CHAPTER THREE

WORK AND HEAT

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.

The total energy of a system on a unit mass basis is denoted by e and is expressed as

$$e = \frac{E}{m} \qquad \text{(kJ/kg)}$$

In thermodynamic analysis, it is often helpful to consider the various forms of energy that make up the total energy of a system in two groups:

- macroscopic form of energy
- microscopic form of energy

Conti.

1.Macroscopic form of energy

are forms of energy in which system possesses as a whole with respect to some outside reference frame, such as kinetic and potential energies.

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

2. Microscopic form of energy

are those related to the molecular structure of a system and the degree of the molecular activity, and they are independent of outside reference frames. The sum of all the microscopic forms of energy is called the internal energy of a system and is denoted by *U*.

Conti.

The macroscopic energy of a system is related to motion and the influence of some external effects such as gravity, magnetism, electricity, and surface tension.

Macroscopic energy of a system

kinetic energy

$$KE = m\frac{V^2}{2} \qquad (kJ)$$

(The energy that a system possesses as a result of its motion)
This is for translating body

or, on a unit mass basis,

$$ke = \frac{V^2}{2} \qquad (kJ/kg)$$

where V denotes the velocity of the system relative to some fixed reference frame. The kinetic energy of a rotating solid body is given by $\frac{1}{2}I\omega^2$ where I is the moment of inertia of the body and ω is the angular velocity.

Conti.

Potential energy(PE)

$$PE = mgz \quad (kJ)$$

or, on a unit mass basis,

$$pe = gz \quad (kJ/kg)$$

Energy possessed as a result of its elevation in a gravitational field

The magnetic, electric, and surface tension effects are significant in some specialized cases only and are usually ignored. In the absence of such effects, the total energy of a system consists of the kinetic, potential, and internal energies and is expressed as

$$E = U + KE + PE = U + m\frac{V^2}{2} + mgz \quad (kJ)$$

or, on a unit mass basis,

$$e = u + ke + pe = u + \frac{V^2}{2} + gz \quad (kJ/kg)$$

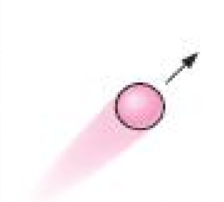
Conti.

Internal energy

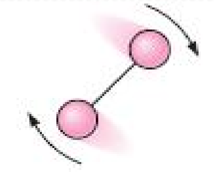
Internal energy is defined as the sum of all the microscopic forms of energy of a system.

It is related to the molecular structure and the degree of molecular activity and can be viewed as the sum of the kinetic and potential energies of the molecules.

To have a better understanding of internal energy, let us examine a system at the molecular level.



translational motion of molecules → molecules possess translational kinetic energy



atoms of polyatomic molecules rotate about their axis → molecules possess rotational kinetic energy

Conti.

atoms of polyatomic molecules vibrate about their common mass-center back-and –forth → molecules possess vibrational kinetic energy

electrons of the atom rotate → possess rotational kinetic energy

electron spin about their axis → possess spin energy

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

Conti.

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

The average velocity and the degree of activity of the molecules are proportional to the temperature of the gas.

Therefore, at higher temperatures, the molecules possess higher kinetic energies, and as a result the system has a higher internal energy.

The internal energy is also associated with various *binding forces between* the molecules of a substance, between the atoms within a molecule, and between the particles within an atom and its nucleus.

During phase-change process energy is added to break the bond between the molecules of the substance. Due to this added energy internal energy of the system increase. The internal energy associated with phase of a system is latent energy.

Phase-change process can occur without a change in the chemical composition of a system.

Conti.

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. The internal energy associated with the atomic bonds in a molecule is called chemical energy.

During a chemical reaction, such as a combustion process, some chemical bonds are destroyed while others are formed. As a result, the internal energy changes.

- ✓ change in structure of electrons of atoms
- ✓ an atom preserves its identity during a chemical reaction

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

The tremendous amount of energy associated with the strong bonds within the nucleus of the atom itself is called nuclear energy.

- ✓ nuclear reaction involves changes in the core or nucleus.
- ✓ atoms loses it’s identity during a nuclear reaction.

Conti.

Forms of energy which constitute the total energy of a system can be

1.Static form of energy

total energy of a system can be contained or stored

2.Dynamic form of energy

not stored in the system

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 closed system are heat transfer and work.

An energy interaction is heat transfer if its driving force is a temperature difference. Otherwise it is work, as explained in the next section. A control volume can also exchange energy via mass transfer since any time mass is transferred into or out of a system, the energy content of the mass is also transferred with it.

ENERGY TRANSFER BY HEAT

Energy can cross the boundary of a closed system in two distinct forms:

heat

and

work

It is important to distinguish between these two forms of energy. Therefore, they will be discussed first, to form a sound basis for the development of the laws of thermodynamics.

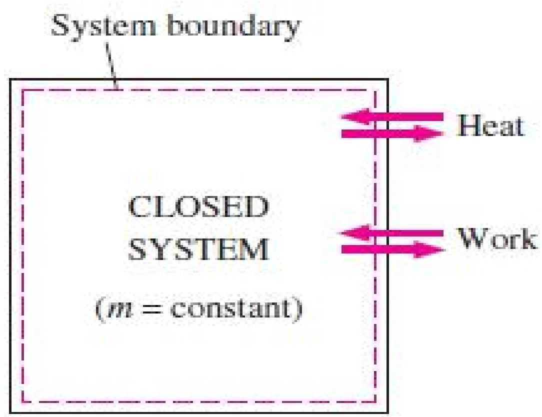


Fig. Energy can cross the boundaries of a closed system in the form of heat and work.

Conti.

HEAT

is a form of energy that is transferred across the boundary of a system to another system or surroundings by virtue of temperature difference.

No heat transfer takes place between two systems that are at same temperature.

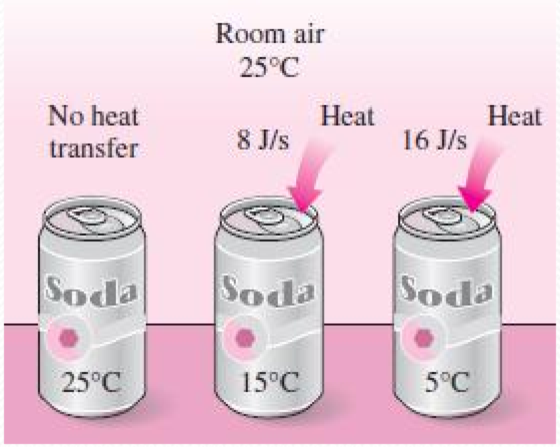


Fig. Temperature difference is the driving force for heat transfer. The larger the temperature difference, the higher is the rate of heat transfer.

Conti.

Adiabatic process

a process during which there is no heat transfer.

The word adiabatic comes from the Greek word adiabatos, which means not to be passed.

There are two ways a process can be adiabatic:

1.Either the system is well insulated so that only a negligible

amount of heat can pass through the boundary, or

2. both the system and the surroundings are at the same temperature and therefore there is no driving force (temperature difference) for heat transfer.

An adiabatic process should not be confused with an isothermal process. Even though there is no heat transfer during an adiabatic process, the energy content and thus the temperature of a system can still be changed by other means such as work.

Conti.

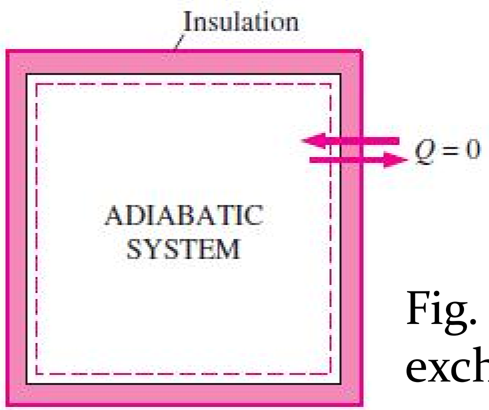


Fig. During an adiabatic process, a system exchanges no heat with its surroundings.

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

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

Conti.

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 fig below. 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:

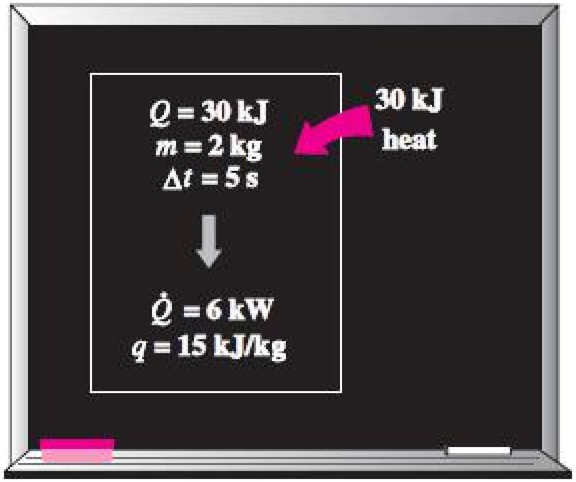
$$Q = \int_{t_1}^{t_2} \dot{Q}\, dt \qquad \text{(kJ)}$$

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

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

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

Conti.



The relationships among q, Q, and $\dot{Q}$.

Energy transfer by work

In mechanics work is defined in terms of macroscopically observable forces and displacement. Mathematically it is expressed as

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

This relation can be used to find the work required to raise a weight, to stretch a wire, or to move a charge particle through a magnetic field.

However, in thermodynamics, we deal with interactions between system or control volume and the surroundings. It becomes advantages to tie this definitions with the concepts of systems,properties,and processes. With this in mind work is defined as follows;

work is done by a system if the sole effect on the surrounding could be the raising of a weight.

energy can cross the boundary of a closed system in the form of heat or work. Therefore, if the energy crossing the boundary of a closed system is not heat, it must be work.

Cont…

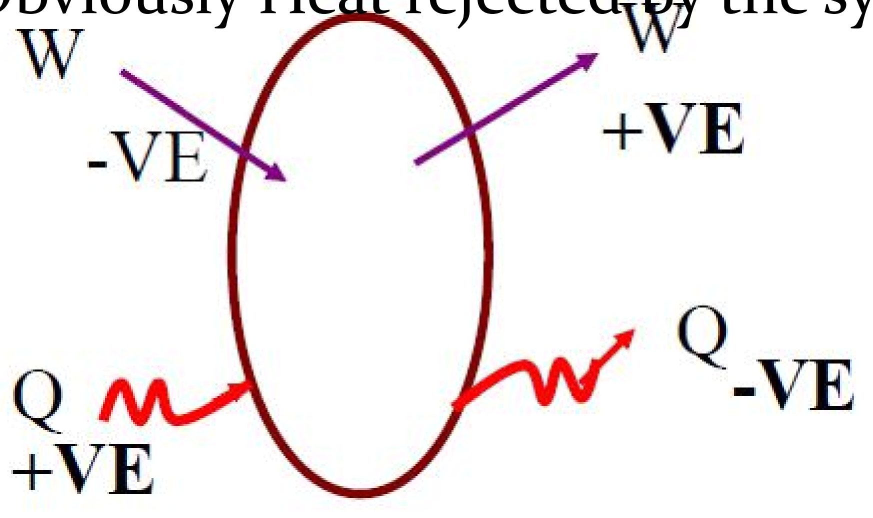
- The work done by a system in the direction of motion is positive.
- The work done on the system by a force acting opposite to the direction of motion is negative.

- we deal with interactions between systems or control volume and the surrounding.
- - it is defined
- "work is done by a system if the sole effect on the surroundings could be the raising of a weight"

Sign Conventions

Work done BY the system is **POSITIVE**
Obviously work done ON the system is **–ve**

Heat given TO the system is **POSITIVE**
Obviously Heat rejected by the system is **-ve**



Conti.

More specifically, work is 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.

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 1and 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

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

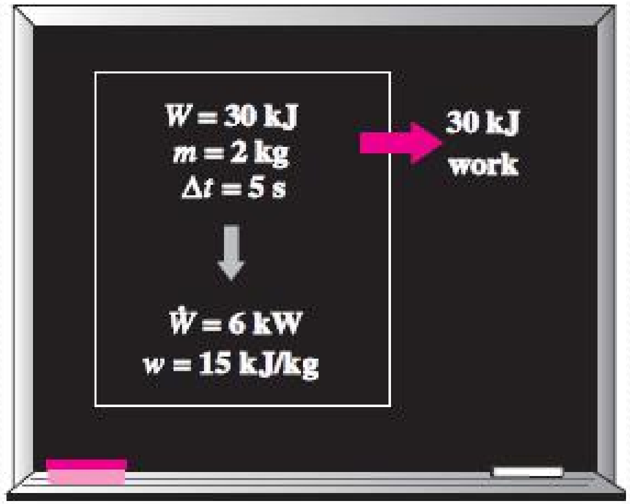
The work done *per unit time* is called **power** and is denoted $\dot{W}$
The unit of power is kJ/s, or kW.

Conti.

$$p = w = \frac{\delta W}{\delta t} \qquad \text{(kw)}$$

A popular unit for power(English units) which persists to this day is the horsepower(hp),given by the equivalence

1hp=0.746kw



The relationships among w, W, and $\dot{W}$.

Conti.

Electrical work

electrons crossing the system boundary do electrical work on the system. In an electric field, electrons in a wire move under the effect of electromotive forces, doing work as shown below.

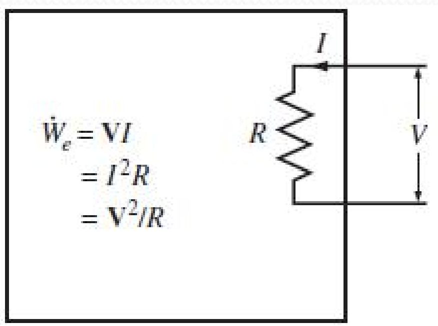


Fig. Electrical power in terms of resistance R, current I, and potential difference **V.**

When Q coulombs of electrical charge move through a potential difference V, the electrical work done is

$$W_e = VQ$$

which can also be expressed in the rate form as

$$\dot{W}_e = VI \qquad \text{(W)}$$

Conti.

where $\dot{W}_e$ is the **electrical power** and I is the number of electrical charges flowing per unit time, that is, the *current* . In general, both $\mathbf{V}$ and I vary with time, and the electrical work done during a time interval Δt is expressed as

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

When both $\mathbf{V}$ and I remain constant during the time interval Δt, it reduces to

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

Other forms of work

Shaft work

Energy transmission with a rotating shaft is very common in engineering practice .

Often 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

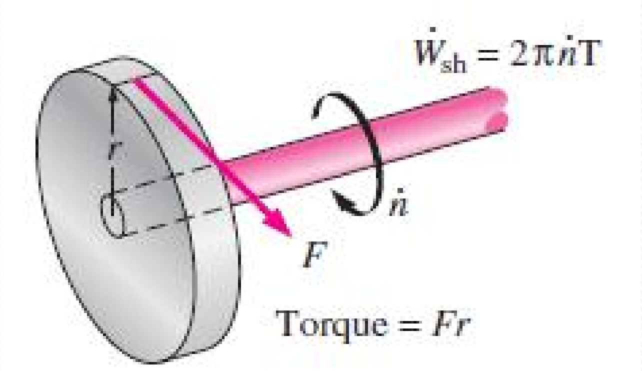


Fig. Shaft work is proportional to the torque applied and the number of revolutions of the shaft.

Conti.

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

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

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

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

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

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

Conti.

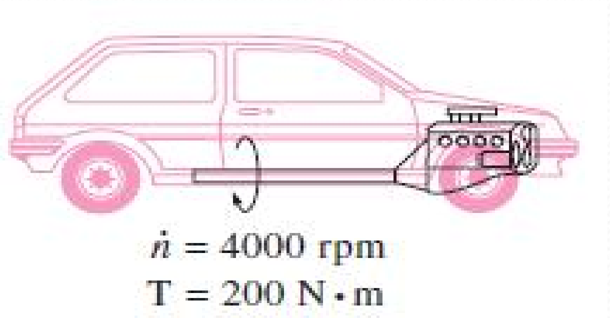
Example

Determine the power transmitted through the shaft of a car when the torque applied is 200 N · m and the shaft rotates at a rate of 4000 revolutions per minute (rpm).

Solution

$$\dot{W}_{sh} = 2\pi\dot{n}T = (2\pi)\left(4000\frac{1}{\text{min}}\right)(200\ \text{N}\cdot\text{m})\left(\frac{1\ \text{min}}{60\ \text{s}}\right)\left(\frac{1\ \text{kJ}}{1000\ \text{N}\cdot\text{m}}\right)$$

$$= \mathbf{83.8\ kW} \qquad \text{(or 112 hp)}$$



Conti.

Spring Work

It is common knowledge that when a force is applied on a spring, the length of the spring changes (Fig. below).

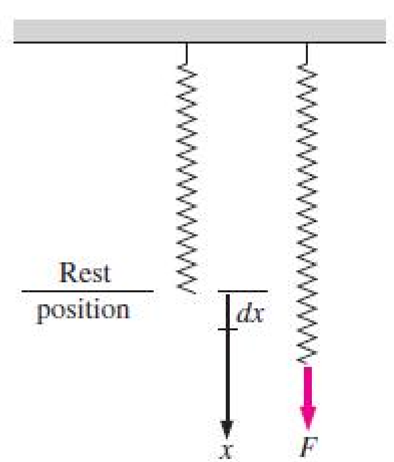


Fig. Elongation of a spring under the influence of a force.

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

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

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

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

where k is the spring constant and has the unit kN/m.

Conti.

The displacement x is measured from the undisturbed position of the spring (that is, x= 0 when F= 0). Substituting above equation into the previous one and integrating yield

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

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.

MOVING BOUNDARY WORK

One form of mechanical work frequently encountered in practice is associated with the expansion or compression of a gas in a piston–cylinder device.

During this process, part of the boundary (the inner face of the piston) moves back and forth.

Therefore, the expansion and compression work is often called **moving boundary work, or simply boundary work or PdV work.**

This kind of work involve in automobile engine and compressors.

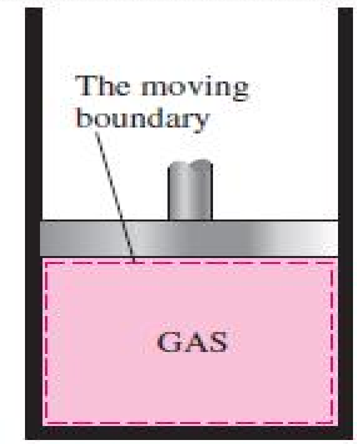


fig. The work associated with a moving boundary is called boundary work.

Conti.

Consider the gas enclosed in the piston-cylinder device

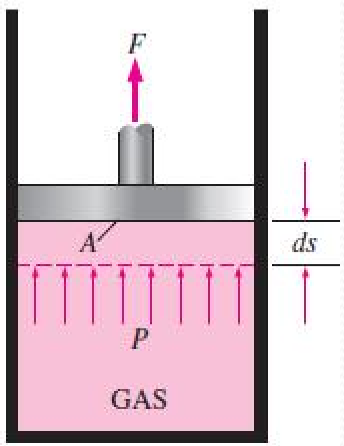
let p=initial pressure of the gas

V=total volume

A= cross-sectional

process is quasi-equilibrium process

→ a process during which the system remains nearly in equilibrium at all times.



A gas does a differential amount of work δW_b as it forces the piston to move by a differential amount ds.

conti.

If the piston is allowed to move a distance *ds* in a quasi-equilibrium manner, the differential work done during this process is

$$\delta W_b = F\,ds = PA\,ds = P\,dV$$

That is, the boundary work in the differential form is equal to the product of the absolute pressure P and the differential change in the volume dV of the system. This expression also explains why the moving boundary work is sometimes called the P dV work.

Sign

p(absolute pressure)=always +ve

Volume change dV =is +ve during expansion because volume increase and the system do positive work

=is –ve during compression because volume decrease and system do –ve work.

Conti.

The total boundary work done during the entire process as the piston moves is obtained by adding all the differential works from the initial state to the final state:

$$W_b = \int_1^2 P\,dV \qquad \text{(kJ)}$$

evaluated if P=f(V) is known.

The area under the process curve on a P-V diagram is equal, in magnitude, to the work done during a quasi-equilibrium expansion or compression process of a closed system.

Conti.

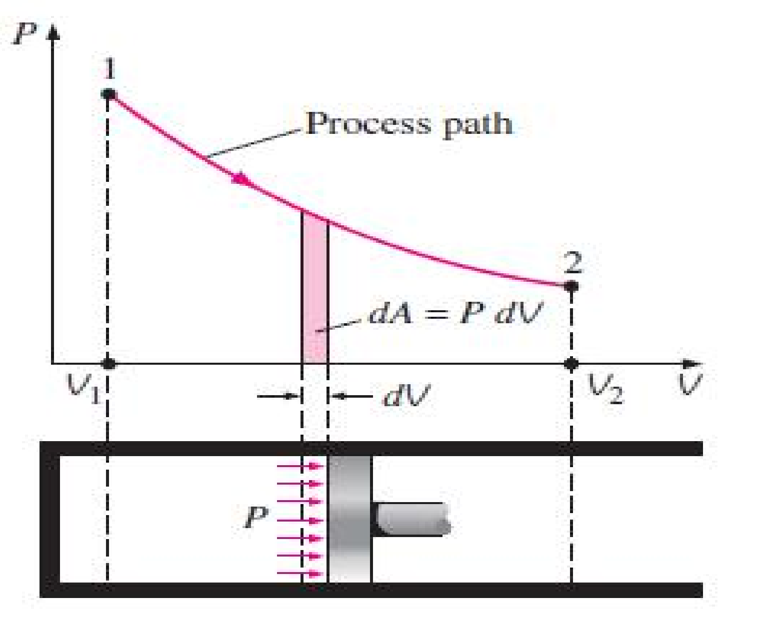


Fig. The area under the process curve on a P-V diagram represents the boundary work.

On this diagram, the differential area dA is equal to P dV, which is the differential work. The total area A under the process curve 1–2 is obtained by adding these differential areas:

$$\text{Area} = A = \int_1^2 dA = \int_1^2 P\,dV$$

Conti.

A gas can follow several different paths as it expands from state 1 to state 2. In general, each path will have a different area underneath it, and since this area represents the magnitude of the work, the work done will be different for each process.

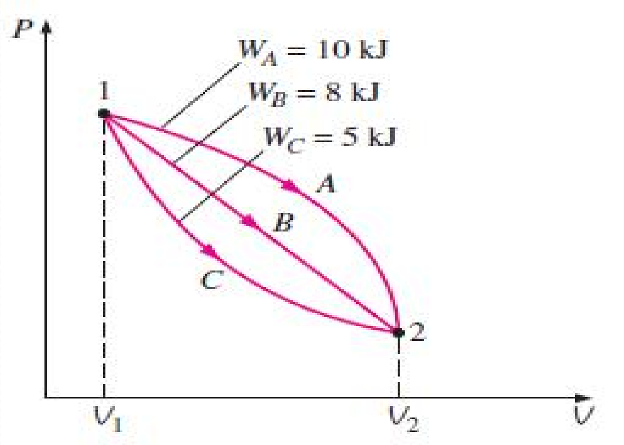


Fig.The boundary work done during a process depends on the path followed as well as the end states.

work is a path function (i.e., it depends on the path followed as well as the end states).

If work were not a path function, no cyclic devices (car engines, power plants) could operate as work-producing devices.

The work produced by these devices during one part of the cycle would have to be consumed during another part, and there would be no net work output.

Conti.

The cycle shown in Fig.below. produces a net work output because the work done by the system during the expansion process (area under path A) is greater than the work done on the system during the compression part of the cycle (area under path B), and the difference between these two is the net work done during the cycle (the colored area).

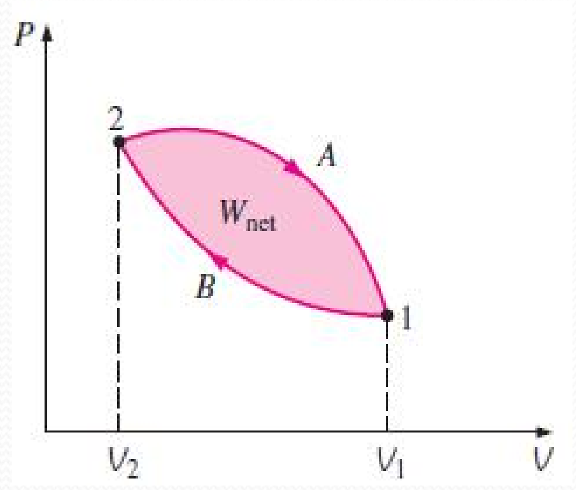
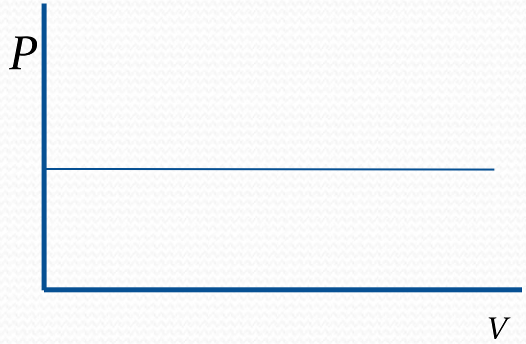


Fig. The net work done during a cycle is the difference between the work done by the system and the work done on the system.

- Moving boundary work for a **constant pressure**

$$W_b = P\,[v_2 - v_1]$$



UNITS OF WORK

Work is expressed as the product of force and displacement

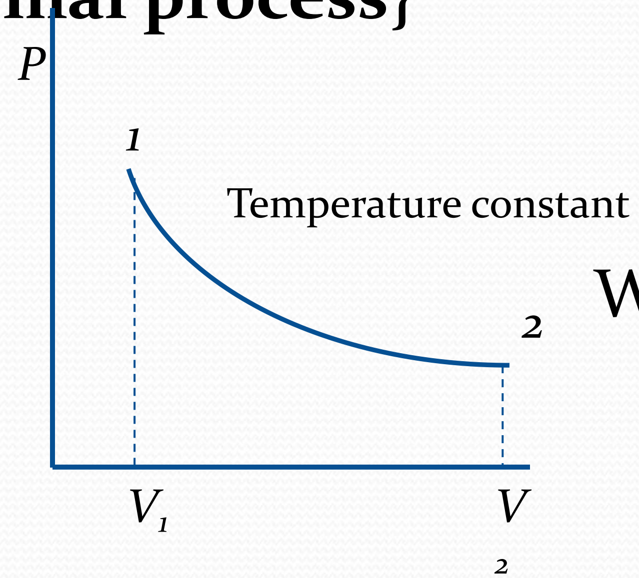
1J=1Nm

1KJ=10^3 1hp=0.746kw power the rate of doing work

1MJ=10^6

1GJ=10^9

- Boundary work for a **constant temperature {isothermal process}**



PV=mRT=C

$W_b = P_1 V_1 \ln(V_2/V_1)$

proof.......

Polytropic Process

During actual expansion and compression processes of gases, pressure and volume are often related by

$$PV^n = C$$

where n and C are constants.

A process of this kind is called a polytropic process see fig. below.

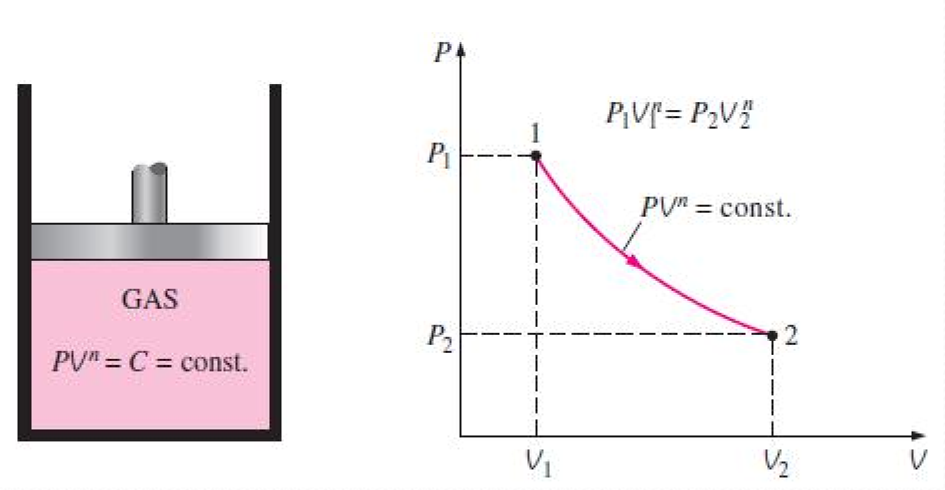


Fig. Schematic and P-V diagram for a polytropic process.

Conti.

Below we develop a general expression for the work done during a polytropic process. The pressure for a polytropic process can be expressed as

$$P = CV^{-n}$$

substitute into $W_b = \int_1^2 P\,dV \quad \text{(kJ)}$,we obtain

$$W_b = \int_1^2 P\,dV = \int_1^2 CV^{-n}\,dV = C\frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1} = \frac{P_2V_2 - P_1V_1}{1-n}$$

since $C = P_1V_1^n = P_2V_2^n$. For an ideal gas ($PV = mRT$), this equation can also be written as

$$W_b = \frac{mR(T_2 - T_1)}{1-n} \qquad n \neq 1 \qquad \text{(kJ)}$$

For the special case of $n = 1$ the boundary work becomes

$$W_b = \int_1^2 P\,dV = \int_1^2 CV^{-1}\,dV = PV\ln\left(\frac{V_2}{V_1}\right)$$

For an ideal gas this result is equivalent to the isothermal process discussed in the previous example.

EXAMPLE.

A rigid tank contains air at 500 kPa and 150°C. As a result of heat transfer to the surroundings, the temperature and pressure inside the tank drop to 65°C and 400 kPa, respectively. Determine the boundary work done during this process.

SOLUTION

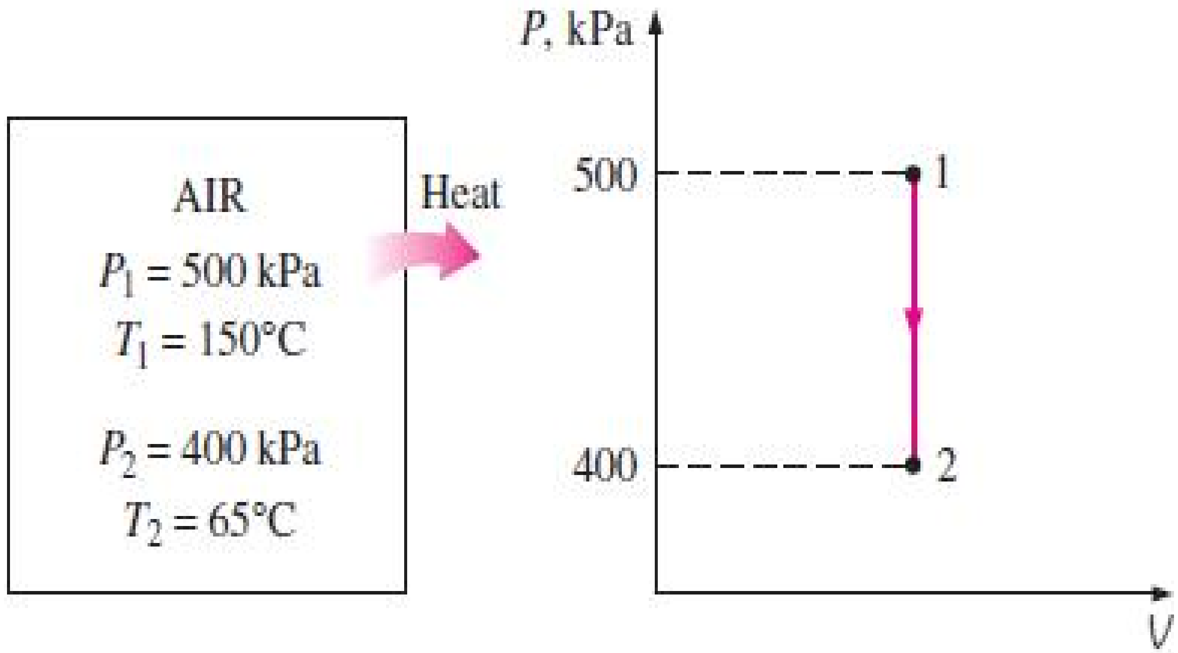
Air in a rigid tank is cooled, and both the pressure and temperature drop. The boundary work done is to be determined.

Rigid tank has a constant volume and dv = 0 .

Therefore, there is no boundary work done during this process. That is, the boundary work done during a constant-volume process is always zero.

$$W_b = \int_1^2 P\, d\mathcal{V}^{\nearrow 0} = 0$$

Conti.



Example.

A gas is contained within a piston-cylinder device initially at 2.0Mpa and $0.02m^3$ .it expands to a final volume of under the following processes

a)Constant pressure

b) PV=constant

c) $PV^{1.4}$ =constant

Find the work done in each process

EXAMPLE

Four kg of saturated liquid water is maintained at a constant pressure of 600 kPa while heat is added until the temperature reaches 600°C. Determine the work done by the water.