According to the path of the working substance**

- Closed cycle gas turbine
- Semi-closed cycle gas turbine
- Open cycle gas turbine



# Advantages And Disadvantages Of Closed Cycle Over Open Cycle

## Advantages

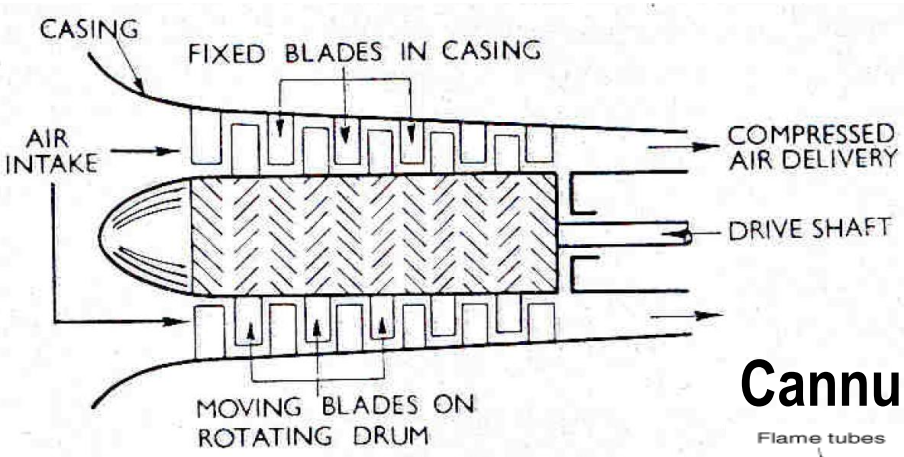
- Small size unites due to applying high pressure fluid flow.
- A wide range of load can be accommodated without change the maximum temperature.
- Closed cycle avoid corrosion of turbine blades due to the contaminated gases as the indirect heating.
- Solid fuel can be applied as the indirect heating is applied.
- Closed cycle is more reliable an has low maintenance cost.

## Disadvantages

- The unit weight per kW is higher than the open cycle.
- A very large air heater compared by the combustion chamber size.
- A large size cooler and hence a large amount of cooling water is required.

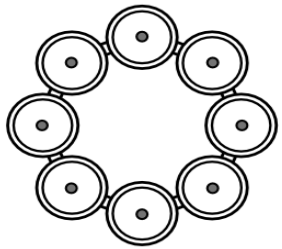
# Gas Turbine Components

- **Air compressor**: The commonly applied type is the axial air compressor which consists of a group of a fixed blades which are fixed in the outer casing and a group of moving blades that are fixed to the central drum. The function of the moving blades is to progress the air through the compressor. The function of the fixed blades is to direct the air stream and act as a diffuser.

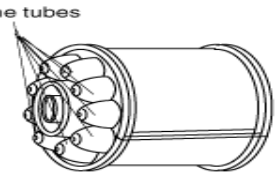


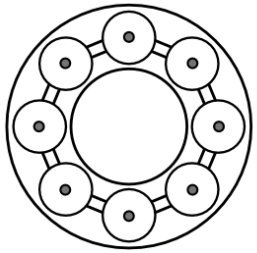

## Can combustor:

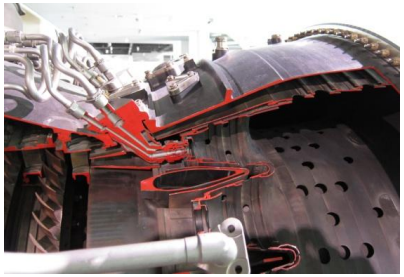


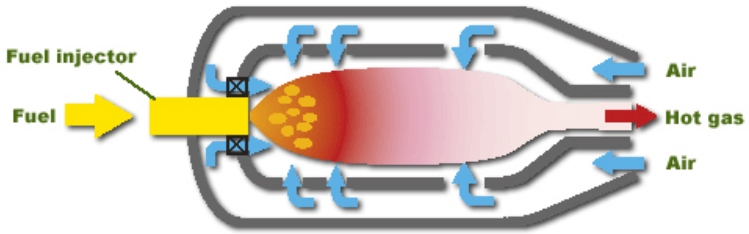


## Cannular (can annular) combustor:





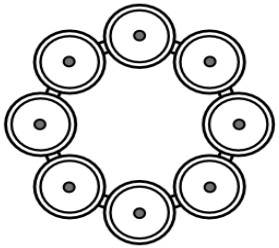


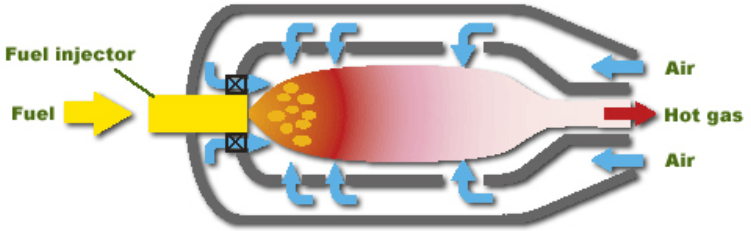

## Annular combustor:

# Gas Turbine Components

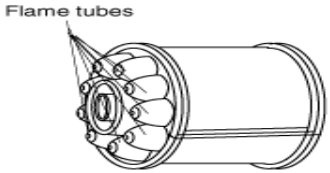
- **Combustion chamber (combustor):**
  - Can combustor:

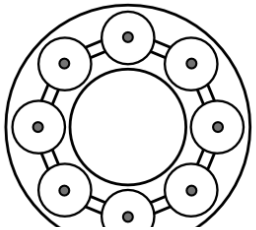


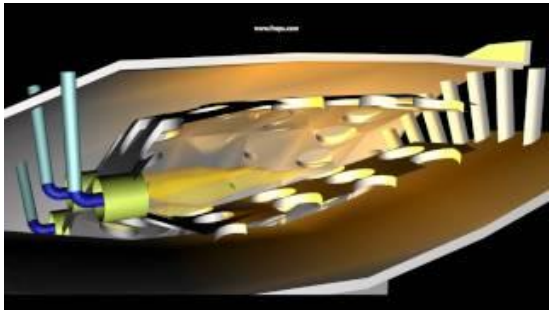


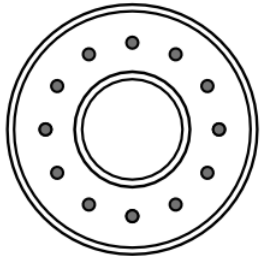


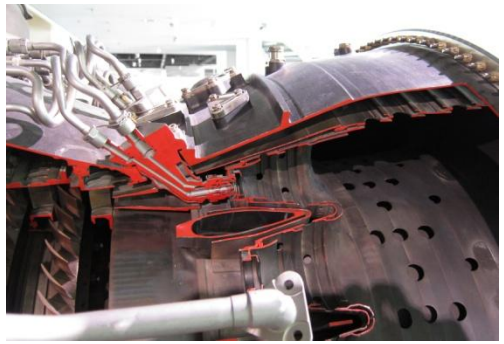

  - Cannular (can annular) combustor:





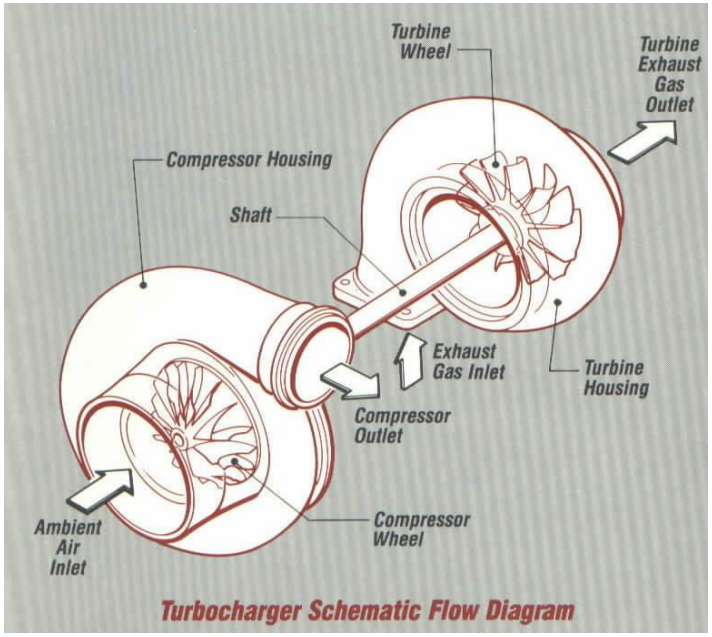


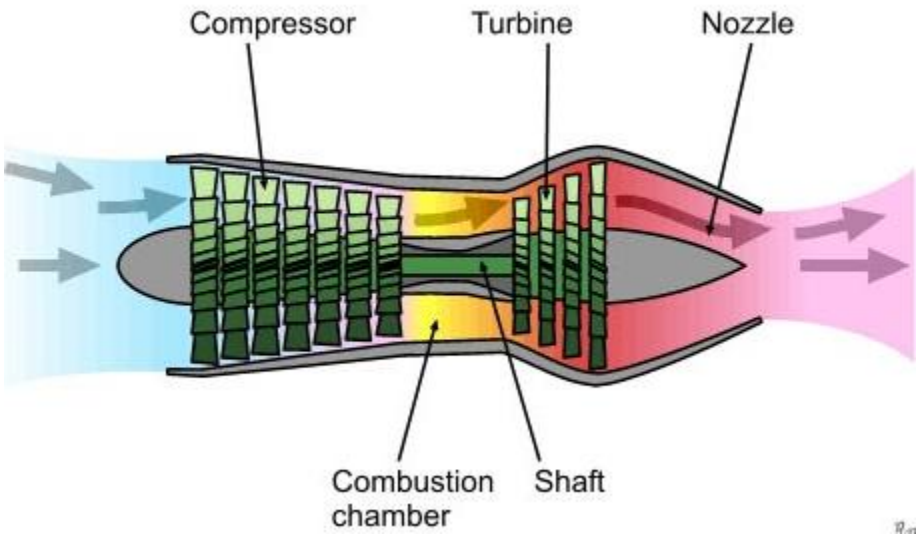


# Gas Turbine Components

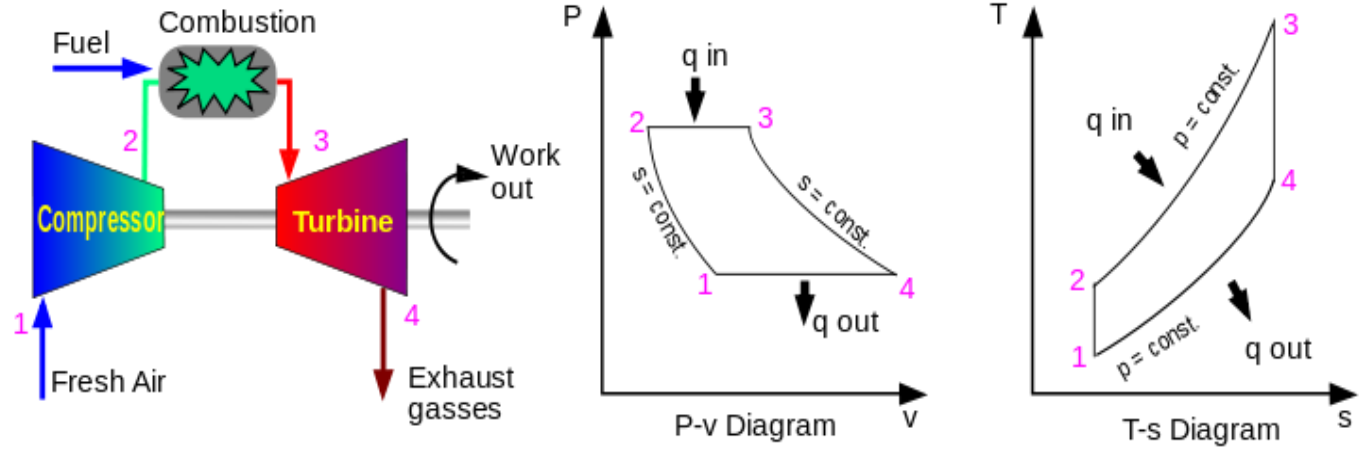
**Turbine**

- Radial flow turbine
- Axial flow turbine



# Analysis of Constant Pressure Closed Cycle GT




Process 1 - 2 Adiabatic compression. $PV^{\gamma} = C$ *or* $S = C$

Process 2 - 3 Isobaric heat addition. $P = C$

Process 3 - 4 Adiabatic/Isentropic expansion. $PV^{\gamma} = C$ *or* $S = C$

Process 4 - 1 Asobaric heat rejection. $P = C$

Work required for compressor $(W_C) = C_p\,(T_2 - T_1)$ kJ/kg of fluid

Work developed by the turbine $(W_T) = C_p\,(T_3 - T_4)$

Network available $(W_{net}) = (W_T - W_C) = C_p\,(T_3 - T_4) - Cp\,(T_2 - T_1)$

Heat supplied per kg. of fluid during the cycle $Q_s = h_3 - h_2 = C_p\,(T_3 - T_2) = m_f \times C.V.$

Thermodynamic efficiency of the cycle is given by

$$\eta_{th} = \frac{W_{net}}{Q_s} = \frac{C_p\,(T_3 - T_4) - Cp\,(T_2 - T_1)}{C_p\,(T_3 - T_2)} = \frac{(T_3 - T_4) - (T_2 - T_1)}{(T_3 - T_2)}$$

$$\eta_{th} = \frac{(T_3 - T_2) - (T_4 - T_1)}{(T_3 - T_2)} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

but for isentropic process $P_1V_1^{\gamma} = P_2V_2^{\gamma}$ *and* $P_3V_3^{\gamma} = P_4V_4^{\gamma}$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \text{ and } \frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}} \text{ but } \frac{P_2}{P_1} = \frac{P_3}{P_4} = R_p = \text{Pressure Ratio}$$

$$\frac{T_2}{T_1} = \left(R_p\right)^{\frac{\gamma-1}{\gamma}} \text{ and } \frac{T_3}{T_4} = \left(R_p\right)^{\frac{\gamma-1}{\gamma}} \text{ so } T_2 = T_1\left(R_p\right)^{\frac{\gamma-1}{\gamma}} \text{ and } T_4 = \frac{T_3}{\left(R_p\right)^{\frac{\gamma-1}{\gamma}}}$$

$$\eta_{th} = 1 - \frac{1}{\left(R_p\right)^{\frac{\gamma-1}{\gamma}}} \text{ (range 40\% to 65\%)}$$

# Simple Brayton Cycle

**Problem 1** - Air enters the compressor at 1 bar, 25°C in a gas turbine Unit. The pressure leaving the compressor is 10 bar, and the maximum temperature in the cycle is 1100°C. Determine:

- The pressure and temperature at each point in the cycle
- The compressor pressure ratio
- The compressor work, turbine work, and cycle efficiency. ($C_p$ for air = 1.0052 kJ/kg.K)

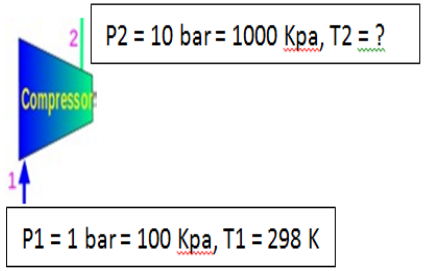
Process 1 - 2 Adiabatic compression. $PV^{\gamma} = C \quad or \quad S = C$

Process 2 - 3 Isobaric heat addition. $P = C$

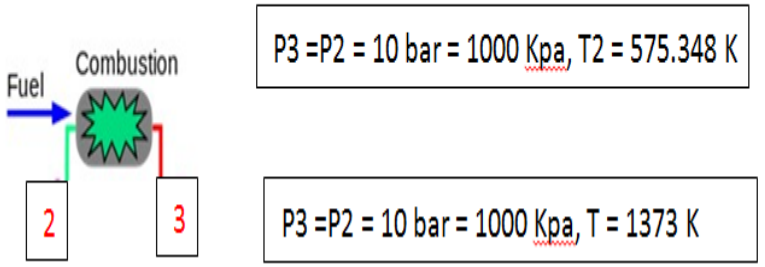
Process 3 - 4 Adiabatic/Isentropic expansion. $PV^{\gamma} = C \quad or \quad S = C$

Process 4 - 1 Asobaric heat rejection. $P = C$

Find the inlet & outlet pressure and temperature for the compressor ( P1,T1,P2,T2 )



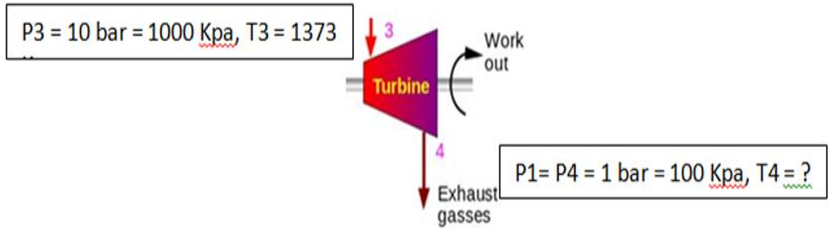

Find the inlet & outlet pressure and temperature for the Combution (P2,T2, P3,T3 )




$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \rightarrow T_2 = \left(\frac{1000}{100}\right)^{\frac{0.4}{1.4}} \times 298 = 575.348\ K$$

# Simple Brayton Cycle

Find the inlet & outlet pressure and temperature for the Turbine ( P3,T3,P4,T4 )




$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}} \rightarrow \frac{1373}{T_4} = \left(\frac{1000}{100}\right)^{\frac{0.4}{1.4}} =$$

$$T_4 = \frac{1373}{1.930697} = 711.142\ K = 438.142\ C$$

- The compressor ratio $= \frac{P_2}{P_1} = \frac{1000}{100} = 10$
- Compressor Work :

$$Wc = C_P \times (T_2 - T_1) = 1.005 \times (575.348 - 298) = 278.735\ kJ/kg$$

- Turbine Work :

$$Wt = C_P \times (T_3 - T_4) = 1.005 \times (1373 - 711.142) = 665.1673\ kJ/kg$$

- Heat Supply ( heat added to the system )

$$Qs = C_P \times (T_3 - T_2) = 1.005 \times (1373 - 575.348) = 801.64026\ kJ/kg$$

- The cycle Efficiency :

$$\eta = \frac{W_t - W_c}{Q_s} = \frac{665.1673 - 278.735}{801.64026} = 48.21\ \%$$

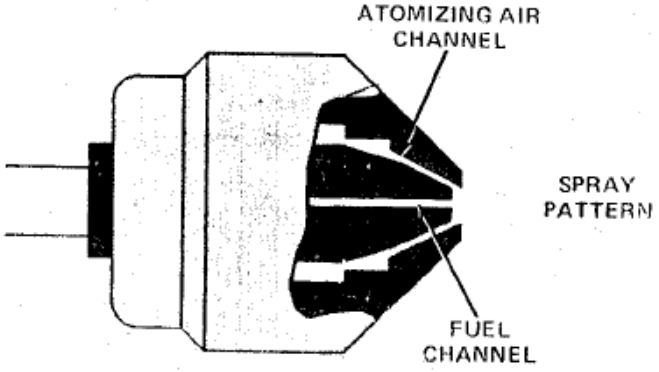
**Problem 2.** Air is used as the working fluid in a simple ideal Brayton cycle that has a pressure ratio of 12, a compressor inlet temperature of 300 K, and a turbine inlet temperature of 1000 K. Determine the required mass flow rate of air for a net power output of 70 MW, assuming both the compressor and the turbine have an isentropic efficiency of 100 percent Assume constant specific heats at room temperature. Answers: (a) 352 kg/s

**Problem3**. A gas-turbine power plant operates on the simple ideal Brayton cycle with air as the working fluid and delivers 32 MW of power. The minimum and maximum temperatures in the cycle are 310 and 900 K, and the pressure of air at the compressor exit is 8 times the value at the compressor inlet. Determine

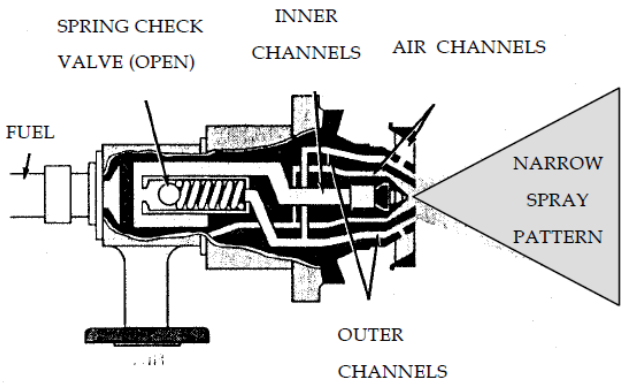
1. the mass flow rate of air through the cycle
2. The cycle thermal efficiency

# Gas Turbine Auxiliary System

**1- Fuel system:** This system to mix the compressed air and the fuel to be burned in the combustor. That to produce a hot gases to turn the turbine.




Simple fuel nozzle




Duplex fuel nozzle

Lube oil system: The primary job of the lube oil system is to lubricate and cool the gas turbine's mechanical parts such as bearings, coupling and gears.

3- Cooling systems:

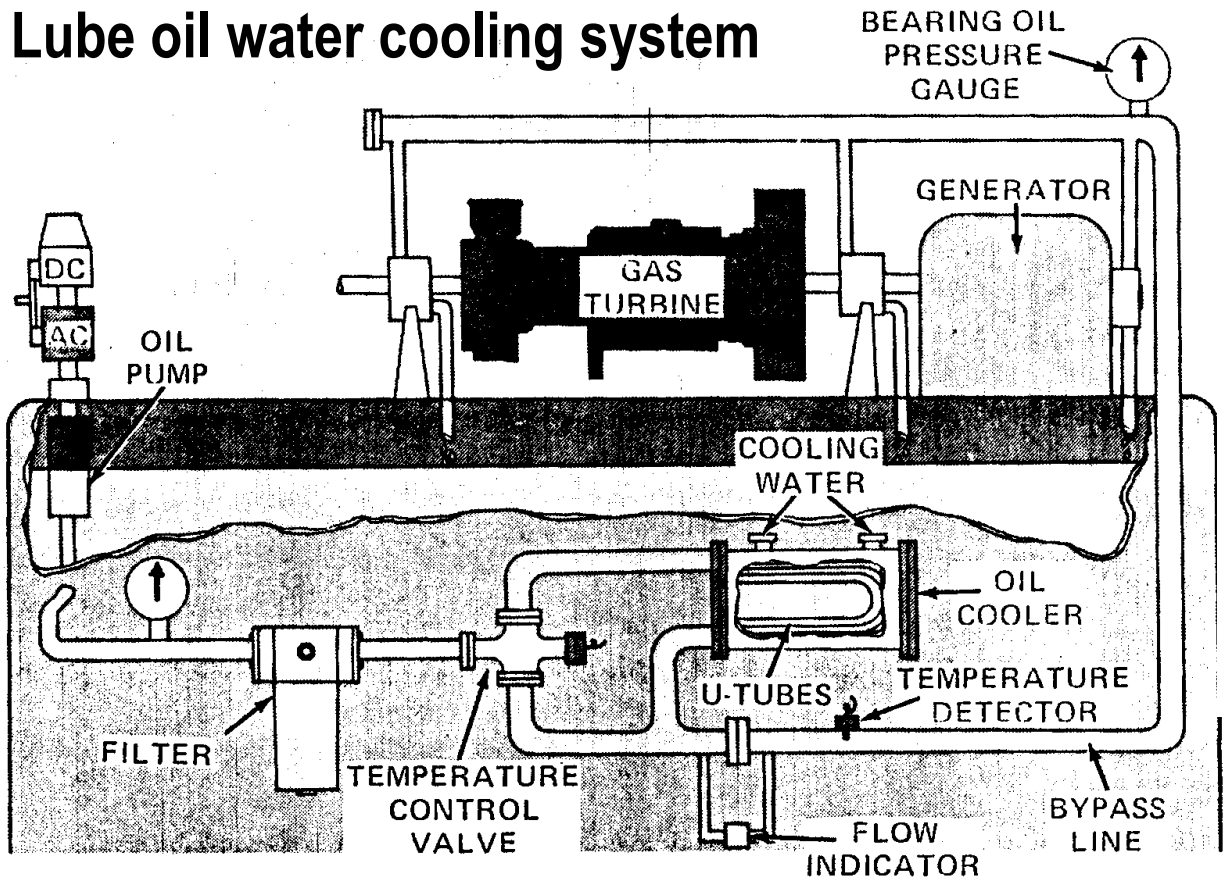
Turbine blade cooling: The blade cooling techniques are used to protect the blade materials against the high temperature of working gases and avoid thermal expansion of blades.

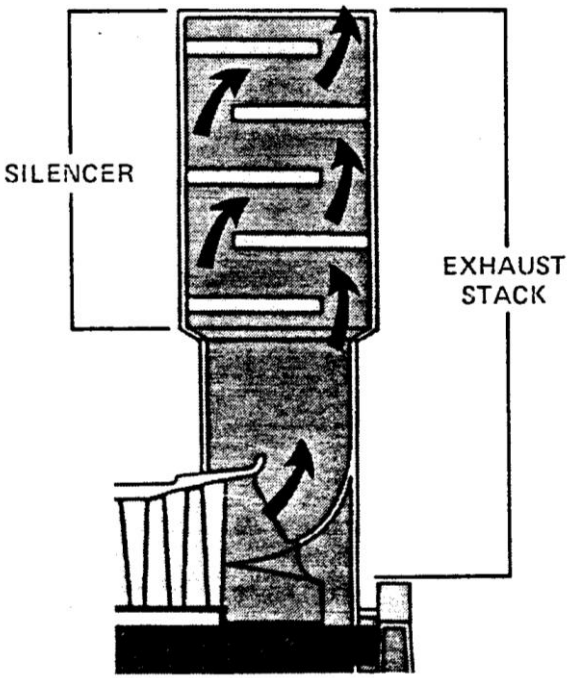
Liquid cooling: The lube oil need to be cooled through a heat exchanger that uses water or air to remove the heat from the oil.

Air Cooling:

# Gas Turbine Auxiliary System

## Lube oil water cooling system



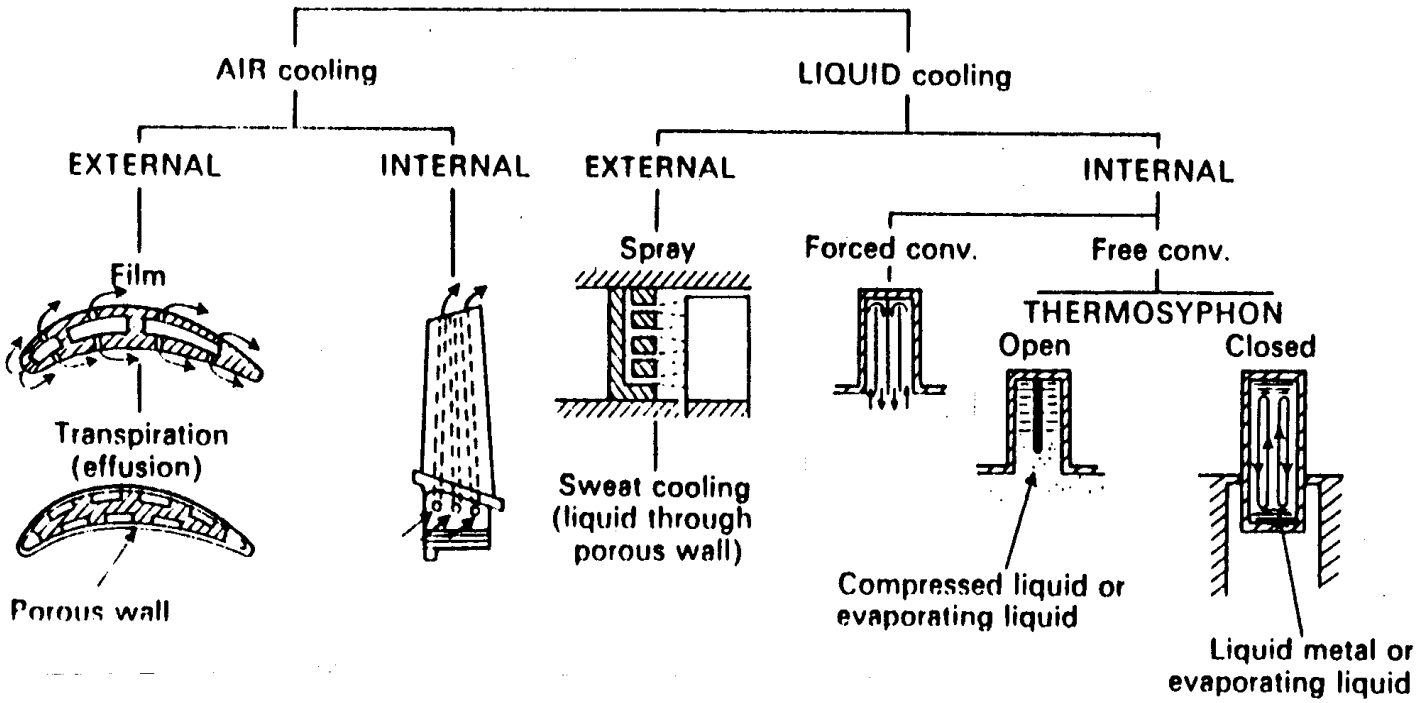




Exhaust silencer system

**Silencer:** It is a series of baffles located in the exhaust stack to damp the noise around the gas turbine.

# Gas Turbine Auxiliary System

- **STARTING SYSTEMS**
  - Air Motors
  - Diesel Engines
  - Electric Motors
- **COOLING SYSTEM**



# Applied Thermodynamics: An Engineering Approach

**Seventh Edition in SI Units**

**Yunus A. Cengel, Michael A. Boles**

**McGraw-Hill, 2011**

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