

## Chapter two

### Energy Conservation and 1<sup>st</sup> law of thermodynamics

#### Energy (E)

Energy is a fundamental concept of thermodynamics and one of the most significant aspects of engineering analysis. A basic idea is that energy can be *stored* within systems in various forms. Energy also can be *converted* from one form to another and *transferred* between systems. For closed systems, energy can be transferred by *work* and *heat transfer*. The total amount of energy is *conserved* in all conversions and transfers. For open system mass and energy balances for control volumes are introduced according to conservation of mass and conservation of energy principles. The unit of energy is J and equal to N.m.

#### Energy Sources and forms

##### Sources

- 1- Traditional types (depleted ناضبة types) fossil energy like oil, coal and natural gas
- 2- Renewable energy sources:
  - Solar Energy
  - Tidal Energy طاقة المد والجزر
  - Energy waves of the seas and oceans
  - Waterfalls مساقط المياه، الشلالات energy
  - Wind energy
  - Geothermal energy

**Forms:** Fig. 2.1 indicates the general form of energies that effect on the system.

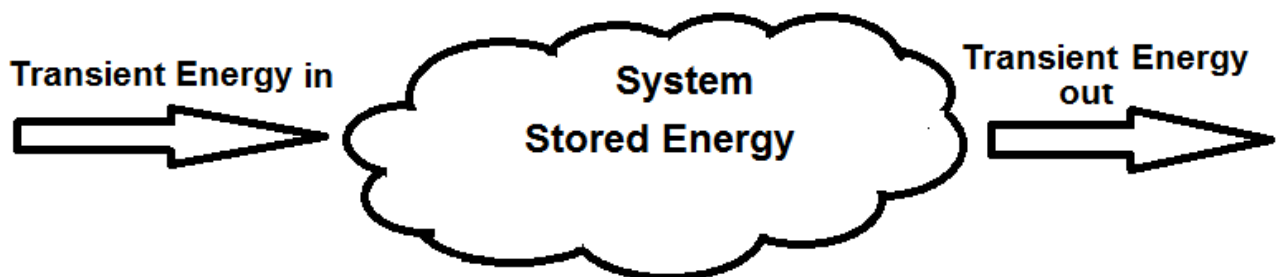
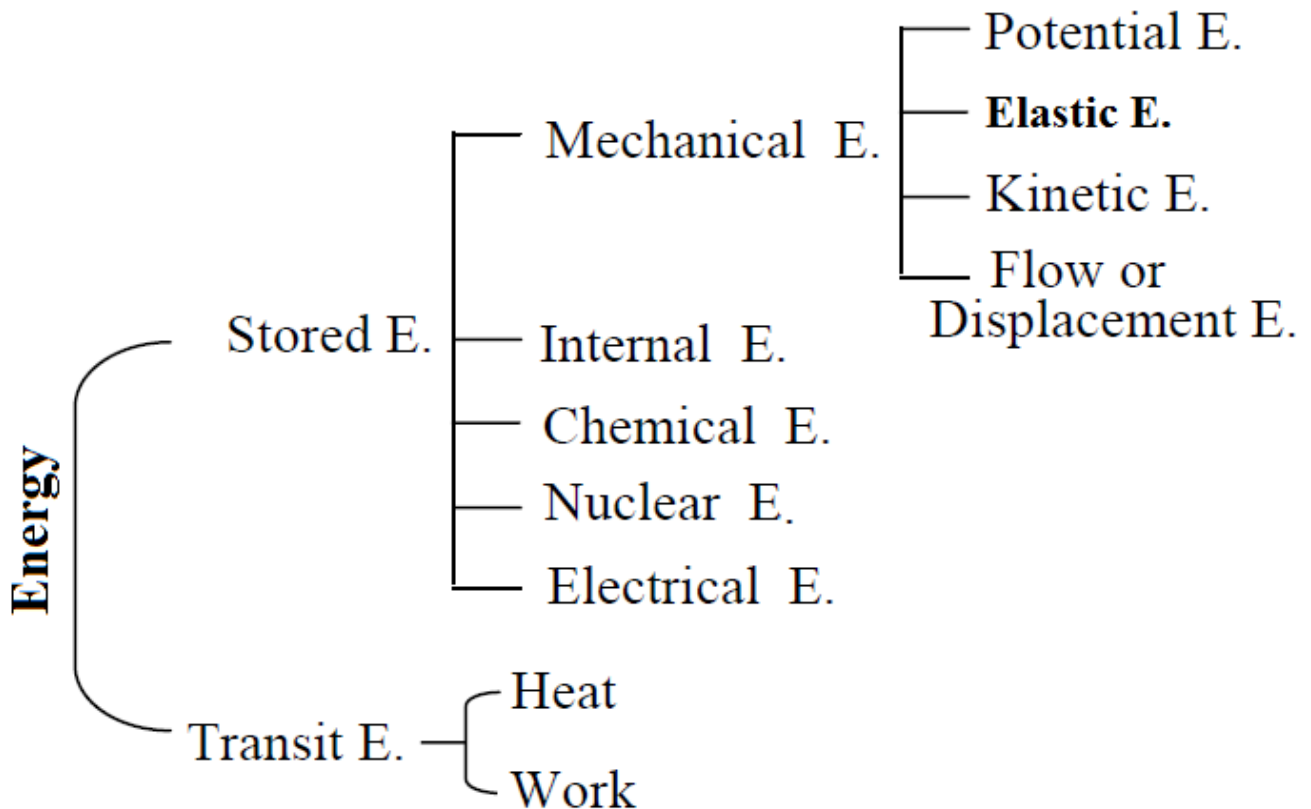


Figure 2.1 System and energy forms



**Stored energy:** it is energy available and *contained* or *stored* in a system, thus can be viewed as the *static* forms of energy and divided into:

1- Mechanical energy: it is related to the motion and acceleration of the system and include

- Potential energy (PE): sometimes called gravitational energy or energy of position which related to the elevation of the system with respect to the reference level as: (see figure 2.2)

$$PE = \text{weight} * Z = mgZ$$

The variation of it is  $\Delta PE = mg \Delta Z$

And the specific potential energy  $Pe = gZ$

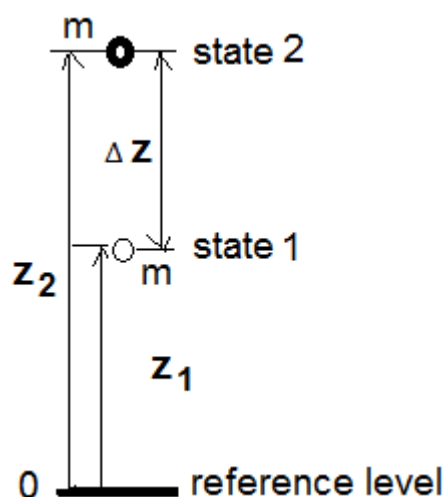


Figure 2.2 potential energy variations

- Elastic energy

Elastic energy can be stored mechanically in a compressed gas or liquid, a coiled spring, or a stretched elastic band.

- Kinetic Energy (KE): is the energy of a system as a result of its motion relative to some reference frame. When all parts of a system move with the same velocity ( $c$ ), kinetic energy can be expressed as:

$$KE = mc^2/2$$

For unit mass

$$Ke = c^2/2$$

And for rotating bodies

$$KE = I\omega^2/2$$

where  $I$  is the moment of inertia of the body and  $\omega$  is the angular velocity.

The variation of kinetic energy between two states is depending on the variation of velocity (if the body accelerates or decelerates). The variation is:

$$\Delta KE_{12} = \int_1^2 mc dc$$

This for general variation of velocity and the velocity may be function of time, distance, or etc. For uniform of variation of velocity (constant acceleration or deceleration) the variation becomes:

$$\Delta KE_{12} = m(c_2^2 - c_1^2)/2$$

In addition to the mechanical concept of kinetic energy, it is in general concept the motion of waves, electrons, atoms, molecules, substances, and objects.

- Flow or Displacement Energy ( $pV$ ): the pressure of a flowing fluid is associated with its mechanical energy. Where the fluid under a pressure can be displace the unfixed body contact with it and considered has a stored mechanical energy, this energy is proportional to fluid pressure and the volume. In fact, the pressure unit Pa is equivalent to  $\text{Pa} = \text{N}/\text{m}^2 = \text{N} \cdot \text{m}/\text{m}^3 = \text{J}/\text{m}^3$ , which is energy per unit volume, and the product  $pV$  or its equivalent  $p/\rho$  has the unit  $\text{J}/\text{kg}$ , which is energy per unit mass, sometimes called *flow work*, and expressed in terms of fluid properties, and it is convenient to view it as part of the energy of a flowing fluid and call it *flow energy*.

Therefore, the mechanical energy of a flowing fluid can be expressed on a unit mass basis as

$$e_{\text{mech}} = \frac{p}{\rho} + \frac{c^2}{2} + gZ$$

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

## 2- Internal Energy U

The internal energy is associated with the molecular structure and molecular activity of a system.

The molecule as a whole can move in x, y and z directions with respective components of velocities and hence possesses kinetic energy. There can be rotation of molecule about its center of mass and then the kinetic energy associated with rotation is called rotational energy.

In addition the bond length undergoes change and the energy associated with it is called vibrational energy. The electron move around the nucleus and they possess a certain energy that is called electron energy. The microscopic modes of energy are due to the internal structure of the matter and hence **sum of all microscopic modes of energy is called the internal energy takes symbol U** and the specific internal energy takes symbol u.

The portion of the internal energy of a system associated with the kinetic energies of the molecules is called the **sensible energy** (Fig. 2.3 a). The average velocity and the degree of activity of the molecules are proportional to the temperature of the matter. The forces that bind the *molecules* to each other are, as one would expect, strongest in solids and weakest in gases. The internal energy associated with the phase of a system is called the **latent energy** see Fig. 2.3 b.

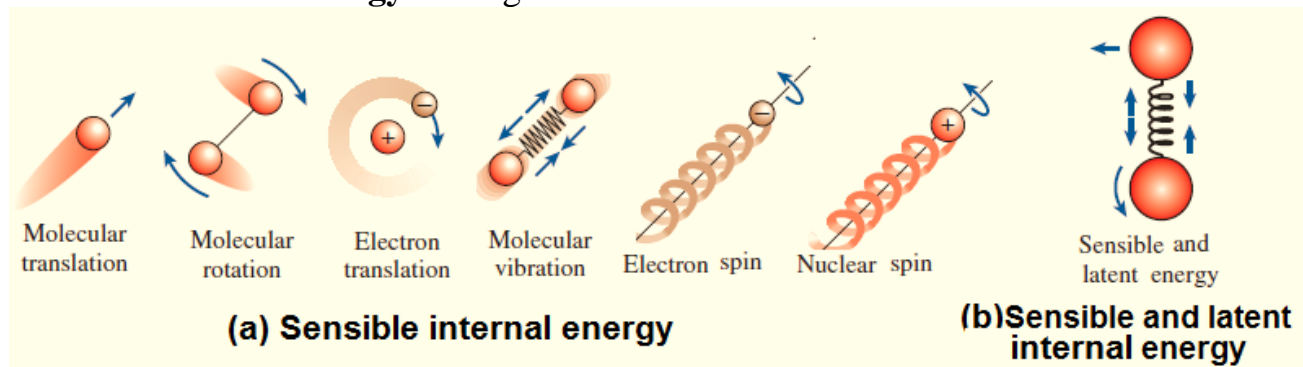


Figure 2.3 The various forms of microscopic energies that make up *sensible & latent* energy.

## 3- Chemical Energy

Chemical energy is stored in the bonds between the **atoms** in compounds (An atom consists of neutrons and positively charged protons bound together by very strong nuclear forces in the nucleus, and negatively charged electrons orbiting around it). This stored energy is transformed when bonds are broken or formed through *chemical reactions*.

When we burn sugar (a compound made of the elements *hydrogen*, *oxygen*, and *carbon*) in our bodies, the elements are reorganized into water and carbon dioxide. These reactions both absorb and release energy, but the overall result is that we get energy from the sugar, and our bodies use that energy to do work.

Chemical reactions that produce net energy are *exothermic*. When wood is burned, the chemical reactions taking place are *exothermic*. Electromagnetic and **thermal energy** are released. Only some chemical reactions release energy. *Endothermic* reactions need energy to start and to continue, such as by adding heat or light.

#### 4- Nuclear Energy

The nuclear forces are much larger than the forces that bind the electrons to the nucleus.

The tremendous مروع amount of energy associated with the strong bonds within the nucleus of the atom itself is called nuclear energy. Obviously، بوضوح we need not be concerned with nuclear energy in thermodynamics unless, of course, we deal with fusion اندماج or fission انشطار reactions. A chemical reaction involves changes in the structure of the electrons of the atoms, but a nuclear reaction involves changes in the core or nucleus. Therefore, an atom preserves تحفظ its identity during a chemical reaction but loses it during a nuclear reaction. Atoms may also possess *electric and magnetic dipole-moment energies* when subjected to external electric and magnetic fields due to the twisting of the magnetic dipoles produced by the small electric currents associated with the orbiting electrons.

#### 5- Electrical Energy

Electrical energy is the movement of electrical charges. Everything is made of tiny صغيرة جدا particles called atoms. Atoms are made of even smaller particles called electrons, protons, and neutrons. Applying a force can make some of the electrons move. Electrical charges moving through a wire is called electricity.

#### Transit Energy

Energy can cross the boundary of a closed system in two distinct forms: *heat* and *work*.

**Heat:** When a body is put in a medium that is at a different temperature, energy transfer occurs between the body and the surrounding medium until thermal equilibrium is established, that is, the body and the medium reach the same temperature. The direction of energy transfer is always from the higher temperature body to the lower temperature one. Once the temperature equality is established, energy transfer stops. In the processes described above, energy is said to be transferred in the form of heat.

**Heat is defined as the form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference.** That is, an energy interaction is heat only if it takes place because of a temperature difference. Then it follows that there cannot be any heat transfer between two systems that are at the same temperature.

A process during which there is no heat transfer is called an **adiabatic process**. The word *adiabatic* comes from the Greek word *adiabatos*, which means *not to be passed*. There are two ways a process can be **adiabatic**: **Either the system is well insulated so that only a negligible amount of heat can pass through the boundary, or both the system and the surroundings are at the same temperature and therefore there is no driving force (temperature difference) for heat transfer.**

As a form of energy, heat has energy units, kJ (or Btu) being the most common one. The amount of heat transferred during the process between two states (states 1 and 2) is denoted by  $Q_{12}$ , or just  $Q$ . Heat transfer *per unit mass* of a system is denoted  $q$  and is determined from

$$q = Q/m \quad (\text{kJ/kg})$$

Sometimes it is desirable to know the *rate of heat transfer* (the amount of heat transferred per unit time) instead of the total heat transferred over some time interval. The heat transfer rate is denoted  $\dot{Q}$  where the overdot stands for the time derivative, or “per unit time.” The heat transfer rate  $\dot{Q}$  has the unit kJ/s, which is equivalent to kW. When  $\dot{Q}$  varies with time, the amount of heat transfer during a process is determined by integrating  $\dot{Q}$  over the time interval of the process:

$$Q = \int_{t_1}^{t_2} \dot{Q} dt \quad (\text{kJ})$$

When  $\dot{Q}$  remains constant during a process, this relation reduces to

$$Q = \dot{Q} \Delta t \quad (\text{kJ})$$

where  $\Delta t = t_2 - t_1$  is the time interval during which the process takes place.

**Work: work is the energy transfer associated with a force acting through a distance.**

*If the energy crossing the boundary of a closed system is not heat, it must be work.*

Then we can simply say that an energy interaction that is not caused by a temperature difference between a system and its surroundings is work.

A rising piston, a rotating shaft, and an electric wire crossing the system boundaries are all associated with work interactions.

Work is also a form of energy transferred like heat and, therefore, has energy units such as kJ. The work done during a process between states 1 and 2 is denoted by  $W_{12}$ , or simply  $W$ . The work done *per unit mass* of a system is denoted by  $w$  and is expressed as

$$w = W/m \quad (\text{kJ/kg})$$

The work done *per unit time* is called **power** and is denoted  $\dot{W}$ . The unit of power is kJ/s, or kW.

Heat and work are *energy transfer mechanisms* between a system and its surroundings, and there are many similarities between them:

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

**Path functions** have **inexact differentials** designated by the symbol  $\delta$ . Therefore, a differential amount of heat or work is represented by  $\delta Q$  or  $\delta W$ , respectively, instead of  $dQ$  or  $dW$ . Properties, however, are **point functions** (i.e., they depend on the state only, and not on how a system reaches that state), and they have **exact differentials**

designated by the symbol  $d$ . A small change in volume, for example, is represented by  $dV$ , and the total volume change during a process between states 1 and 2 is

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

That is, the volume change during process 1–2 is always the volume at state 2 minus the volume at state 1, regardless of the path followed (Fig. 2–4). The total work done during process 1–2, however, is

$$\int_1^2 \delta W = W_{12} \quad \text{not } \Delta W$$

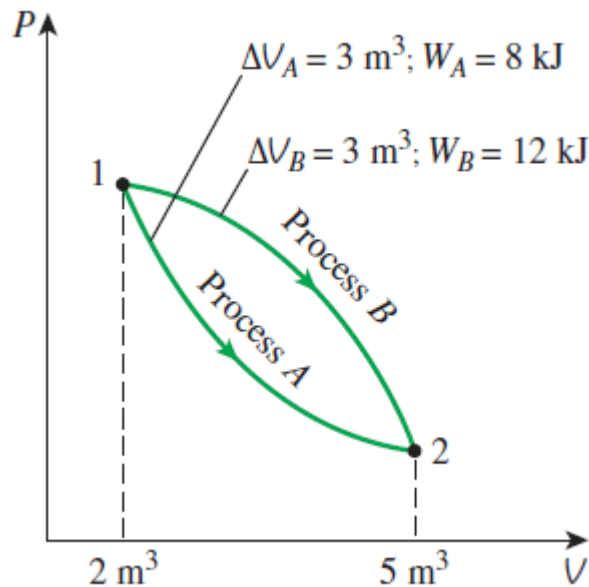


Figure 2.4 Properties are point functions; but heat and work are path functions (their magnitudes depend on the path followed).

## MECHANICAL FORMS OF WORK

There are several different ways of doing work, each in some way related to a force acting through a distance (Fig. 2.5a). In elementary mechanics, the work done by a constant force  $F$  on a body displaced a distance  $s$  in the direction of the force is given by

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

If the force  $F$  is not constant, the work done is obtained by adding (i.e., integrating) the differential amounts of work,

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

one needs to know how the force varies with displacement to perform this integration. There are two requirements for a work interaction between a system and its surroundings to exist: (1) there must be a *force* acting on the boundary, and (2) the boundary must *move*. Therefore, the presence of forces on the boundary without any displacement of the boundary does not constitute a work interaction. Likewise, the displacement of the boundary without any force to oppose or drive this motion (such as the expansion of a gas into an evacuated space) is not a work interaction since no energy is transferred. In many thermodynamic problems, mechanical work is the only form of work involved. It is associated with the movement of the boundary of a system

or with the movement of the entire system as a whole. Some common forms of mechanical work are discussed next.

### Shaft Work

Energy transmission with a rotating shaft is very common in engineering practice. If the torque  $T$  applied to the shaft is constant, which means that the force  $F$  applied is also constant. For a specified constant torque, the work done during  $n$  revolutions is determined as follows: A force  $F$  acting through a moment arm  $r$  generates a torque  $T$  of (Fig. 2.5b)

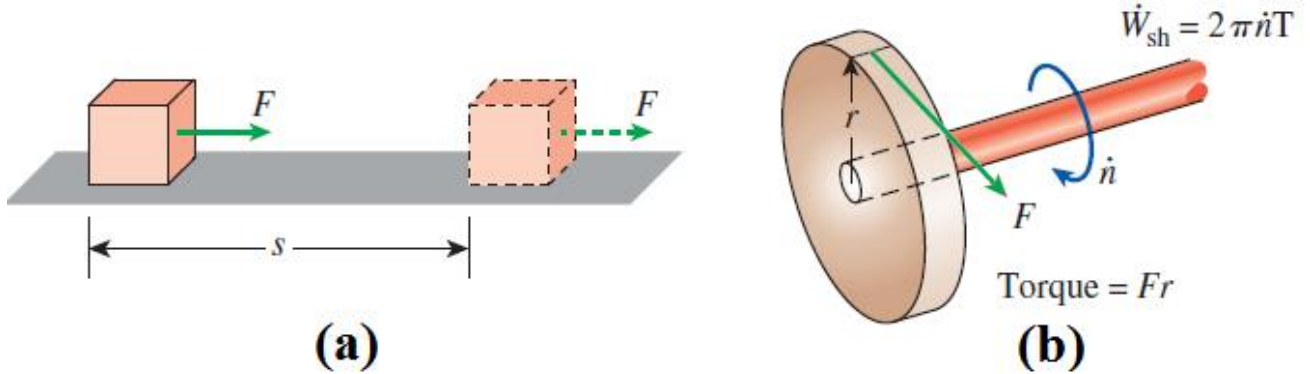


Figure 2.5 (a) The work done is proportional to the force applied ( $F$ ) and the distance traveled ( $s$ ). (b) Shaft work is proportional to the torque applied and the number of revolutions of the shaft.

$$T = Fr \rightarrow F = T/r$$

This force acts through a distance  $s$ , which is related to the radius  $r$  by

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

Then the shaft work is determined from

$$W_{sh} = Fs = \left(\frac{T}{r}\right)(2\pi rn) = 2\pi nT \quad (kJ)$$

The power transmitted through the shaft is the shaft work done per unit time, which can be expressed as

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

where  $\dot{n}$  is the number of revolutions per unit time.

### Spring Work

It is common knowledge that when a force is applied on a spring, the length of the spring changes (Fig. 2.6a). When the length of the spring changes by a differential amount  $dx$  under the influence of a force  $F$ , the work done is

$$\delta W_{spring} = Fdx$$



To determine the total spring work, we need to know a functional relationship between  $F$  and  $x$ . For linear elastic springs, the displacement  $x$  is proportional to the force applied (Fig. 2.6b). That is,

$$F = kx \quad (kN)$$

where  $k$  is the spring constant and has the unit kN/m. The displacement  $x$  is measured from the undisturbed position of the spring (that is,  $x = 0$  when  $F = 0$ ). Substituting Eqs. above and integrating yield

$$W_{spring} = \frac{1}{2} k(x_2^2 - x_1^2) \quad (kJ)$$

where  $x_1$  and  $x_2$  are the initial and the final displacements of the spring, respectively, measured from the undisturbed position of the spring.

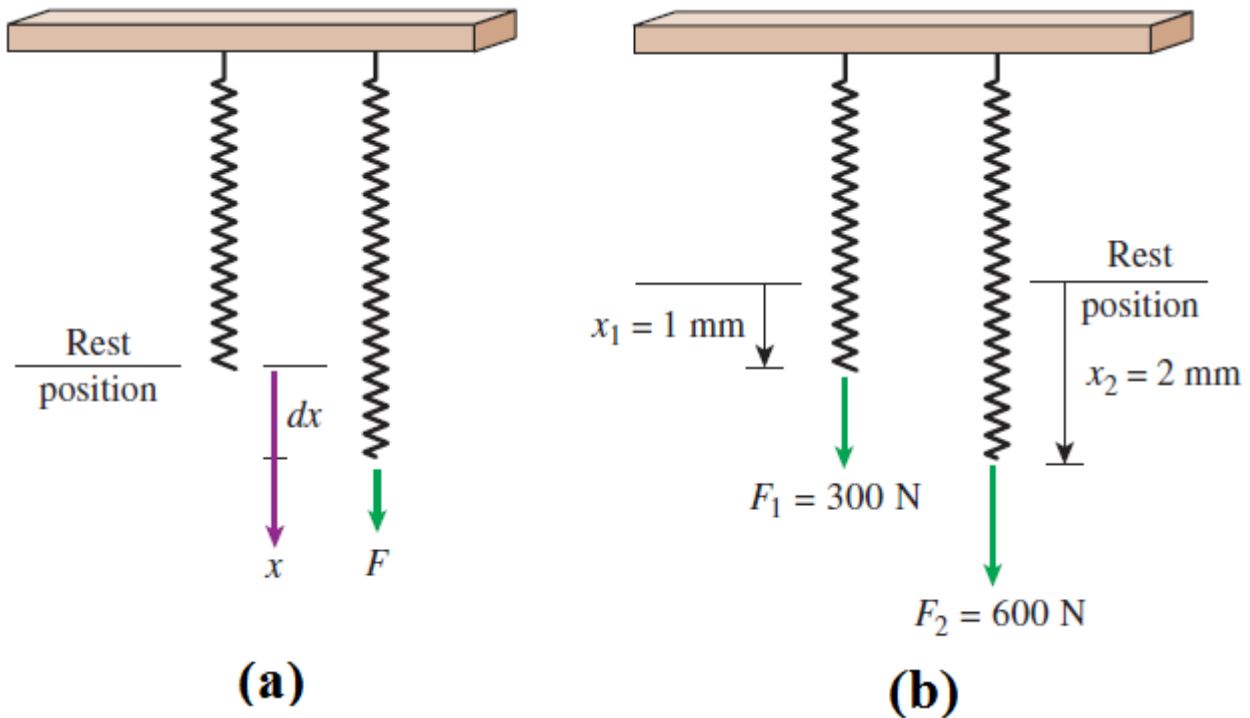
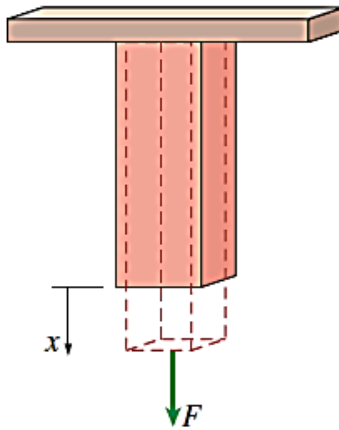


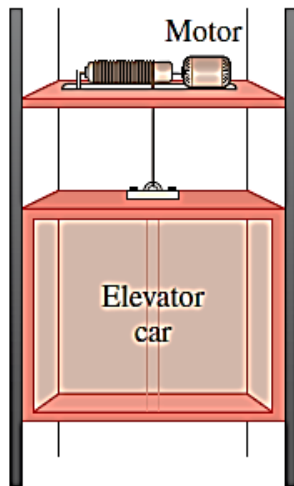
Figure 2.6 (a) Elongation of a spring under the influence of a force. (b) The displacement of a linear spring doubles when the force is doubled.



### Work Done on Elastic Solid Bars

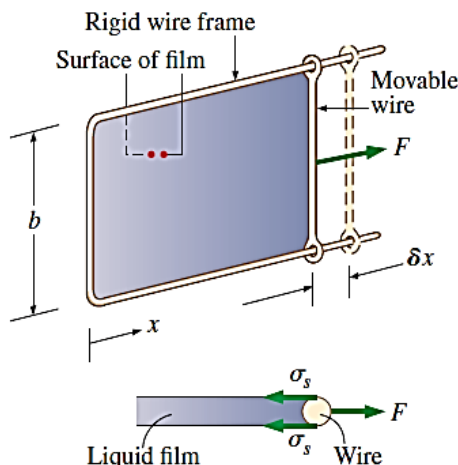
we can determine the work associated with the expansion or contraction of an elastic solid bar (see the figure) by replacing pressure  $P$  exerted on it by its counterpart مائظظه in solids, **normal stress**  $\bar{\sigma}_n = F/A$ , in the work expression:

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



### Work Done to Raise or to Accelerate a Body

When a body is raised in a gravitational field, its potential energy increases. Likewise, when a body is accelerated, its kinetic energy increases. The conservation of energy principle requires that an equivalent amount of energy must be transferred to the body. In this case energy is not heat since it is not driven by a temperature difference. Therefore, it must be work. Then we conclude that (1) the work transfer needed to raise a body is equal to the change in the potential energy of the body, and (2) the work transfer needed to accelerate a body is equal to the change in the kinetic energy of the body. (see the elevator car in the figure).



Stretching a liquid film with a U-shaped wire, and the forces acting on the movable wire of length  $b$ .

### Work Associated with the Stretching of a Liquid Film

Consider a liquid film such as soap film suspended on a wire frame (see the figure). We know from experience that it will take some force to stretch this film by the movable portion of the wire frame. This force is used to overcome the microscopic forces between molecules at the liquid-air interfaces. These microscopic forces are perpendicular to any line in the surface, and the force generated by these forces per unit length is called the **surface tension**  $\sigma_s$  whose unit is N/m. Therefore, the work associated with the stretching of a film is also called **surface tension work**. It is determined from

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

where  $dA = 2b dx$  is the change in the surface area of the film. The factor 2 is due to the fact that the film has two surfaces in contact with air. The force acting on the movable wire as a result of surface tension effects is  $F = 2b \sigma_s$  where  $\sigma_s$  is the surface tension force per unit length.

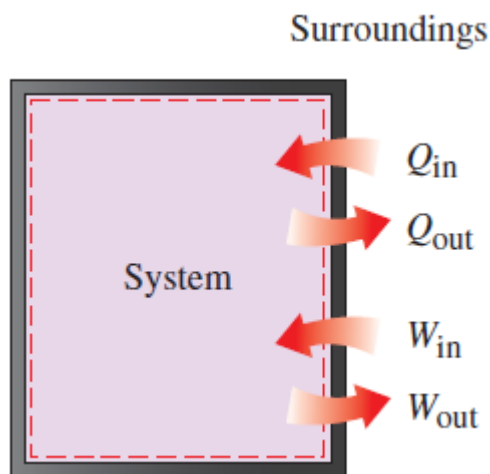
### Other Forms of Work

Some examples of nonmechanical work modes are **electrical work**,  $W_e = \mathbf{V}N$  where the generalized force is the **voltage**  $\mathbf{V}$  (the electrical potential) and the generalized

displacement is the *electrical charge*,  $N$  or in electric power form  $\dot{W}_e = VI$  where  $I$  is the number of electrical charges flowing per unit time, that is, the *current*; **magnetic work**, where the generalized force is the *magnetic field strength* and the generalized displacement is the total *magnetic dipole moment*; and electrical polarization work, where the generalized force is the *electric field strength* and the generalized displacement is the *polarization of the medium* (the sum of the electric dipole rotation moments of the molecules).

## Heat and Work Sign

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*. One way of doing that is to adopt a sign convention. The generally accepted formal sign convention for heat and work interactions is as follows: *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*. Another way is to use the subscripts *in* and *out* to indicate direction (Fig. 2–10).



## THE FIRST LAW OF THERMODYNAMICS

The *first law of thermodynamics*, also known as the *conservation of energy principle*, provides a sound basis for studying the relationships among the various forms of energy and energy interactions. Based on experimental observations, the first law of thermodynamics states that *energy can be neither created nor destroyed during a process; it can only change forms*.

### Energy Balance

The conservation of energy principle can be expressed as follows: *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*. That is,

$$\left( \begin{array}{c} \text{Total Energy} \\ \text{Entering the System} \end{array} \right) - \left( \begin{array}{c} \text{Total Energy} \\ \text{Leaving the System} \end{array} \right) = \left( \begin{array}{c} \text{Change in the Total} \\ \text{Energy of the System} \end{array} \right)$$

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

This relation is often referred to as the **energy balance** and is applicable to any kind of system undergoing any kind of process. The successful use of this relation to solve engineering problems depends on understanding the various forms of energy and recognizing the forms of energy transfer.

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

The determination of the energy change of a system during a process involves the evaluation of the energy of the system at the beginning and at the end of the process, and taking their difference. That is,

$$\text{Energy change} = \text{Energy at final state} - \text{Energy at initial state}$$

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

Note that energy is a property, and the value of a property does not change unless the state of the system changes.

In the absence of electric, magnetic, and surface tension effects (i.e., for simple compressible systems), the change in the total energy of a system during a process is the sum of the changes in its internal, kinetic, and potential energies and can be expressed as

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

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

for **stationary systems**, the changes in kinetic and potential energies are zero (that is,  $\Delta KE = \Delta PE = 0$ ), and the total energy change reduces to  $\Delta E = \Delta U$  for such systems.

### Mechanisms of Energy Transfer, $E_{in}$ and $E_{out}$

Energy can be transferred to or from a system in three forms: *heat*, *work*, and *mass flow*. Energy interactions are recognized at the system boundary as they cross it, and they represent the energy gained or lost by a system during a process. The only two forms of energy interactions associated with a fixed mass or closed system are *heat transfer* and *work*.

**1. Heat Transfer,  $Q$**  Heat transfer to a system (heat gain) increases the energy of the molecules and thus the internal energy of the system, and heat transfer from a system (heat loss) decreases it since the energy transferred out as heat comes from the energy of the molecules of the system.

**2. Work Transfer,  $W$**  An energy interaction that is not caused by a temperature difference between a system and its surroundings is work. A rising piston, a rotating shaft, and an electrical wire crossing the system boundaries are all associated with work interactions. Work transfer to a system (i.e., work done on a system) increases the energy of the system, and work transfer from a system (i.e., work done by the system) decreases it since the energy transferred out as work comes from the energy contained in the system. Car engines and hydraulic, steam, or gas turbines produce work while compressors, pumps, and mixers consume work.

**3. Mass Flow,  $m$**  Mass flow in and out of the system serves as an additional mechanism of energy transfer. When mass enters a system, the energy of the system increases because mass carries energy with it (in fact, mass is energy). Likewise, when some mass leaves the system, the energy contained within the system decreases because the leaving mass takes out some energy with it. For example, when some hot water is taken out of a water heater and is replaced by the same amount of cold water, the energy content of the hot-water tank (the control volume) decreases as a result of this mass interaction (Fig. 2–11).

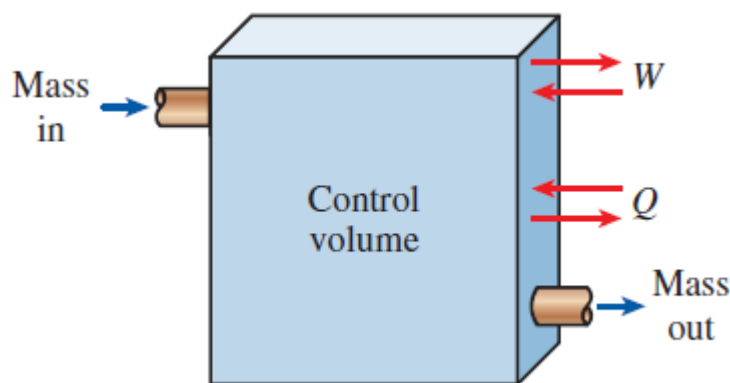


Figure 2-11 The energy content of a control volume can be changed by mass flow as well as heat and work interactions.

Noting that energy can be transferred in the forms of heat, work, and mass, and that the net transfer of a quantity is equal to the difference between the amounts transferred in and out, the energy balance can be written more explicitly as

$$E_{\text{in}} - E_{\text{out}} = (Q_{\text{in}} - Q_{\text{out}}) + (W_{\text{in}} - W_{\text{out}}) + (E_{\text{mass, in}} - E_{\text{mass, out}}) = \Delta E_{\text{system}}$$

where the subscripts “in” and “out” denote quantities that enter and leave the system, respectively. All six quantities on the right side of the equation represent “amounts,” and thus they are *positive* quantities. The direction of any energy transfer is described by the subscripts “in” and “out.” The heat transfer  $Q$  is zero for adiabatic systems, the work transfer  $W$  is zero for systems that involve no work interactions, and the energy transport with mass  $E_{\text{mass}}$  is zero for systems that involve no mass flow across their

boundaries (i.e., closed systems). Energy balance for any system undergoing any kind of process can be expressed more compactly as

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{\text{system}}}_{\text{Change in internal, kinetic, potential, etc., energies}} \quad (\text{kJ})$$

or, in the **rate form**, as

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{\text{system}}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \quad (\text{kW})$$

For constant rates, the total quantities during a time interval  $\Delta t$  are related to the quantities per unit time as

$$Q = \dot{Q} \Delta t, \quad W = \dot{W} \Delta t, \quad \text{and} \quad \Delta E = (dE/dt) \Delta t \quad (\text{kJ})$$

The energy balance can be expressed on a **per unit mass** basis as

$$e_{\text{in}} - e_{\text{out}} = \Delta e_{\text{system}} \quad (\text{kJ/kg})$$

which is obtained by dividing all the quantities of  $E$  by the mass  $m$  of the system. Energy balance can also be expressed in the differential form as

$$\delta E_{\text{in}} - \delta E_{\text{out}} = dE_{\text{system}} \quad \text{or} \quad \delta e_{\text{in}} - \delta e_{\text{out}} = de_{\text{system}}$$

For a closed system undergoing a **cycle**, the initial and final states are identical, and thus  $\Delta E_{\text{system}} = E_2 - E_1 = 0$ . Then the energy balance for a cycle simplifies to  $E_{\text{in}} - E_{\text{out}} = 0$  or  $E_{\text{in}} = E_{\text{out}}$ . Noting that a closed system does not involve any mass flow across its boundaries, the energy balance for a cycle can be expressed in terms of heat and work interactions as

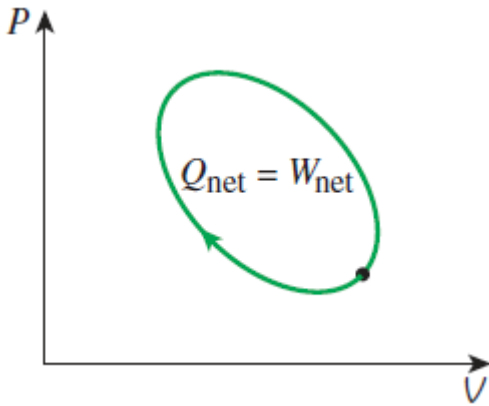
$$W_{\text{net, out}} = Q_{\text{net, in}} \quad \text{or} \quad \dot{W}_{\text{net, out}} = \dot{Q}_{\text{net, in}} \quad (\text{for a cycle})$$

That is, the net work output during a cycle is equal to net heat input (Fig. 2–12).

The energy balance (or the first-law) relations already given are intuitive in nature and are easy to use when the magnitudes and directions of heat and work transfers are known. However, when performing a general analytical study or solving a problem that involves an unknown heat or work interaction, we need to assume a direction for the heat or work interactions. In such cases, it is common practice to use the classical thermodynamics sign convention and to assume heat to be transferred *into the system* (heat input) in the amount of  $Q$  and work to be done *by the system* (work output) in the

amount of  $W$ , and then to solve the problem. The energy balance relation in that case for a closed system and reasonable ملائم for most thermodynamic systems becomes

$$Q_{net,in} - W_{net,out} = \Delta E_{system} \quad \text{or} \quad Q - W = \Delta E$$



**FIGURE 2–12** For a cycle  $\Delta E = 0$ , thus  $Q = W$ .

where  $Q = Q_{net,in} = Q_{in} - Q_{out}$  is the *net heat input* and  $W = W_{net,out} = W_{out} - W_{in}$  is the *net work output*. Obtaining a negative quantity for  $Q$  or  $W$  simply means that the assumed direction for that quantity is wrong and should be reversed.

## ENERGY CONVERSION EFFICIENCIES

*Efficiency* is one of the most frequently used terms in thermodynamics, and it indicates how well an energy conversion or transfer process is accomplished. Efficiency, in general, can be expressed in terms of the desired output and the required input as

$$\text{Efficiency} = \text{Desired output} / \text{Required input}$$

## THE IDEAL (OR PERFECT)-GAS

The ideal gas model is an approximate model نموذج تقريبي of gases that is often used to simplify calculations on real gases. An ideal gas has the following properties:

1. There are no intermolecular forces between the gas particles.
2. The volume occupied by the particles is negligible compared to the volume of the container they occupy.
3. The only interactions تفاعلات متبادلة between the particles and with the container walls are perfectly elastic collisions تصادمات.
4. The specific heats of the gas are slightly and approximated linearly change over small temperature intervals (a few hundred degrees or less).

Note that an elastic collision is one in which the total kinetic energy is conserved (i.e. no energy is transferred from translation into rotation or vibration, and no chemical reaction occurs). Of course, in a real gas, the atoms or molecules have a finite size, and at close range they interact with each other through a variety of intermolecular forces.

## THE IDEAL-GAS EQUATION OF STATE

Any equation that relates the pressure, temperature, and specific volume of a substance is called an **equation of state**. Property relations that involve other properties of a substance at equilibrium states are also referred to as equations of state. There are several equations of state, some simple and others very complex. The simplest and best-known equation of state for substances in the gas phase is the ideal-gas equation of state. This equation predicts the  $P$ - $v$ - $T$  behavior of a gas quite accurately within some properly selected region.

*Gas* and *vapor* are often used as synonymous مترادفة words. The vapor phase of a substance is customarily called a *gas* when it is above the critical temperature.

*Vapor* usually implies a gas that is not far from a state of condensation.

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

$$p = R \left( \frac{T}{v} \right) \quad \text{or} \quad pv = RT$$

where the constant of proportionality  $R$  is called the **gas constant**. Equation above is called the **ideal-gas equation of state**, or simply the **ideal-gas relation**, and a gas that obeys this relation is called an **ideal gas**. In this equation,  $P$  is the absolute pressure,  $T$  is the absolute temperature, and  $v$  is the specific volume. The gas constant  $R$  is different for each gas and is determined from

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

where  $R_u$  is the **universal gas constant** and  $M$  is the molar mass (also called *molecular weight*) of the gas. The constant  $R_u$  is the same for all substances, and its value is 8.31447 kJ/kmol·K

The **molar mass**  $M$  can simply be defined as *the mass of one mole* (also called a *gram-mole*, abbreviated gmol) *of a substance in grams*, or *the mass of one kmol* (also called a *kilogram-mole*, abbreviated kgmol) *in kilograms*.

The mass of a system is equal to the product of its molar mass  $M$  and the mole number  $N$ :

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

The values of  $R$  and  $M$  for several substances are given in Table 2.1. The ideal-gas equation of state can be written in several different forms:

$$V = mv \quad \rightarrow \quad pV = mRT$$

$$mR = (MN)R = NR_u \quad \rightarrow \quad pV = NR_u T$$



$$V = N \bar{v} \quad \rightarrow \quad p \bar{v} = R_u T$$

where  $\bar{v}$  is the molar specific volume, that is, the volume per unit mole (in m<sup>3</sup>/kmol). A bar above a property denotes values on a *unit-mole basis* throughout this text.

**Table 2.1 Different substances have different gas constants.**

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

The properties of an ideal gas at two different states are related to each other by

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$$

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

In the range of practical interest, many familiar gases such as air, nitrogen, oxygen, hydrogen, helium, argon, neon, krypton, and even heavier gases such as carbon dioxide can be treated as ideal gases with negligible error (often less than 1 percent). Dense gases such as water vapor in steam power plants and refrigerant vapor in refrigerators, however, should not be treated as ideal gases. Instead, the property tables should be used for these substances.

## ENTHALPY

In many thermodynamic analyses the sum of the internal energy  $U$  and the product of pressure  $p$  and volume  $V$  appear. Because the sum  $U + pV$  occurs so frequently in subsequent discussions, it is convenient to give the combination Greek name, ***enthalpy***, (in some reference called heat content) and a distinct symbol,  $H$ . By definition

$$H = U + pV \quad (\text{J, kJ})$$

Since  $U$ ,  $p$ , and  $V$  are all properties, this combination is also a property. Enthalpy can be expressed on a unit mass basis

$$h = u + p v \quad (\text{J/kg, kJ/kg})$$

and per mole

$$\bar{h} = \bar{u} + p \bar{v} \quad (\text{J/mol, kJ/kmol})$$

## SPECIFIC HEATS

The **specific heat** is defined as *the energy required to raise the temperature of a unit mass of a substance by one degree*. In general, this energy depends on how the process is executed. In thermodynamics, we are interested in two kinds of specific heats:

**specific heat at constant volume**  $c_v$  and **specific heat at constant pressure**  $c_p$ .

Physically, the specific heat at constant volume  $c_v$  can be viewed as *the energy required to raise the temperature of the unit mass of a substance by one degree as the volume is maintained constant*. The energy required to do the same as the pressure is maintained constant is the specific heat at constant pressure  $c_p$ . This is illustrated in Fig. 2-13. The specific heat at constant pressure  $c_p$  is always greater than  $c_v$  because at constant pressure the system is allowed to expand and the energy for this expansion work must also be supplied to the system.

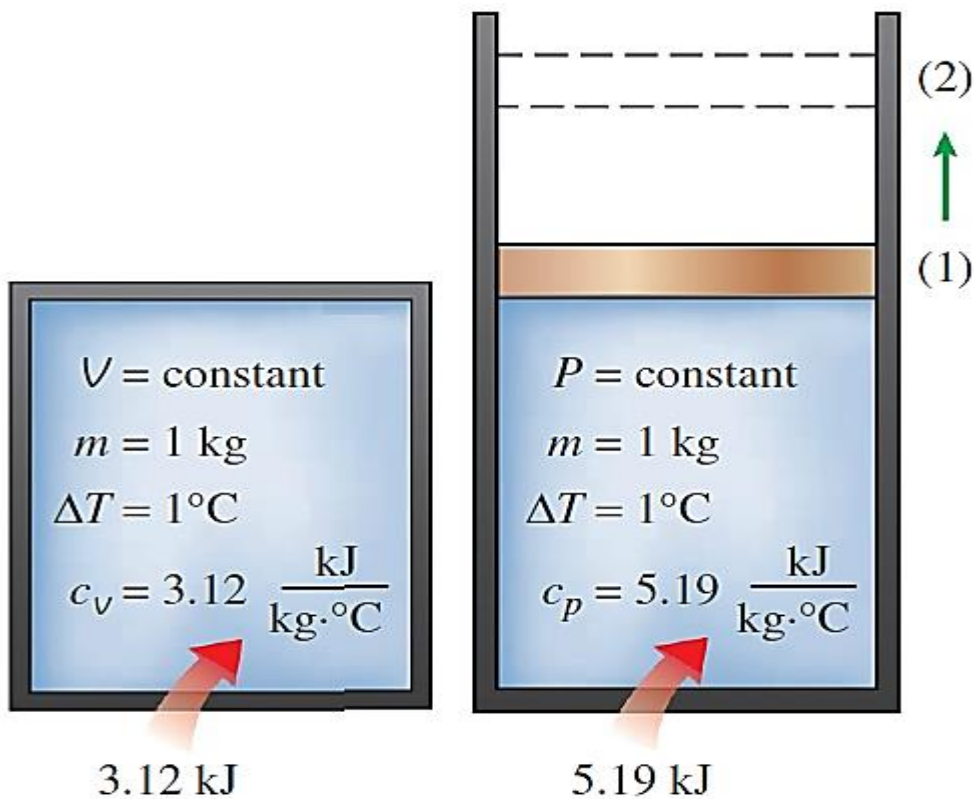


Figure 2-13 Constant-volume and constant pressure specific heats  $c_v$  and  $c_p$  (values given are for helium gas).

Consider a fixed mass in a stationary closed system undergoing a constant-volume process (and thus no expansion or compression work is involved). The conservation of energy principle  $e_{\text{in}} - e_{\text{out}} = \Delta e_{\text{system}}$  for this process can be expressed in the differential form as

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

The left-hand side of this equation represents the net amount of energy transferred to the system. From the definition of  $c_v$ , this energy must be equal to  $c_v dT$ , where  $dT$  is the differential change in temperature. Thus,  $c_v dT = du$  at constant volume or

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

In the case of constant pressure the heat added convert to increase in internal and expansion work is often called **moving boundary work**, simply **boundary work** or **displacement work**. Some call it the  $pv$  work or

$$\delta e_{in} - \delta e_{out} = d(u + pv) = dh$$

net amount of energy transferred to the system. From the definition of  $c_p$ , must be equal to  $c_p dT$ , and an expression for the specific heat at constant pressure  $c_p$  can be obtained by considering a constant-pressure expansion or compression process. It yields

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

Also specific heats are function of temperature and pressure and vary slightly (not very large) with them.

## INTERNAL ENERGY, ENTHALPY, AND SPECIFIC HEATS OF IDEAL GASES

In his classical experiment, Joule (1843) submerged two tanks connected with a pipe and a valve in a water bath, as shown in Fig. 2-14. Initially, one tank contained air at a high pressure and the other tank was evacuated. When thermal equilibrium was attained, he opened the valve to let air pass from one tank to the other until the pressures equalized. Joule observed no change in the temperature of the water bath and assumed that no heat was transferred to or from the air. Since there was also no work done, he concluded that the internal energy of the air did not change even though the volume and the pressure changed. Therefore, he reasoned, the internal energy is a function of temperature only and not a function of pressure or specific volume. (Joule later showed that for gases that deviate significantly *تختلف بشكل كبير* from ideal gas behavior, the internal energy is not a function of temperature alone.) That is,

$$u = u(T)$$

Using the definition of enthalpy and the equation of state of an ideal gas, we have

$$h = u + pv \quad \text{but} \quad pv = RT \quad \text{then} \quad h = u + RT$$

Since  $R$  is constant and  $u = u(T)$ , it follows that the enthalpy of an ideal gas is also a function of temperature only:

$$h = h(T)$$

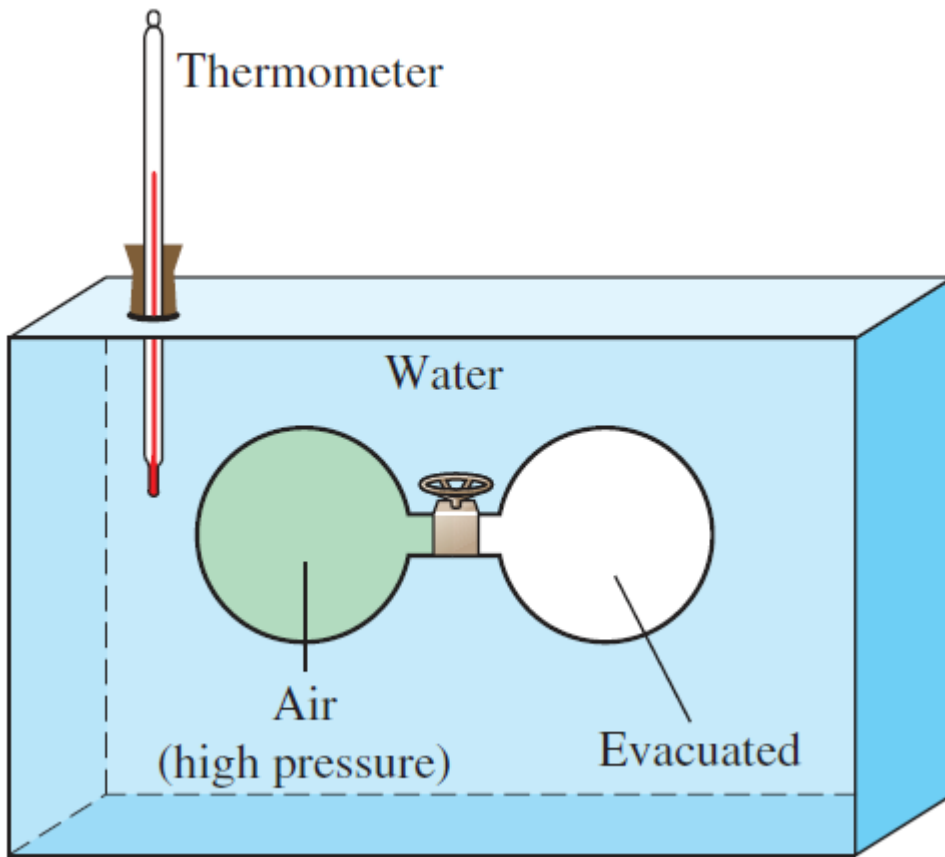


Figure 2-14 Schematic of the experimental apparatus used by Joule.

Since  $u$  and  $h$  depend only on temperature for an ideal gas, the specific heats  $c_v$  and  $c_p$  also depend, at most, on temperature only. Therefore, at a given temperature,  $u$ ,  $h$ ,  $c_v$ , and  $c_p$  of an ideal gas have fixed values regardless of the specific volume or pressure.

Thus, for ideal gases, the differential changes in the internal energy and enthalpy of an ideal gas can be expressed as

$$du = c_v(T) dT$$

$$dh = c_p(T) dT$$

The change in internal energy or enthalpy for an ideal gas during a process from state 1 to state 2 is determined by integrating these equations

$$\Delta u = u_2 - u_1 = \int_1^2 c_v(T) dT$$

And

$$\Delta h = h_2 - h_1 = \int_1^2 c_p(T) dT$$

Since the variation of specific heats of an ideal gas with temperature is smooth and may be approximated as linear over small temperature intervals (a few hundred degrees or less). Therefore, the specific heat functions can be replaced by the constant average specific heat values. Then, the integrations in these equations can be performed, yielding

$$u_2 - u_1 = c_{v,avg}(T_2 - T_1)$$

$$h_2 - h_1 = c_{p,avg}(T_2 - T_1)$$

### Specific Heat Relations of Ideal Gases

A special relationship between  $c_p$  and  $c_v$  for ideal gases can be obtained by differentiating the relation  $h = u + RT$ , which yields

$$dh = du + R dT$$

Replacing  $dh$  by  $c_p dT$  and  $du$  by  $c_v dT$  and dividing the resulting expression by  $dT$ , we obtain

$$c_p = c_v + R$$

This is an important relationship for ideal gases since it enables us to determine  $c_v$  from a knowledge of  $c_p$  and the gas constant  $R$ .

At this point, we introduce another ideal-gas property called the **specific heat ratio**  $\gamma$  or adiabatic index, which is defined as

$$\gamma = c_p / c_v$$

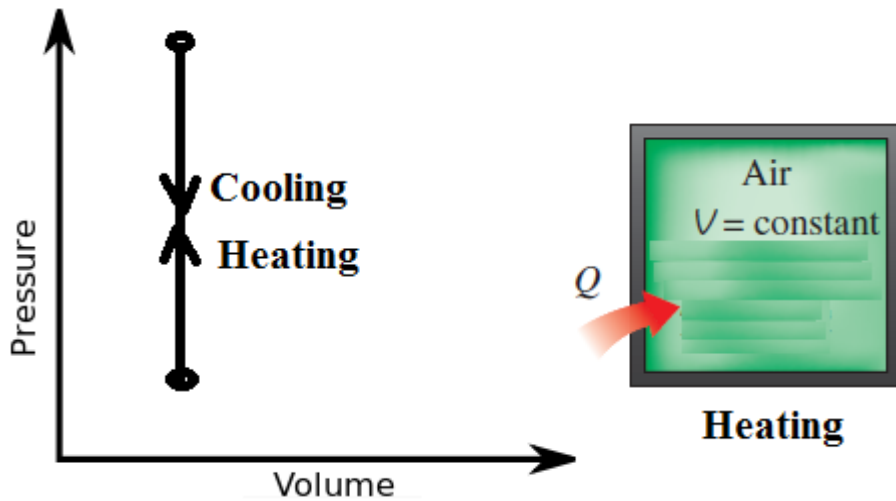
The specific ratio also varies with temperature, but this variation is very mild قليل. For monatomic gases, its value is essentially constant at 1.667. Many diatomic gases, including air, have a specific heat ratio of about 1.4 at room temperature.

### Closed System Processes

#### 1. Constant Volume (Isochoric) Heating or Cooling Process:

The process is described by:  $V = \text{const.}$  &  $\frac{p}{T} = \text{const.}$

From 1<sup>st</sup> law  $Q - W = \Delta U$ , since the volume remains constant there is no work transfer:  $W=0$  and  $Q = \Delta U = mc_v \Delta T$



**Figure 2.15 constant volume process**

## 2. Constant Pressure (Isobaric) Heating or Cooling Process

The process is described by:  $p = \text{const.}$  &  $V/T = \text{const.}$

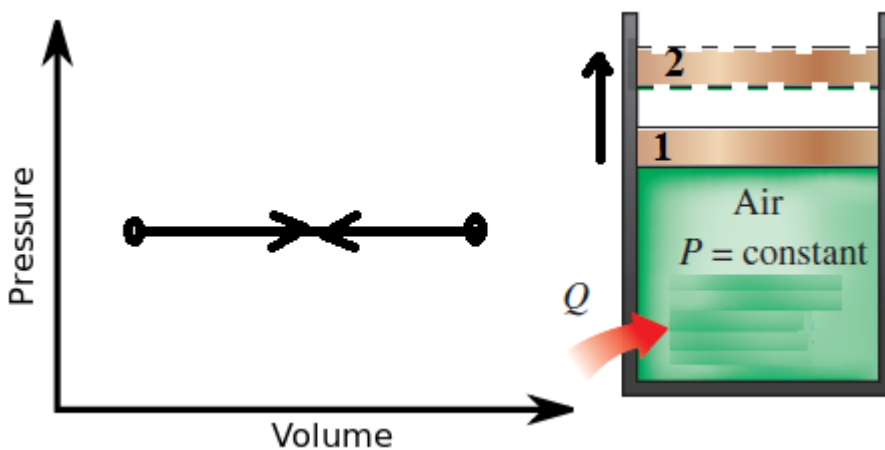
From 1st law  $Q - W = \Delta U$ , since the pressure remains constant the work transfer :

$$W_{12} = p(V_2 - V_1) = mR(T_2 - T_1) \quad \text{and} \quad \Delta U_{12} = mc_v(T_2 - T_1)$$

therefore  $Q_{12} = mR(T_2 - T_1) + mc_v(T_2 - T_1)$

or  $Q_{12} = m(R + c_v)(T_2 - T_1)$

but  $c_p = c_v + R$  then  $Q_{12} = mc_p(T_2 - T_1) = \Delta H_{12}$



**Figure 2.16 constant pressure process**

## 3. Constant Temperature (Isothermal) Process

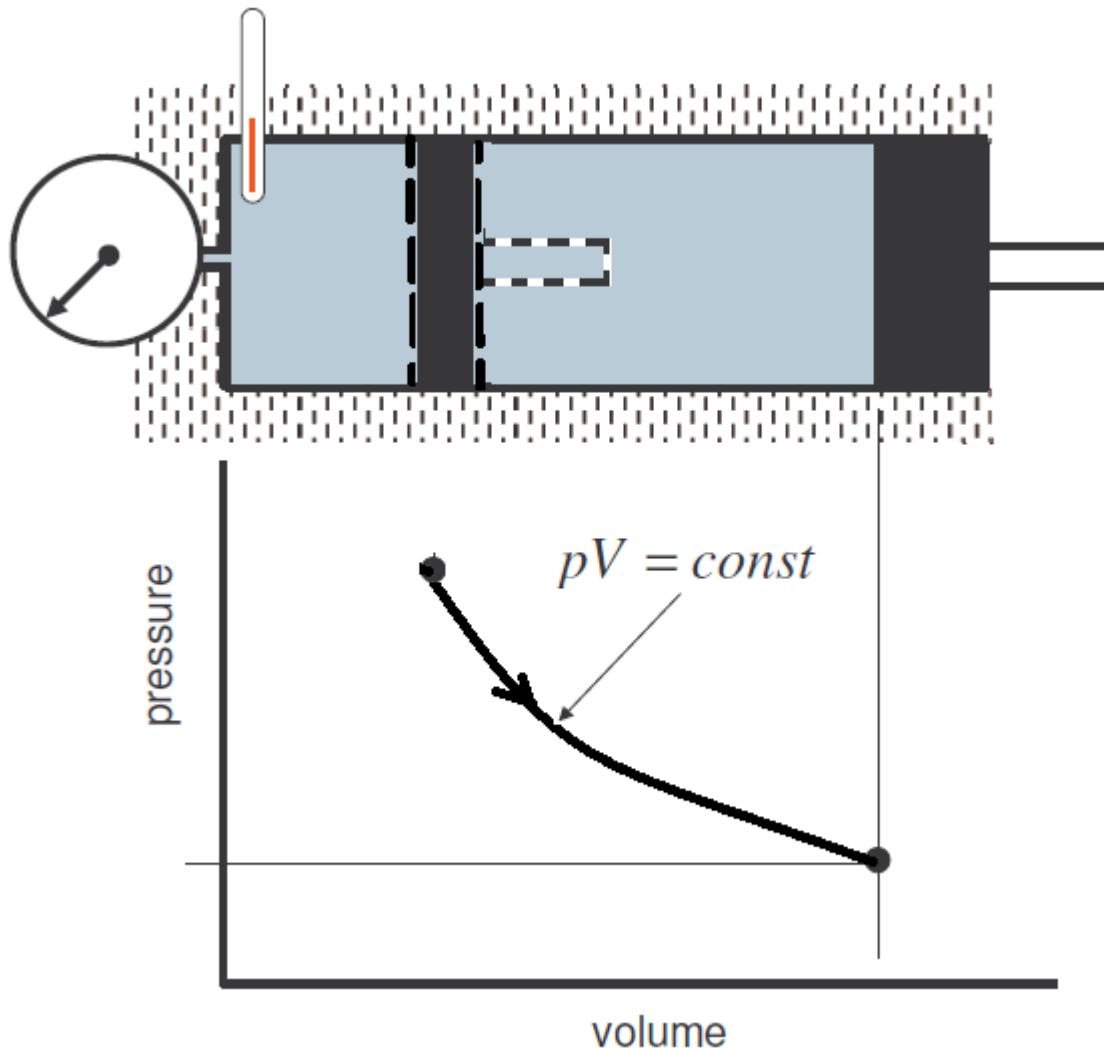
The process occurs if adding/ rejecting heat and moving the piston very slowly to expand/compress the gas without increasing/decreasing the temperature for the piston-cylinder assembly below.

For this process  $T = \text{const.}$  and  $pV = mRT = \text{const.}$

where  $\Delta U_{12} = mc_v(T_2 - T_1)$  and  $T_2 = T_1 = \text{const.}$  then  $\Delta U_{12} = 0$

therefore  $Q_{12} = W_{12} = \int_1^2 p dV$  but  $p = \frac{c}{V} = \frac{p_1 V_1}{V} = \frac{mRT}{V}$

then  $Q_{12} = W_{12} = c \int_1^2 \frac{dV}{V} = c[\ln V_2 - \ln V_1] = c \ln \frac{V_2}{V_1} = mRT \ln \frac{V_2}{V_1}$



**Figure 2.17 constant temperature process**

#### 4. Adiabatic Process $Q = 0$

If there is no heat transfer (an adiabatic process) the temperature changes because the work transfer increases or decreases the internal energy. In practice, this may be closely achieved by carrying out the process very rapidly – giving no time for heat transfer to occur, or by ensuring the system is very well insulated.

For this process  $Q = 0$  and  $-W = \Delta U$  or  $-pdV = mc_v dT$  \*

But  $H = U + pV$  and  $dH = dU + pdV + Vdp = \delta Q + Vdp$

Then for adiabatic process  $dH = Vdp$  or  $Vdp = mc_p dT$  \*\*

Dividing Eq. \*\* on Eq. \* we have  $-\frac{Vdp}{pdV} = \frac{c_p}{c_v} = \gamma$  or  $\frac{dp}{p} = -\gamma \frac{dV}{V}$

also  $\frac{dp}{p} + \gamma \frac{dV}{V} = 0$  and by integrating we get  $\ln p + \gamma \ln V = \text{const.}$

$$\rightarrow \ln p + \ln V^\gamma = \text{const.} \rightarrow \ln pV^\gamma = \text{const.} \rightarrow pV^\gamma = e^{\text{const.}} = \text{const.}$$

The work done  $W_{12} = \int_1^2 p dV = \int_1^2 \frac{c}{V^\gamma} dV = c \int_1^2 V^{-\gamma} dV = \frac{1}{1-\gamma} (cV_2^{1-\gamma} - cV_1^{1-\gamma})$

$$\text{but } c = p_1 V_1^\gamma = p_2 V_2^\gamma \quad \text{then} \quad W_{12} = \frac{1}{1-\gamma} (p_2 V_2^\gamma V_2^{1-\gamma} - p_1 V_1^\gamma V_1^{1-\gamma})$$

$$\text{And } W_{12} = \frac{p_2 V_2 - p_1 V_1}{1-\gamma} = \frac{mR(T_2 - T_1)}{1-\gamma}$$

Also for this process

$$\text{From } \frac{p_2}{p_1} = \left( \frac{V_1}{V_2} \right)^\gamma$$

$$p_1 V_1 = nRT_1 \quad \text{and} \quad p_2 V_2 = nRT_2$$

$$\text{we get } \frac{p_2}{p_1} = \left( \frac{nRT_1 / p_1}{nRT_2 / p_2} \right)^\gamma = \left( \frac{T_1 p_2}{T_2 p_1} \right)^\gamma = \left( \frac{p_2}{p_1} \right)^\gamma \left( \frac{T_1}{T_2} \right)^\gamma$$

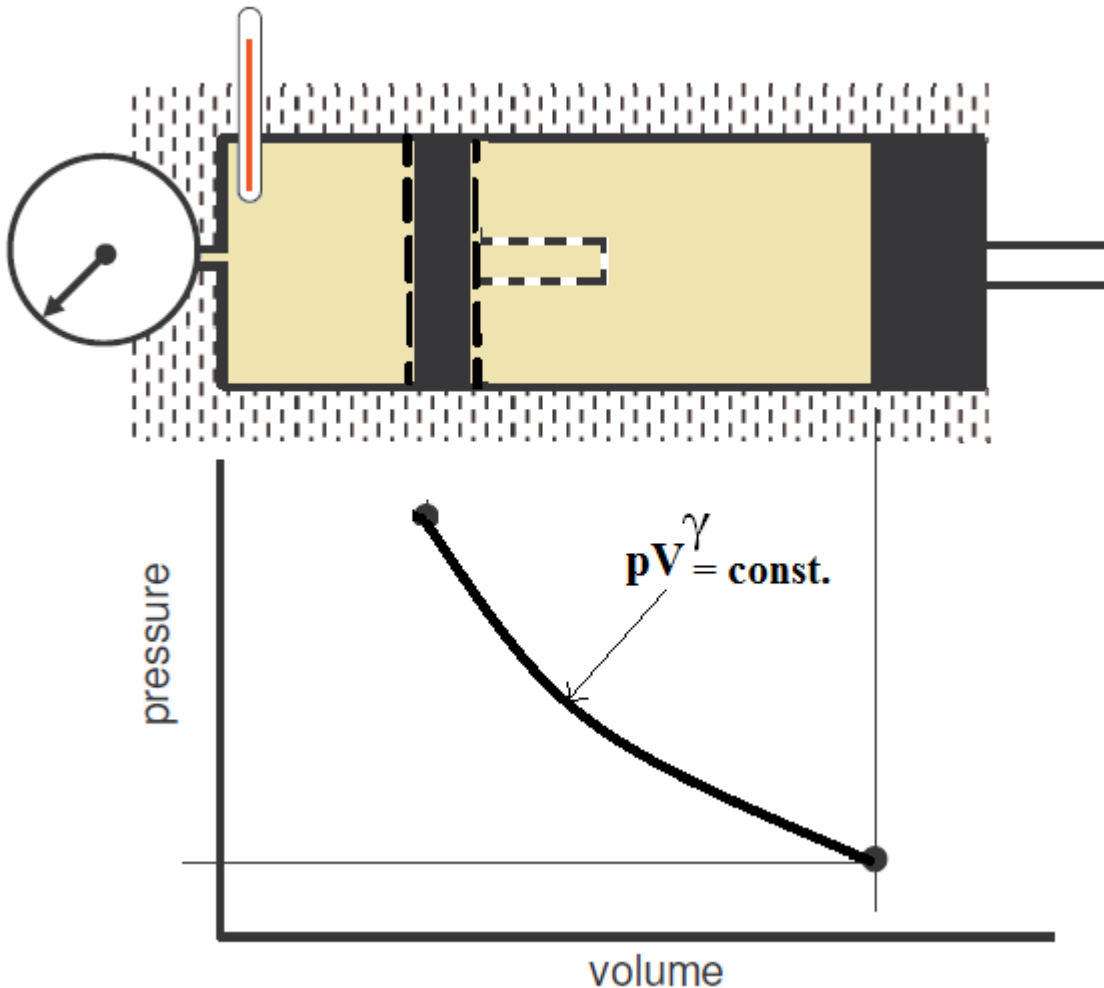
$$\text{or } \frac{T_1}{T_2} = \left( \frac{p_2}{p_1} \right)^{\frac{1-\gamma}{\gamma}} \quad \text{or} \quad \frac{T_2}{T_1} = \left( \frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}}$$

Similarly:

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

Fig. 2.18 indicates the process on pV diagram.





**Figure 2.18 adiabatic process**

#### 5. Polytropic متعدد المناحي Process

This process sometimes called general process and occurs by varying different properties (volume, pressure, temperature, and work or heat transfer.

The relationship between the pressure and volume during compression or expansion of an ideal gas can be described analytically. One form of this relationship is given by the equation  $pV^n = \text{const.}$  where  $n$  is a constant for the particular process and called a polytropic index. A thermodynamic process described by the above equation is called a polytropic process.

For a polytropic process between two states 1-2  $p_1V_1^n = p_2V_2^n = \text{const.}$

When  $n=0$ ,  $p = \text{constant}$ , and the process is a constant pressure or an isobaric process.

When  $n \rightarrow \infty$ ,  $V = \text{constant}$ , and the process is a constant volume or an isochoric process.

When  $n=1$ ,  $pV = \text{constant}$ , and the process is a constant temperature or an isothermal process. When  $n=\gamma$ , it is called adiabatic process.

For a polytropic process  $Q - W = \Delta U$  ,  $\Delta U = mc_v\Delta T \rightarrow U_{12} = mc_v(T_2 - T_1)$

$$\text{and } W_{12} = \frac{p_2V_2 - p_1V_1}{1 - n} = \frac{mR(T_2 - T_1)}{1 - n}$$

$$\text{also } Q_{12} = \frac{mR(T_2 - T_1)}{1 - n} + mc_v(T_2 - T_1)$$

**or for unit mass**

$$q = C_v (T_2 - T_1) + \frac{R (T_1 - T_2)}{n - 1}$$

$$\text{but } C_v = \frac{R}{\gamma - 1}$$

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

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

$$= \left( \frac{1}{n - 1} - \frac{1}{\gamma - 1} \right) R (T_1 - T_2)$$

$$= \left[ \frac{(\gamma - 1) - (n - 1)}{(n - 1)(\gamma - 1)} \right] R (T_1 - T_2)$$

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

$$q = \frac{\gamma - n}{\gamma - 1} \cdot w \quad \longrightarrow \quad Q = \frac{\gamma - n}{\gamma - 1} W$$

**and similar to adiabatic process**

From  $\frac{p_2}{p_1} = \left( \frac{V_1}{V_2} \right)^n$

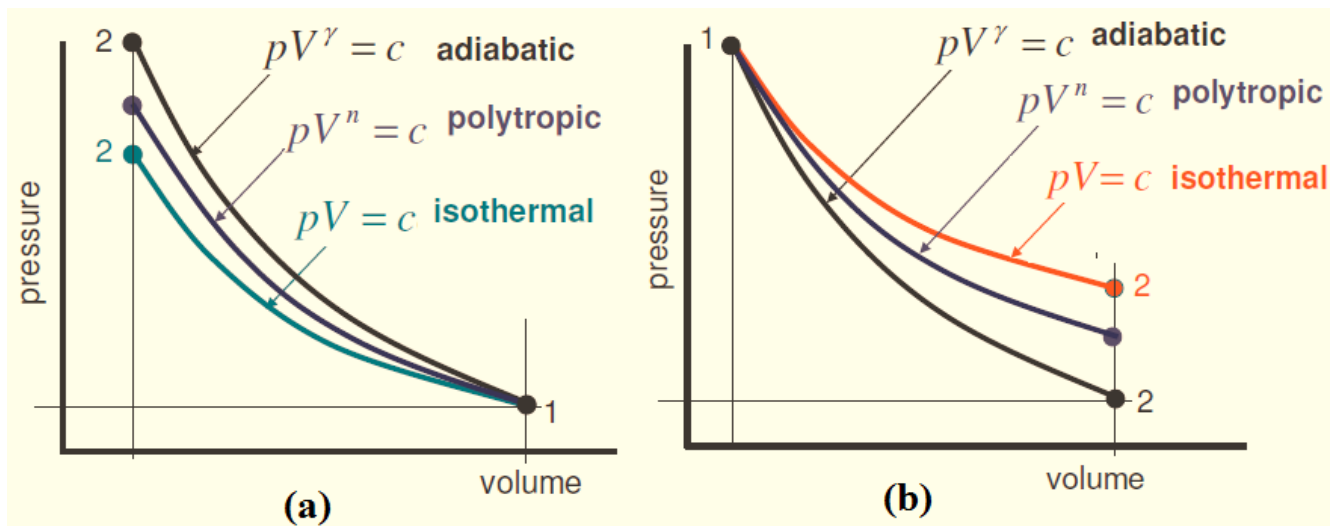
$p_1 V_1 = nRT_1$  and  $p_2 V_2 = nRT_2$

we get  $\frac{p_2}{p_1} = \left( \frac{nRT_1 / p_1}{nRT_2 / p_2} \right)^n = \left( \frac{T_1 p_2}{T_2 p_1} \right)^n = \left( \frac{p_2}{p_1} \right)^n \left( \frac{T_1}{T_2} \right)^n$

or  $\frac{T_1}{T_2} = \left( \frac{p_2}{p_1} \right)^{\frac{1-n}{n}}$  or  $\frac{T_2}{T_1} = \left( \frac{p_2}{p_1} \right)^{\frac{n-1}{n}}$

Similarly:

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



**Figure 2.19 isothermal, polytropic and adiabatic (a) compression (b) expansion process**

## MASS AND ENERGY ANALYSIS OF CONTROL VOLUMES

Now, we extend the energy analysis to systems that involve mass flow across their boundaries i.e., control volumes, with particular emphasis to steady-flow systems.

### Conservation of Mass Principle

The **conservation of mass principle** for a control volume can be expressed as: *The net mass transfer to or from a control volume during a time interval  $\Delta t$  is equal to the net change (increase or decrease) of the total mass within the control volume during  $\Delta t$*  see Fig (2.20). That is,

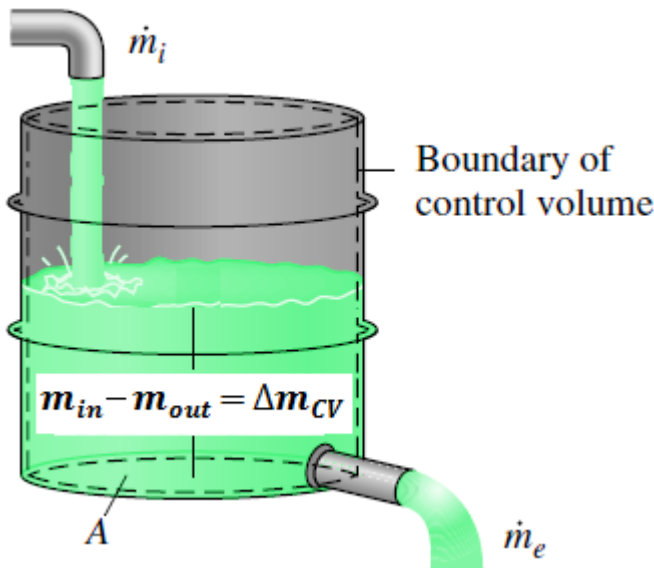
$$\left( \begin{array}{c} \text{Total mass entering} \\ \text{the CV during } \Delta t \end{array} \right) - \left( \begin{array}{c} \text{Total mass leaving} \\ \text{the CV during } \Delta t \end{array} \right) = \left( \begin{array}{c} \text{Net change of mass} \\ \text{within the CV during } \Delta t \end{array} \right)$$

or 
$$m_{in} - m_{out} = \Delta m_{CV}$$

where  $\Delta m_{CV} = m_{final} - m_{initial}$  is the change in the mass of the control volume during the process. It can also be expressed in *rate form* as

$$\dot{m}_{in} - \dot{m}_{out} = dm_{CV}/dt$$

Equations above are often referred to as the **mass balance** and are applicable to any control volume undergoing any kind of process.



**Figure 2.20** Conservation of mass principle

*The conservation of mass principle for a general steady flow system  $\Delta m_{CV} = 0$  with multiple inlets and outlets is expressed in rate form as*

$$\sum_{in} \dot{m} = \sum_{out} \dot{m}$$

It states that *the total rate of mass entering a control volume is equal to the total rate of mass leaving it*. For (single-stream one inlet and one outlet) steady-flow systems,

$$\dot{m}_{in} = \dot{m}_{out} \rightarrow \rho_1 V e_1 A_1 = \rho_2 V e_2 A_2$$

Where  $A_1$ , and  $A_2$  are the mass inlet and outlet area respectively. Also  $V e_1$  and  $V e_2$  are the mass inlet and outlet velocity respectively.

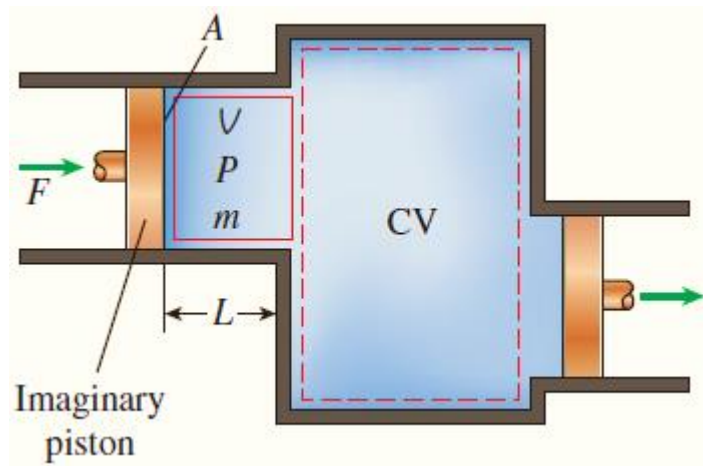
For steady, incompressible flow (no change in density):  $\sum_{in} \dot{V} = \sum_{out} \dot{V}$

And for Steady, incompressible flow (single stream, one inlet and one outlet):

$$\dot{V}_{in} = \dot{V}_{out} \rightarrow V e_1 A_1 = V e_2 A_2$$

## FLOW WORK AND THE ENERGY OF A FLOWING FLUID

Consider a fluid element of volume  $V$  as shown in Fig. 2.21. The fluid immediately upstream forces this fluid element to enter the control volume; thus, it can be regarded as an imaginary piston. The fluid element can be chosen to be sufficiently small so that it has uniform properties throughout. *The flow work per unit mass is  $w_{flow} = pv$* . The flow work relation is the same whether the fluid is pushed into or out of the control volume



**Figure 2.21** Schematic for flow work.

Total energy of a simple compressible system consists of three parts: internal, kinetic, and potential energies. On a unit-mass basis, it is expressed as

$$e = u + ke + Pe = u + \frac{V e^2}{2} + gZ$$

The fluid entering or leaving a control volume possesses an additional form of energy—the *flow energy*  $pv$ , as already discussed. Then the total energy of a **flowing fluid** on a unit-mass basis (denoted by  $\Theta$ ) becomes.

$$\theta = pv + e = pv + u + ke + Pe$$

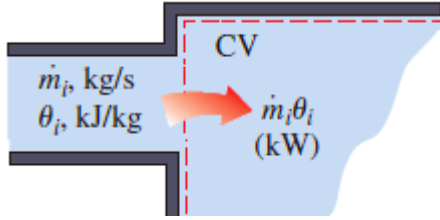
But the combination  $pv + u$  has been previously defined as the enthalpy  $h$ . Therefore,

$$\theta = h + ke + Pe = h + \frac{Ve^2}{2} + gZ$$

### Energy Transport by Mass

Amount of energy transport:  $E_{mass} = m\theta = m\left(h + \frac{Ve^2}{2} + gZ\right)$

Rate of energy transport:  $\dot{E}_{mass} = \dot{m}\theta = \dot{m}\left(h + \frac{Ve^2}{2} + gZ\right)$



**FIGURE 2.22** the product  $\dot{m}_i\theta_i$  is the energy transported into control volume by mass per unit time.

In general, the total energy transported by mass into or out of the control volume is not easy to determine since the properties of the mass at each inlet or exit may be changing with time as well as over the cross section. Thus, the only way to determine the energy transport through an opening as a result of mass flow is to consider sufficiently small differential masses  $dm$  that have uniform properties and to add their total energies during flow.

Again noting that  $\theta$  is total energy per unit mass, the total energy of a flowing fluid of mass  $\delta m$  is  $\theta\delta m$ . Then the total energy transported by mass through an inlet or exit ( $m_i\theta_i$  and  $m_e\theta_e$ ) is obtained by integration. At an inlet, for example, it becomes

$$E_{in,mass} = \int_{m_i} \theta_i \delta m_i = \int_{m_i} \left( h + \frac{Ve^2}{2} + gZ \right) \delta m_i$$

Most flows encountered in practice can be approximated as being steady and one-dimensional.

### ENERGY ANALYSIS OF STEADY-FLOW SYSTEMS

The *mass balance* for a general steady-flow system was given previously as

$$\sum_{in} \dot{m} = \sum_{out} \dot{m}$$

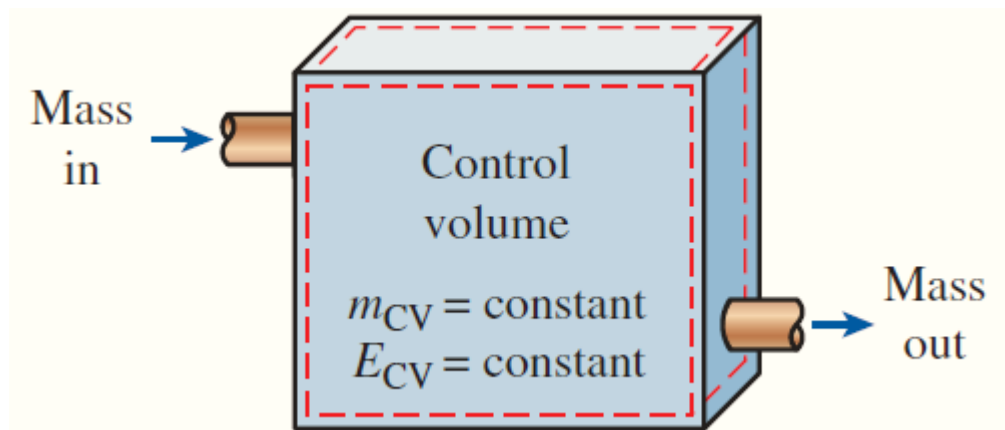
During a steady-flow process see Fig.2.23, the total energy content of a control volume remains constant ( $E_{CV} = \text{constant}$ ), and thus the change in the total energy of the

control volume is zero ( $\Delta E_{CV} = 0$ ). Therefore, the amount of energy entering a control volume in all forms (by heat, work, and mass) must be equal to the amount of energy leaving it. Then the rate form of the general energy balance reduces for a steady-flow process to

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{\frac{dE_{\text{system}}}{dt}}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \xrightarrow{0 \text{ (steady)}} = 0$$

**Or**

**Energy balance**  $\underbrace{\dot{E}_{in}}_{\text{Rate of net energy transfer in by heat, work, and mass}} = \underbrace{\dot{E}_{out}}_{\text{Rate of net energy transfer out by heat, work, and mass}}$



**FIGURE 2.23** Under steady-flow conditions, the mass and energy contents of a control volume remain constant.

Noting that energy can be transferred by heat, work, and mass only, the energy balance for a general steady-flow system can also be written more explicitly as

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}\theta = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}\theta$$

Or

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{each\ in} \dot{m} \left( h + \frac{Ve^2}{2} + gZ \right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{each\ out} \dot{m} \left( h + \frac{Ve^2}{2} + gZ \right)$$

In such cases, it is common practice to assume heat to be transferred *into the system* (heat input) at a rate of  $\dot{Q}$ , and work produced *by the system* (work output) at a rate of  $\dot{W}$ , and then solve the problem. The first-law or energy balance relation in that case for a general steady-flow system becomes

$$\dot{Q} - \dot{W} = \sum_{\text{each out}} \dot{m} \left( h + \frac{Ve^2}{2} + gZ \right) - \sum_{\text{each in}} \dot{m} \left( h + \frac{Ve^2}{2} + gZ \right)$$

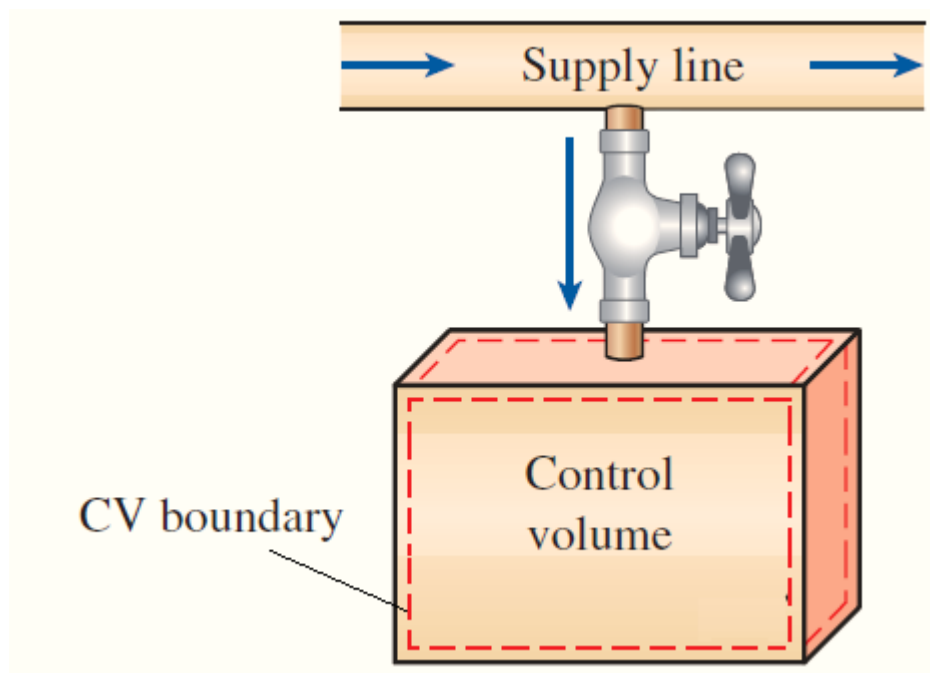
For single-stream devices, the steady-flow energy balance equation becomes

$$\dot{Q} - \dot{W} = \dot{m} \left[ h_2 - h_1 + \frac{Ve_2^2 - Ve_1^2}{2} + g(Z_2 - Z_1) \right]$$

## ENERGY ANALYSIS OF UNSTEADY-FLOW PROCESSES

**Unsteady-flow, or transient flow**, processes involve changes within the control volume with time. The steady-flow relations developed earlier are obviously **بوضوح** not applicable to these processes.

Some familiar unsteady-flow processes are the charging of rigid vessels from supply lines (Fig. 2.24), discharging a fluid from a pressurized vessel, driving a gas turbine with pressurized air stored in a large container, inflating tires or balloons, and even cooking with an ordinary pressure cooker. **Unlike steady-flow processes, unsteady-flow processes start and end over some finite time period instead of continuing indefinitely. Therefore in this section, we deal with changes that occur over some time interval  $\Delta t$  instead of with the rate of changes (changes per unit time).**



**Figure 2.24** Charging of a rigid tank from a supply line is an unsteady-flow process since it involves changes within the control volume.



An *unsteady-flow system*, in some respects, is similar to a closed system, except that the mass within the system boundaries does not remain constant during a process. Another difference between steady- and unsteady-flow systems is that steady-flow systems are fixed in space, size, and shape. Unsteady-flow systems, however, are not. They are usually stationary; that is, they are fixed in space, but they may involve moving boundaries and thus boundary work. The *mass balance* for any system undergoing any process can be expressed as (*mentioned previously*).

$$m_{in} - m_{out} = \Delta m_{CV}$$

where  $\Delta m_{CV} = m_{\text{final}} - m_{\text{initial}}$  is the change in the mass of the control volume during the process. For control volumes, it can also be expressed more explicitly as

$$m_i - m_e = (m_2 - m_1)_{CV}$$

where  $i$  = inlet,  $e$  = exit, 1 = initial state, and 2 = final state of the control volume. Often one or more terms in the equation above are zero. For example,  $m_i = 0$  if no mass enters the control volume during the process,  $m_e = 0$  if no mass leaves, and  $m_1 = 0$  if the control volume is initially evacuated.

The energy content of a control volume changes with time during an unsteady-flow process. The magnitude of change depends on the amount of energy transfer across the system boundaries as heat and work as well as on the amount of energy transported into and out of the control volume by mass during the process. When an unsteady-flow process is analyzed, it is important to keep track *طريقة اتباع مسار* of the mass and energy contents of the control volume as well as the energies of the incoming and outgoing flow streams.

The general energy balance was given earlier as

*Energy balance:*

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

The general unsteady-flow process, in general, is difficult to analyze because the properties of the mass at the inlets and exits may change during a process. Most unsteady-flow processes, however, can be represented reasonably well by the **uniform-flow process**, which involves the following idealization:

*(The fluid flow at any inlet or exit is uniform and steady, and thus the fluid properties do not change with time or position over the cross section of an inlet or exit. If they do, they are averaged and treated as constants for the entire process).*

Note that unlike the steady-flow systems, the state of an unsteady-flow system may change with time and that the state of the mass leaving the control volume at any instant is the same as the state of the mass in the control volume at that instant. The initial and final properties of the control volume can be determined from the knowledge of the initial and final states, which are completely specified by two independent intensive properties for simple compressible systems.

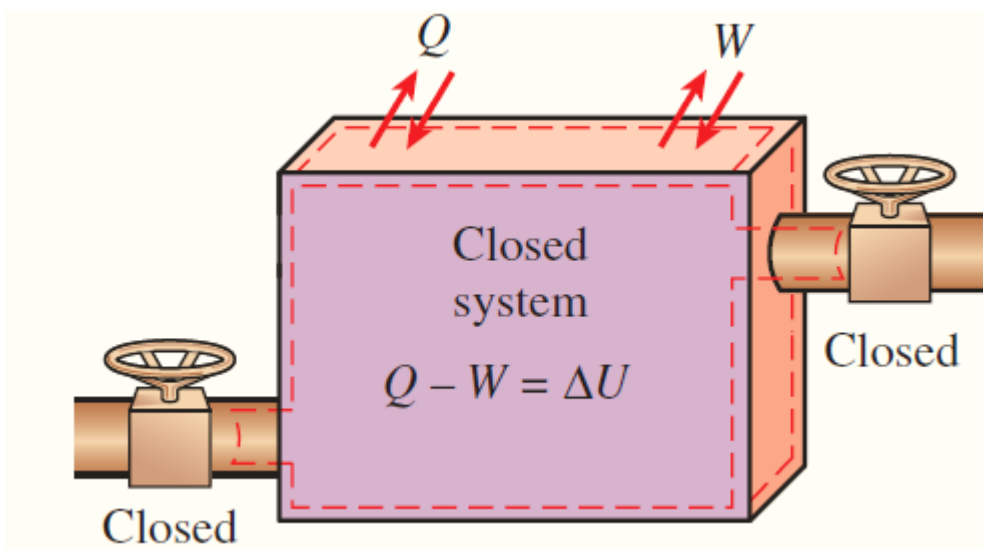
Then the energy balance for a uniform-flow system can be expressed explicitly as

$$Q_{in} + W_{in} + \sum_{in} m\theta - Q_{out} + W_{out} + \sum_{out} m\theta = (m_2e_2 - m_1e_1)_{system}$$

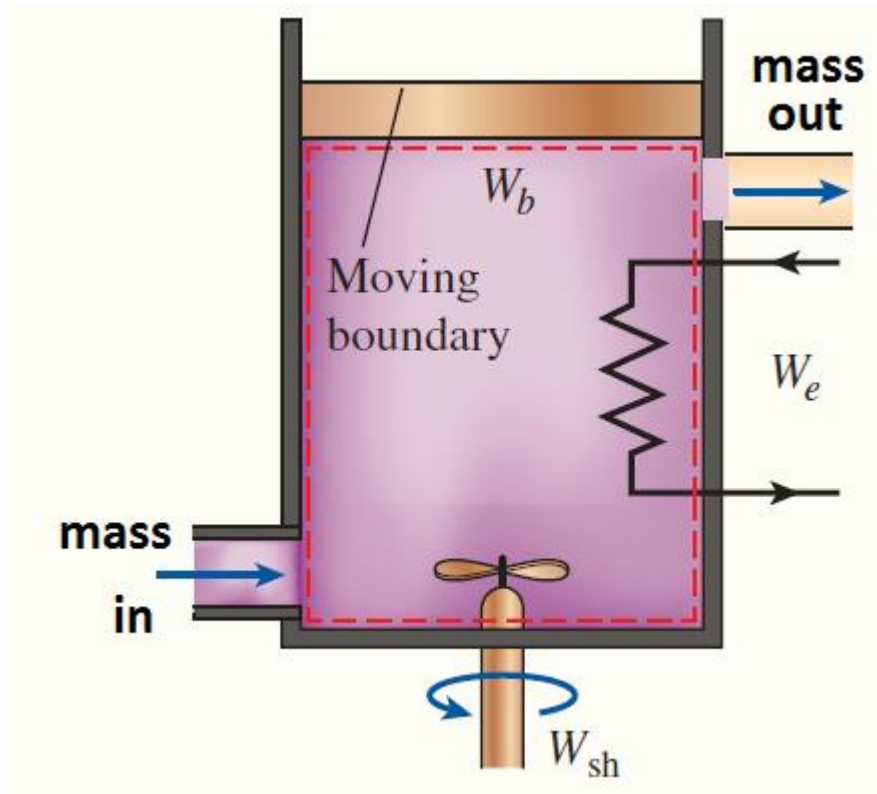
When the kinetic and potential energy changes associated with the control volume and fluid streams are negligible, as is usually the case, the energy balance above simplifies to

$$Q - W = \sum_{out} mh - \sum_{in} mh + (m_2u_2 - m_1u_1)_{system}$$

where  $Q = Q_{net,in} = Q_{in} - Q_{out}$  is the net heat input and  $W = W_{net,out} = W_{out} - W_{in}$  is the net work output. Note that if no mass enters or leaves the control volume during a process ( $m_i = m_e = 0$ , and  $m_1 = m_2 = m$ ), this equation reduces to the energy balance relation for closed systems (Fig. 2.25). Also note that an unsteady-flow system may involve boundary work as well as electrical and shaft work (Fig. 2.26).



**Figure 2.25** The energy equation of a uniform flow system reduces to that of a closed system when all the inlets and exits are closed.



**Figure 2.26** a uniform-flow system may involve mass energy, electrical, shaft, and boundary work all at once.

Although both the steady-flow and uniform-flow processes are somewhat idealized, many actual processes can be approximated reasonably well by one of these with satisfactory results نتائج مقبولة. The degree of satisfaction depends on the desired accuracy and the degree of validity of the assumptions made.

**EXAMPLE:** A garden hose خرطوم السقي attached with a nozzle is used to fill a 10-gal bucket بلو. The inner diameter of the hose is 2 cm, and it reduces to 0.8 cm at the nozzle exit. If it takes 50 s to fill the bucket with water, determine (a) the volume and mass flow rates of water through the hose, and (b) the average velocity of water at the nozzle exit.

**SOLUTION:** A garden hose is used to fill a water bucket. The volume and mass flow rates of water and the exit velocity are to be determined.

**Assumptions:** 1. Water is a nearly incompressible substance. 2. Flow through the hose is steady. 3. There is no waste الرش of water by splashing ضياع.

**Properties:** We take the density of water to be 1000 kg/m<sup>3</sup> 5 1 kg/L.



figure 2.27

**Analysis (a)** Noting that 10 gal of water are discharged in 50 s, the volume and mass flow rates of water are

$$\dot{V} = \frac{V}{\Delta t} = \frac{10 \text{ gal}}{50 \text{ s}} \left( \frac{3.7854 \text{ L}}{1 \text{ gal}} \right) = 0.757 \text{ L/s}$$

$$\dot{m} = \rho \dot{V} = \left( \frac{1 \text{ kg}}{\text{L}} \right) \left( 0.757 \frac{\text{L}}{\text{s}} \right) = 0.757 \text{ kg/s}$$

(b) The cross-sectional area of the nozzle exit is

$$A_e = \pi r_e^2 = \pi (0.4 \text{ cm})^2 = 0.5027 \text{ cm}^2 = 0.5027 * 10^{-4} \text{ m}^2$$

The volume flow rate through the hose and the nozzle is constant. Then the average velocity of water at the nozzle exit becomes

$$V_{e_e} = \frac{\dot{V}}{A_e} = \frac{0.757 \frac{\text{L}}{\text{s}}}{0.5027 * 10^{-4} \text{ m}^2} \left( \frac{1 \text{ m}^3}{1000 \text{ L}} \right) = 15.1 \text{ m/s}$$

**Discussion:** It can be shown that the average velocity in the hose is 2.4 m/s. Therefore, the nozzle increases the water velocity by over six times.

## Mixing Chambers

In engineering applications, mixing two streams of fluids takes place is commonly referred to as a mixing chamber. The mixing chamber may be an ordinary T-elbow or a Y-elbow in a shower, for example, serves as the mixing chamber for the cold- and hot-water streams (Fig. 2.28).

The conservation of mass principle for a mixing chamber requires that the sum of the incoming mass flow rates equal the mass flow rate of the outgoing mixture.

Mixing chambers are usually 1) well insulated معزولة جيدا ( $q = 0$ ). 2) Do not involve لا يتضمن any kind of work ( $w = 0$ ). 3) Also, the kinetic and potential energies of the fluid streams are usually negligible ( $ke = 0$ ,  $pe = 0$ ). Then all there is left in the energy equation is the total energies of the incoming streams and the outgoing mixture, or

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$

### **EXAMPLE: Mixing of Hot and Cold Waters in a Shower**

Consider an ordinary shower دوش where hot water at 60°C is mixed with cold water at 10°C. If it is desired that a steady stream of warm water at 43.3°C be supplied, determine the ratio of the mass flow rates of the hot to cold water. Assume the heat losses from the mixing chamber to be negligible and the mixing to take place at a pressure of 1.38 bar. Take the enthalpy values at 1.38 bar and 60°C, 43.3°C, and 10°C are 251.38, 181.6 and 42.06 kJ/kg respectively.

**SOLUTION** In a shower, cold water is mixed with hot water at a specified temperature. For a specified mixture temperature, the ratio of the mass flow rates of the hot to cold water is to be determined.

**Assumptions:** 1. This is a steady-flow process since there is no change with time at any point and thus  $\Delta m_{CV} = 0$  and  $\Delta E_{CV} = 0$ . 2. The kinetic and potential energies are negligible,  $ke = pe = 0$ . 3. Heat losses from the system are negligible and thus  $Q = 0$ . 4. There is no work interaction involved.

**Analysis:** We take the *mixing chamber* as the system (Fig. 2.29). This is a *control volume* since mass crosses the system boundary during the process. We observe that there are two inlets and one exit. Under the stated assumptions and observations, the mass and energy balances for this steady-flow system can be expressed in the rate form as follows:

$$\text{Mass balance: } \dot{m}_{in} - \dot{m}_{out} = \frac{dm_{CV}}{dt} = 0 \rightarrow \dot{m}_{in} = \dot{m}_{out} \rightarrow \dot{m}_1 + \dot{m}_2 = \dot{m}_3$$

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{\frac{dE_{\text{system}}}{dt}}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \xrightarrow{0 \text{ (steady)}} = 0$$

**Or**

$$\text{Energy balance} \quad \underbrace{\dot{E}_{\text{in}}}_{\text{Rate of net energy transfer in by heat, work, and mass}} = \underbrace{\dot{E}_{\text{out}}}_{\text{Rate of net energy transfer out by heat, work, and mass}}$$

And  $\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$  since  $\dot{Q} = 0, \dot{W} = 0, ke \cong Pe \cong 0$

Combining the mass and energy balances,  $\dot{m}_1 h_1 + \dot{m}_2 h_2 = (\dot{m}_1 + \dot{m}_2) h_3$

Dividing this equation by  $\dot{m}_2$  yields  $y h_1 + h_2 = (y + 1) h_3$

where  $y = \dot{m}_1 / \dot{m}_2$  is the desired mass flow rate ratio. Solving for y and substituting enthalpy values yields  $y = \frac{h_3 - h_2}{h_1 - h_3} = \frac{181.6 - 42.06}{251.32 - 181.6} = 2$

**Discussion:** Note that the mass flow rate of the hot water must be twice the mass flow rate of the cold water for the mixture to leave at 43.3°C.

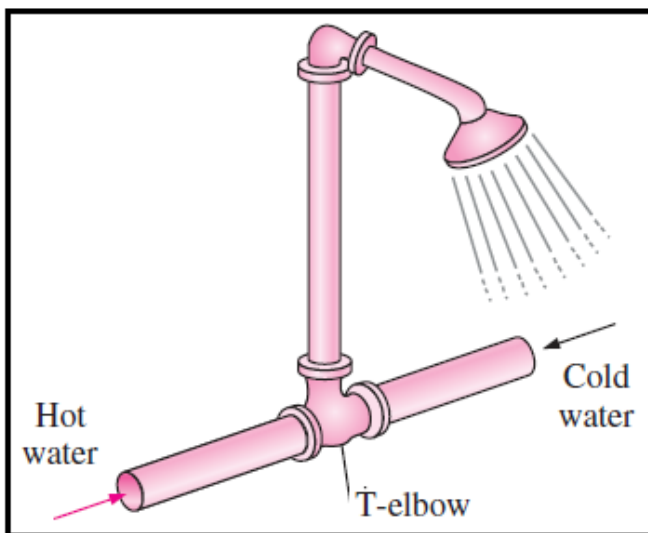


Figure 2.28 the T-elbow of an ordinary example  
Shower serves as the mixing chamber for the hot- and the cold-water streams.

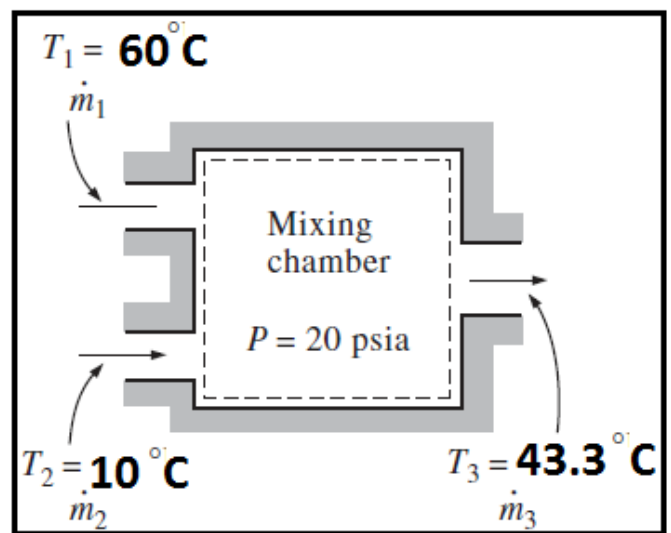


Figure 2.29 mixing chamber of

## Heat Exchangers

As the name implies, heat exchangers are devices where two moving fluid streams exchange heat without mixing. Heat exchangers are widely used in various applications, and they come in various designs. The simplest form of a heat exchanger is a double-tube (also called tube-and-shell) heat exchanger, shown in Fig. 2.30(a). It is composed of two concentric متركزة pipes of different diameters. One fluid flows in the inner pipe, and the other in the annular space between the two pipes. Heat is transferred from the hot fluid to the cold one through the wall separating them الجدار الفاصل بينهما. Sometimes the inner tube makes a couple of turns inside the shell to increase the heat transfer area, and thus the rate of heat transfer Fig. 2.30(b). The mixing chambers discussed earlier are sometimes classified as direct-contact heat exchangers.

The conservation of mass principle for a heat exchanger in steady operation requires that the sum of the inbound (في الملف الداخلي) mass flow rates equal the sum of the outbound (في الغلاف الخارجي) mass flow rates. This principle can also be expressed as follows: *Under steady operation, the mass flow rate of each fluid stream flowing through a heat exchanger remains constant.*

Heat exchangers typically involve no work interactions ( $w = 0$ ) and negligible kinetic and potential energy changes ( $\Delta ke = 0$ ,  $\Delta pe = 0$ ) for each fluid stream. The heat transfer rate associated with heat exchangers depends on how the control volume is selected see Fig 2.31. When the entire heat exchanger is selected as the control volume,  $Q$  becomes zero, since the boundary for this case lies just beneath the insulation and little or no heat crosses the boundary. If, however, only one of the fluids is selected as the control volume, then heat will cross this boundary as it flows from one fluid to the other and  $Q$  will not be zero.  $Q$  in this case will be the rate of heat transfer between the two fluids.

Heat exchangers are intended مقصود منه for heat transfer between two fluids *within* the device, and the outer shell is usually well insulated to prevent لمنع any heat loss to the surrounding المحيط medium.

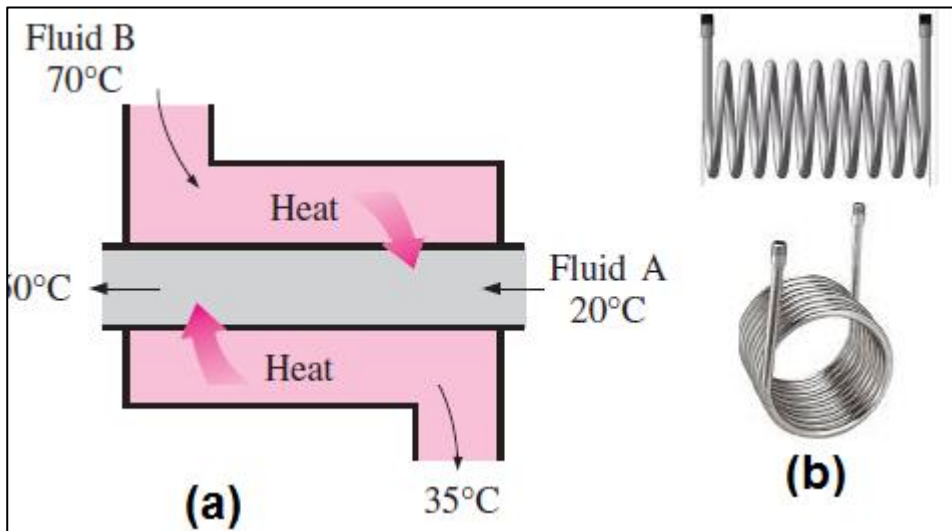


Figure 2.30 (a) double-tube heat exchanger (b) turns of tubes

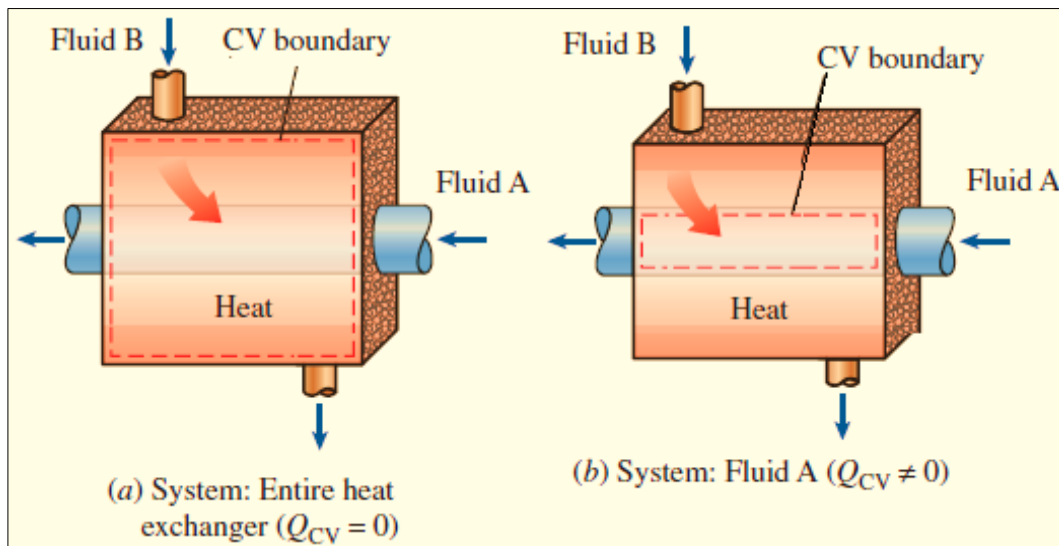


Figure 2.31 control volume selection