

WORK AND HEAT

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Work and heat are two forms of energy and both can be converted to each other. Work can be converted totally to heat while heat can be converted partially to work. Therefore work is considered as high grade energy and heat is a low grade energy.

WORK

In thermodynamics work is defined as follows: “work is done if the sole effect on the surroundings could be the raising of a weight”. The raising of a weight is in effect a force acting through a distance.

In physics work is defined as the acting force multiplied by the distance moved in the direction of force, see fig (4-1).

$$W = \int_1^2 F dX \quad (4-1)$$

Where F (N) is the force and X (m) is the distance moved.

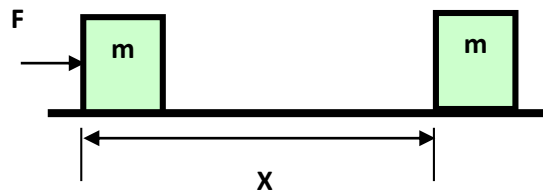


Fig (4-1)

Work is considered as energy in transition since no work done unless there is a force acting through a distance. Therefore work is different than internal energy since work can be done on or by the system while internal energy is contained by the system.

Since the work is one form of energy it has the units of energy (Joule (J) = N.m). The time rate of doing work is power. The units of power is Watt (W=J/s) or its multiples (kW, MW, GW). The work done by the system on its surroundings is positive while the work done by the surroundings on the system is negative.

WORK ON MOVING BOUNDARIES OF SYSTEM

In thermodynamics the work is done either due to expansion process (increase in system volume) or due to compression process (decrease in system volume). In other words when the system undergoes an expansion process it is doing work on the surroundings while when the system undergoes a compression process the work is done by the surroundings on the system. An example

of this system is the piston cylinder arrangement. When the piston moves inside the cylinder which contains a compressible fluid the volume of the cylinder or the volume of the fluid either increases or decreases. The compressible fluid is either gas or vapor while the liquid is incompressible fluid. In incompressible fluids the volume remains approximately constant even when their pressure and temperature change. In order to understand the work done on a moving boundary let us consider the piston cylinder arrangement shown in fig (4-2).

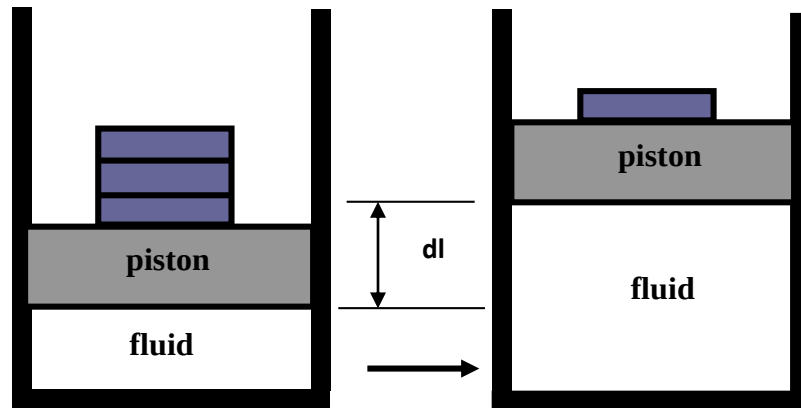


Fig (4-2)

Assume that the piston carries some weights so that when removing one of these weight the fluid inside the cylinder expands. Assume that the piston, the fluid and the cylinder forms a closed system and this system undergoes an expansion process due to removing one of the small weights. This process is a non-flow expansion process. Let us assume the following assumptions:

- 1-The pressure of fluid inside the cylinder exerted on the piston is uniform during the process.
- 2-The fluid temperature inside the cylinder is uniform during the process.
- 3-The fluid passes through a series of internal equilibrium states which means that the processes is internally reversible.

When one small weight is removed from the piston it moves up a distance (dL) and the volume of the cylinder increases. The work done during this expansion process can be calculated as follows:

$$\delta W = F dL \quad (4-2)$$

Where F is the force acting on the piston to move a distance dL .

If the piston cross sectional area is (A) and the pressure inside the cylinder is P , then the F is equal,

$$F = PA \quad (4-3)$$

$$\delta W = P A dL \quad (4-4)$$

$$\therefore \delta W = P dV \quad (4-5)$$

Since $dV = Adl$

The total work done can be calculated by integrating the above equation from the initial state to the final state.

$$W = \int_1^2 \delta W = \int_1^2 P dV \quad (4-6)$$

The integral on the right hand side of the above equation can be solved unless the relationship between pressure and volume during the process is known, i.e. the process is reversible. The work done during any process is represented by the area under the curve on the P-V diagram as shown in fig (4-3).

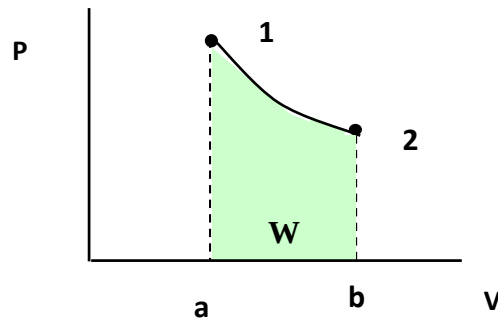


Fig (4-3)

Let us consider the cylinder of a reciprocating internal combustion engine where a piston is moving up and down inside the cylinder. During the upward movement there is a compression process where the cylinder volume decreases while during the downward movement there is an expansion process where the cylinder volume increases as shown in fig (4-4). The piston does work on the working fluid during the compression process which is a negative work and the working fluid does work on the piston during the expansion process which is a positive work. Processes 1-2 and 2-1 may be assumed reversible to simplify the analysis and is represented by the area under the curve for each process. In this case the work done by process 1-2 equals the work done by process 2-1 but with opposite sign. There are an infinite possible paths between states (1) and (2) and since the work is represented by the area under the curve on the P-V diagram and this area depends on the path we can conclude that the work is a path function as shown in fig (4-5). The work is also a transient energy (boundary phenomena).

$$\int_1^2 \delta W \neq W_2 - W_1 \quad (4-7)$$

But,

$$\int_1^2 \delta W = W_{1-2} \quad (4-8)$$

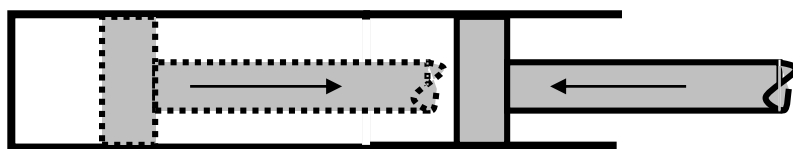
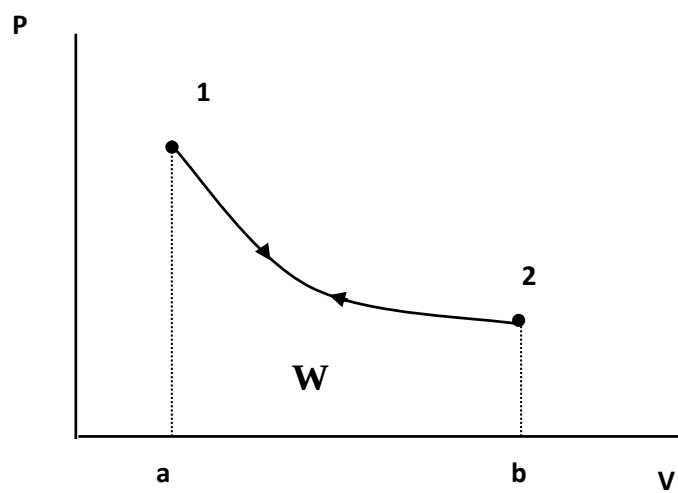


Fig (4-4)

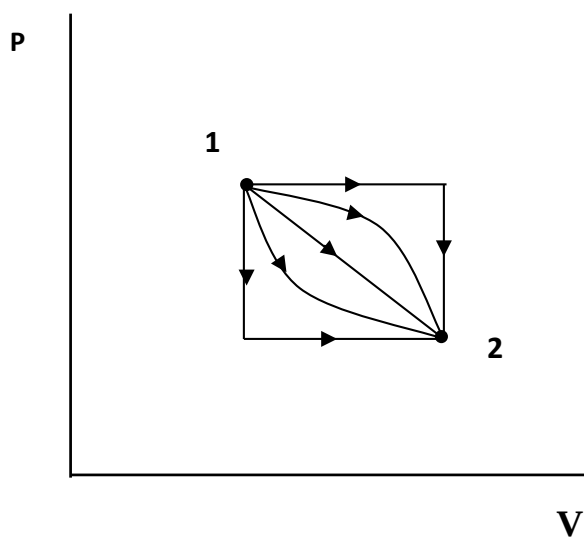


Fig (4-5)

Example 4-1

Consider a piston cylinder arrangement where the piston carries small weights. Initially the pressure of the gas inside the cylinder is 200 kPa and the cylinder volume is 0.04 m³. The cylinder is heated and at the same time the small weights are gradually removed so that the piston moves upward while the gas temperature remains constant. The heating process continues until the cylinder volume becomes 0.1 m³.

Assume that the process is reversible. Since the temperature remains constant during the process it is represented by the following equation.

$$PV = C$$

The work done will be,

$$W = \int_1^2 P dV$$

$$P = \frac{C}{V}$$

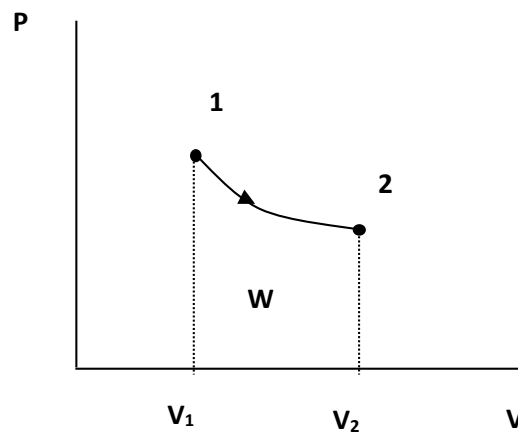
$$W = \int C \frac{dV}{V} = C \int_1^2 \frac{dV}{V}$$

$$W = C \ln \frac{V_2}{V_1}$$

$$C = P_1 V_1$$

$$\therefore W = P_1 V_1 \ln \frac{V_2}{V_1}$$

$$W = 200 \times 0.04 \ln \frac{0.1}{0.04} = 7.33 \text{ kJ}$$



Example 4-2

A piston cylinder arrangement contains 50 kg of water at 200 kPa with a volume of 0.1 m³. The cylinder has piston stops so that the maximum cylinder volume is 0.5 m³. The cylinder is heated until 200 °C. Calculate the cylinder volume and pressure at the end of heating process and the work done on piston during the heating process.

Calculate the specific volume of water inside the cylinder.

$$v = \frac{V}{m} = \frac{0.1}{50} = 0.002 \text{ m}^3/\text{kg}$$

Since v is less than v_g at 200 kPa the steam is wet.

The maximum possible specific volume is when the piston reaches the stops.

$$v_{\max} = \frac{V}{m} = \frac{0.5}{50} = 0.01 \text{ m}^3/\text{kg}$$

The heating process is at constant pressure until the piston reaches the stops and becomes constant volume process if the heating continues.

Assume that the temperature reaches 200 °C before the piston reaches the stops which means the steam state is (200 kPa and 200 °C). At this state the steam should be superheated since the saturation temperature at 200 kPa is 120 °C. The specific volume of the superheated steam is 1.0715 m³/kg (from tables). This is impossible since the maximum possible specific volume is 0.01 m³/kg.

This means that the piston rests on the stops and the heating process continues at constant pressure until 200 °C and the pressure increases.

From tables the specific volume of the saturated steam at 200 °C is ($v_g = 0.127 \text{ m}^3/\text{kg}$) which is larger than the maximum possible specific volume (0.01 m³/kg). Hence the steam is wet and the pressure inside the cylinder will equal the saturation pressure at 200 °C which equals 15.5 bar (from saturated steam table).

The work done during the heating process equals the sum of work done during the constant pressure heating stage and the work done during the constant volume heating stage.

During the constant pressure stage,

$$w = P \int_1^2 dv = P(V_2 - V_1)$$

$$\therefore w = 200 \times (0.5 - 0.1) = 80 \text{ kJ}$$

The work done during the constant volume stage is zero.

Hence the total work done is 80 kJ.

HEAT

Heat is the thermal energy that crosses the boundaries of a system at a certain temperature to the surroundings or adjacent system at lower temperature due to temperature difference. The heat transferred produces changes in the system properties for both systems. Since heat is a transient energy like work the system never possess heat. Heat is like work is a path function (boundary phenomena). Therefore,

$$\int_1^2 \delta Q \neq Q_2 - Q_1 \quad (4-9)$$

But,

$$\int_1^2 \delta Q = Q_{1-2} \quad (4-10)$$

Where Q_{1-2} is the heat transferred to or from the system during the process 1-2.

Since heat is energy it has the units of energy (Joule (J)) or its multiples. The time rate of heat transfer has the units of Watt (W) or its multiples. When the heat is transferred to the system it is positive (heat gained) and when lost from the system it is negative (heat lost).

Modes of Heat Transfer

Heat is transferred from one system to another by three modes namely, conduction, convection and radiation.

Conduction heat transfer occurs between solid systems and governed by Fouriers law.

$$\dot{Q} = -kA \frac{dT}{dx} \quad (4-11)$$

This means that the conduction heat transfer depends on the temperature gradient $\left(\frac{dT}{dx}\right)$ which

is negative. For each pure substance there a property known as thermal conductivity (k).

A is the area of heat transfer (m^2).

Radiation is the heat transferred by electromagnetic radiation from the system (black body) per unit area which depends on its temperature. It is governed by Stefan-Boltzmann law.

$$\dot{q} = \sigma T_s^4 \quad (4-12)$$

Where,

T= Radiant system absolute temperature (K)

σ = Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$).

For each surface there is a property known as thermal emissivity (ϵ). Therefore the rate of heat radiation from a real surface is,

$$\dot{q} = \epsilon \sigma T_s^4 \quad (4-13)$$

Convection heat transfer occurs in fluids (liquid, vapor and gas). It occurs between layers of the same fluid due to density difference caused by temperature gradient between adjacent layers or between a fluid and adjacent solid surface. There are two types of convection either natural convection or forced convection. It is governed by Newton's law.

$$\dot{Q} = h A \Delta T \quad (4-14)$$

Where,

h =convective heat transfer coefficient ($W/m^2.K$)

A =area of heat transfer (m^2)

ΔT =Temperature difference.

Convective heat transfer depends on the convective heat transfer coefficient, the fluid properties and the type of flow.

Comparison between work and heat

1-Both work and heat are transient phenomena.

2-The system never possess work nor heat but work and heat cross the system boundaries during a process.

3-Both work and heat are energy and have the units of energy (J).

4-Both work and heat are boundary phenomena.

5-Both work and heat are path function.

6-Both work and heat are inexact differentials (δW and δQ).

7-Work can be converted totally to heat and therefore it is a high grade energy.

8-Heat is converted partially to work and therefore it is a low grade energy.

9-Work occurs due to a resultant of force acting on the system boundaries.

10-Heat occurs due to temperature difference across system boundaries.

11-Both work and heat are energy quantities and not system properties.