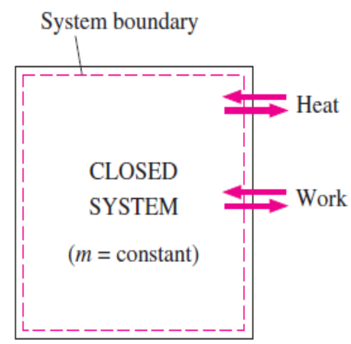
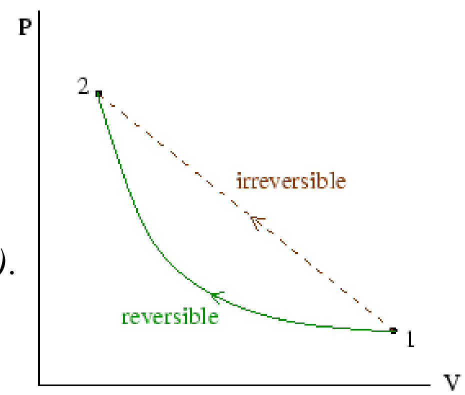
The First Law of Thermodynamics: Closed Systems

Closed systems do not involve any mass flow across their boundaries.
Energy can cross the boundary of a closed system in two distinct forms: heat and work



Reversibility

- *In reversible process (quasi-static process), both the system and its surroundings can be returned to their initial states and the system passes through a continuous series of equilibrium states (continuous line).*
- *In practice, the system undergoing a process cannot be kept in equilibrium in intermediate states and therefore the real processes are considered as irreversible ones (dotted line).*

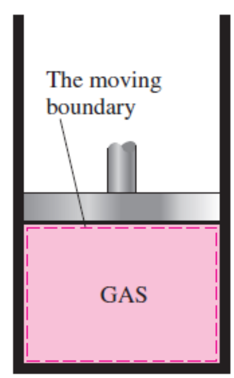


- *The criteria of reversibility are listed as follows:*
  1. *The process must be frictionless (no internal and mechanical frictions)*
  2. *The difference in pressure between the system and its surroundings during the process must be infinitely small (infinitely slow process)*
  3. *The difference in temperature between the system and its surroundings during the process must be infinitely small (heat transferred is infinitely slow)*

- *It is obvious from the above criteria that no process in practice is truly reversible. However, the internal reversibility is approximated as the system can restore its initial state, but the surrounding is impossible to retain its initial state.*

Reversible Work

The work is associated with the expansion or compression of a working fluid 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 such as in automobile engines



(theoretically).

Consider the gas enclosed in the piston–cylinder device, where:

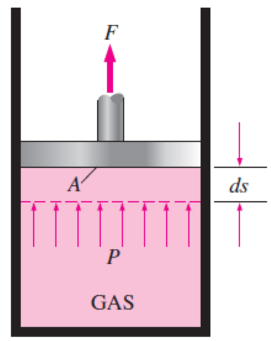
P= the initial pressure of the gas

V= the total volume

A= the cross-sectional area of the piston

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

Differential work done=Acting force*travelled distance



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

$dV = V_2 - V_1$ (d means exact differential and point function)

$\delta W_b \# W_2 - W_1$ (δ means inexact differential and path function)

The total boundary work done during the entire process from the initial state (1) to the final state (2):

$$W_b = {}_1W_2 = W_{12} = \int_1^2 P\,dV \quad (kJ)$$

$$w_b = {}_1w_2 = w_{12} = \int_1^2 P\,dv \quad (kJ/kg)$$

This integral can be evaluated only if we know the functional relationship between P and V during the process. That is, $P = f(V)$ should be available.

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.

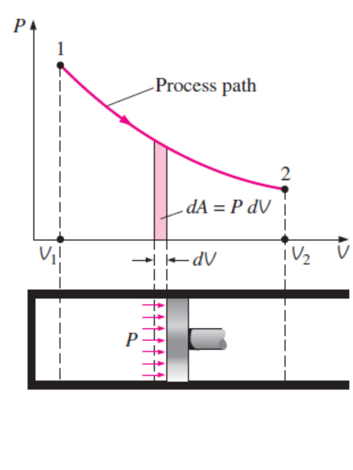
If dV is (+ve), then W_b is (+ve) too ($V_2 > V_1$, expansion process and the work done by the system)

If dV is (-ve), then W_b is (-ve) too ($V_2 < V_1$, compression process and the work done on the system)

If dV =0, then W_b =0 too ($V_2 = V_1$, no work done on or by the system)

The work per unit mass is calculated as:

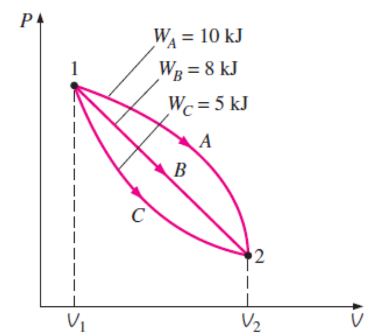
$$w_b = \int_1^2 P\,dv = \frac{W_b}{m} \quad (kJ/kg)$$



The work done per unit time is called power and is denoted by

$$\dot{W} = \frac{W}{\Delta t} \quad (kJ/s=kW)$$

Since the work is path-dependent, thus there are multi values of work (area under the curve)depend on the path of process from state 1 to state 2.

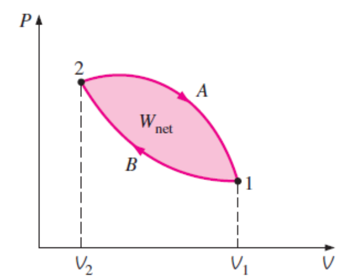


For the cycle, the net work (W_{net}) equals the algebraic sum of the work done by the system (W_{21} expansion) and the work done on the system (W_{12} compression)

$W_{net}=W_{21}+W_{12}$

If $W_{net}>0$, the cycle produces work (engine)

If $W_{net}<0$, the cycle consumes work (refrigerator)



$$W_{12} = W_B = \int_1^2 P\,dV \quad \text{Compression work as } V_2<V_1$$

$$W_{21} = W_A = \int_2^1 P\,dV \quad \text{Expansion work as } V_2>V_1$$

There are other several different ways of doing work such as:

- *Electrical Work*

The electric power is:

$$\dot{W}_e = Vo * I \quad (W)$$

As (Vo) is voltage and (I) is current

$$W = \dot{W}_e \Delta t = Vo * I * \Delta t \quad (J)$$

- *Mechanical Forms of Work*

It is the work done by a constant force F on a body displaced a distance s in the direction of the force

$$W_m = \int_2^1 F\,ds = F\,s \quad (kJ)$$

Some common forms of mechanical work are:

- *Shaft Work*

The shaft work due to applied force (F) through a moment arm (r) to produce torque (Torq) during (n) revolutions is:

$$W_{sh} = F\,s = \frac{Torq}{r}(2\pi nr) = Torq(2\pi n) \quad (kJ)$$

- *Spring Work*

For the spring has spring constant of k, the spring work is:

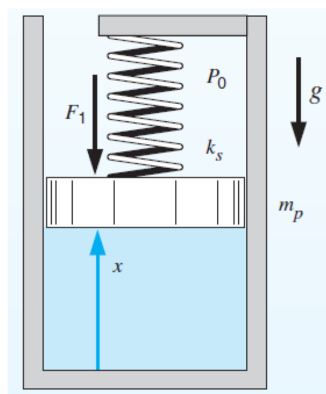
$$W_{sp} = \frac{1}{2}k\,(x_2^{\,2} - x_1^{\,2}) \quad (kJ)$$

where x_1 and x_2 are the initial and the final displacements of the spring, respectively.

For any system, the total work is the summation of all possible work which exist

$$W_{total} = W_b + W_e + W_{sh} + W_s + ...$$

Ex: *Consider a slightly different piston/cylinder arrangement as shown. The piston is loaded with a mass m_p, the outside atmosphere P_0, a linear spring, and a single point force F_1. The piston traps the gas inside with a pressure P. Derive the expression of work done.*



Sol:

A force balance on the piston in the direction of motion yields:

$$\sum F\uparrow - \sum F\downarrow = m_p a = 0$$

$$\sum F\uparrow = \sum F\downarrow$$

$$PA = P_o A + m_p g + F_s + F_1$$

$$P = P_o + \frac{m_p g}{A} + \frac{F_s}{A} + \frac{F_1}{A}$$

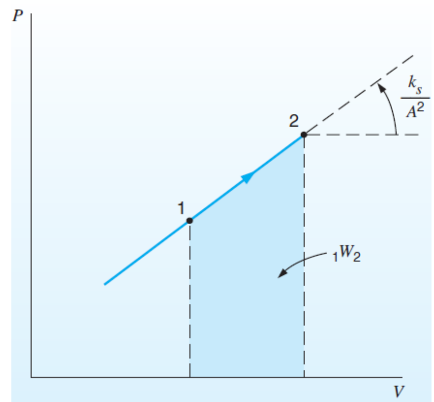
$$F_s = k_s(x - x_o)$$

$$x - x_o = \frac{V - V_o}{A}$$

$$P = P_o + \frac{m_p g}{A} + \frac{F_1}{A} + \frac{k_s(V - V_o)}{A^2}$$

$$P = a + bV$$

Linear relation between $P\,\&\,V$ *with slope* $\frac{k_s}{A^2}$



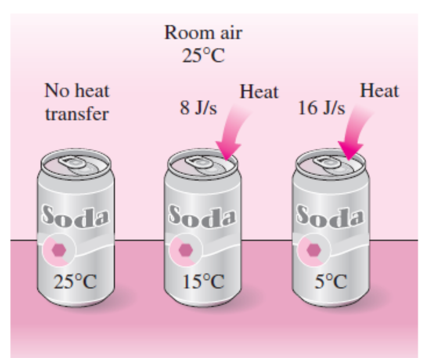
$$W = \int_1^2 P\,dV$$

(Prove !)

$$W = \frac{P_1 + P_2}{2}(V_2 - V_1)$$

Heat Transfer

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.



Transfer of heat into a system is referred to as heat addition (+ve) and the transfer of heat out of a system as heat rejection (-ve)

The amount of heat transferred during the process Between two states (states 1 and 2) is denoted by Q_{12}*, or just Q (kJ)*

Heat transfer per unit mass of a system is denoted by q and is determined from

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

The heat transfer rate $\dot{Q} = \frac{Q}{\Delta t}$ *has the unit kJ/s (kW)*

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

Also, $Q = \dot{Q}\,\Delta t = \int_{t_1}^{t_2} \dot{Q}\,dt \quad (kJ)$

Heat is transferred by three mechanisms: conduction, convection, and radiation