Chemical Engineering (Thermodynamics I) (UCH305)

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Lecture 11

Energy

Forms of Energy

Energy can exist in numerous forms such as:

What is the energy? Ability to do the work.

1) thermal
2) mechanical
3) kinetic
4) potential
5) electric
6) magnetic
7) chemical, and
8) nuclear.

- Besides above, there are:
    1. internal energy, U (or $m \times u$) (J)
    2. enthalpy, H (or $m \times h$) (J)
    3. mass, m (kg)

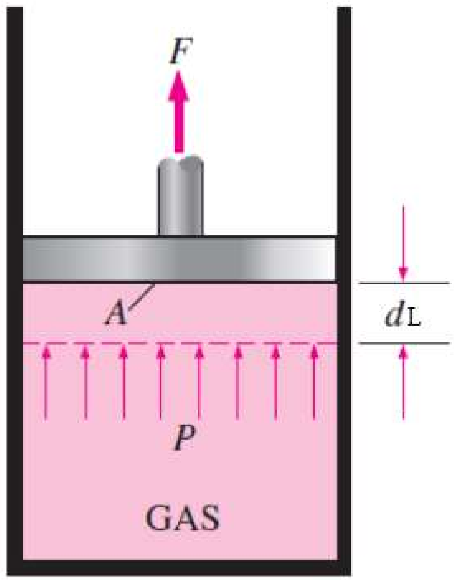
Energy Transfer

- **Energy transfer by :**
  - * Heat Energy (Thermal energy) $[Q = \dot{m} \times cp \times (T_{out} - Tin)]$
    - ♦ Q (Watt = J/s)
    - ♦ q = Q/m (W/kg)
  - * Work Energy (Mechanical energy)

$$[W = p \times \Delta V = p \times A \times \Delta L = F \times \Delta L]$$

$$ds = \int dL = \Delta L$$

- * W (Watt = J/s)
  - ♦ w = W/m (W/kg)



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

Contd…

- Energy can be transferred to or from a ***closed system*** (a fixed mass) to surroundings in two distinct forms:
  - ***heat*** and ***work***.

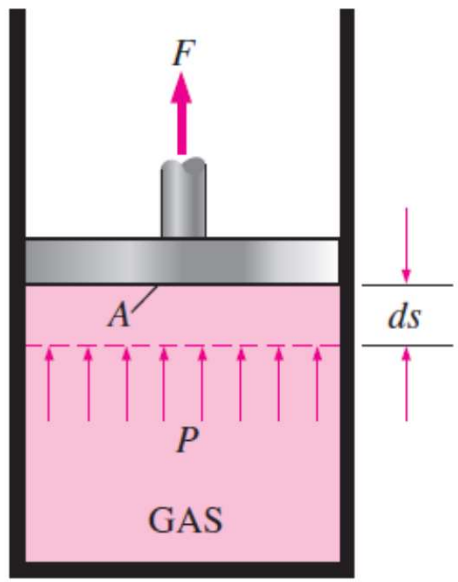
    $(Q - W = \Delta E)$

    Even mass can be considered a form of energy.

- For open System (control volumes),
  - energy can also be transferred by mass flow.

- An energy transfer to or from a ***closed system*** is *heat*, if it is caused by a temperature difference, ΔT (*driving force*).

- Otherwise it is *work*, and it is caused by a force acting through a distance.



Total Energy

- The **total energy** ***E*** of a system is ***sum*** of the any above energies.
  - $(Q - W = \Delta E)$

- The **total energy** of a system on a ***unit mass*** basis is denoted by ***e*** and is expressed as:
  - $(q - w = \Delta e)$

because, $q = Q/m$ (kJ/kg)

$w = W/m$ (kJ/kg)

$e = E/m$ (kJ/kg)

Total Energy

- 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*, and
  - *Microscopic*.

- The ***macroscopic*** forms of energy are those a system possesses as a whole with respect to some outside references, such as kinetic and potential energies (see figure).

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

- The ***microscopic*** forms 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 references.

- The sum of all the ***microscopic forms of energy*** is called the **internal energy** of a system and is denoted by ***U***.

- **Enthalpy**:
    - $H = U + pV$
    - $dH = dU + p\,dV$

- For ideal gas, $dH = m \times c_p \times dT$ or $\Delta H = m \times c_p \times \Delta T$

Macroscopic energy of a system

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

- The ***energy*** that a system possesses as a result of its ***motion*** relative to some reference is called ***kinetic energy*** (KE).

- When all parts of a system move with the same velocity, the kinetic energy is expressed as:

$$\boxed{KE = \tfrac{1}{2} m v^2 \qquad (kJ)}$$

- or, on a unit mass basis,

$$\boxed{ke = \tfrac{1}{2} v^2 \qquad (kJ/kg)}$$

- Where, ***v*** denotes the velocity of the system.

Rotating systems

- The kinetic energy of a rotating solid body is given by
  - KE = $\frac{1}{2} I \omega^2$
  - Where
    - * I = the moment of inertia of the body, and
    - * ω = the angular velocity.

- Moment of inertia of a body, $I = m \times r^2$
- Where
  - m = mass
  - r = effective radius

- The ***energy*** that a system possesses as a result of its elevation in a gravitational field is called **potential energy** (PE) and is expressed as:

$$PE = m \times g \times z \; (= m \times g \times h) \qquad (kJ)$$

- or, on a unit mass basis,

$$pe = g \times z \; (= g \times h) \qquad (kJ/kg)$$

  - where
  - g is the gravitational acceleration, and
  - Z $(=h)$ is the elevation of the centre of gravity of a system relative to some arbitrarily selected reference level.

- 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:

$$E = U + KE + PE = U + \tfrac{1}{2}mv^2 + mgz \qquad (kJ)$$

- or, on a unit mass basis:

$$e = u + ke + pe = u + \tfrac{1}{2}v^2 + gz \qquad (kJ/kg)$$

Closed systems

- Most closed systems remain stationary during a process and thus experience no change in their kinetic and potential energies.

- Closed systems whose velocity and elevation of the center of gravity remain constant during a process are frequently referred to as **stationary systems.**

- The change in the total energy ‘***E***’ of a stationary system is identical to the change in its internal energy ‘***U***’.

- In this subject, a closed system is assumed to be stationary unless stated otherwise.

Open System (Control Volume)

- Control volumes typically involve fluid flow for long periods of time.

- It is convenient to express the energy flow associated with a fluid stream in the rate form (with respect to time).

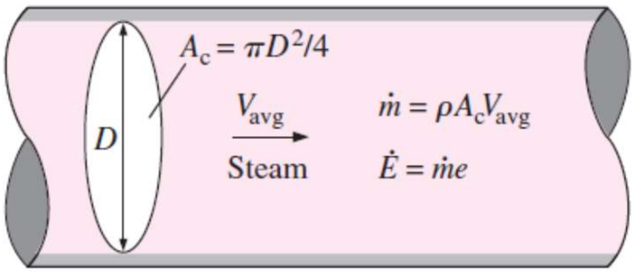
- This is done by incorporating the **mass flow rate '$\dot{m}$'**, which is *the amount of mass flowing through a cross section per unit time*.

- It is related to the **volume flow rate '$\dot{V}$'**, which is the volume of a fluid flowing through a cross section per unit time, by: ***Equation of continuity -***
  - *Mass flow rate:*

$$\dot{m} = \rho \times \dot{V}$$

$$\dot{m} = \rho \times A_c \times v_{avg}$$

- *Mass flow rate:* $\dot{m} = \rho \dot{V} = \rho A_c v_{avg} \quad (kg/s)$



Mass and energy flow rates associated with the flow of steam in a pipe of inner diameter *D* with an average velocity of v_{avg}.

- Here
  - ρ is the fluid density,
  - A_c is the cross-sectional area of flow, and
  - v_{avg} is the average flow velocity normal to A_c.

- The dot over a symbol is used to indicate *time rate*.

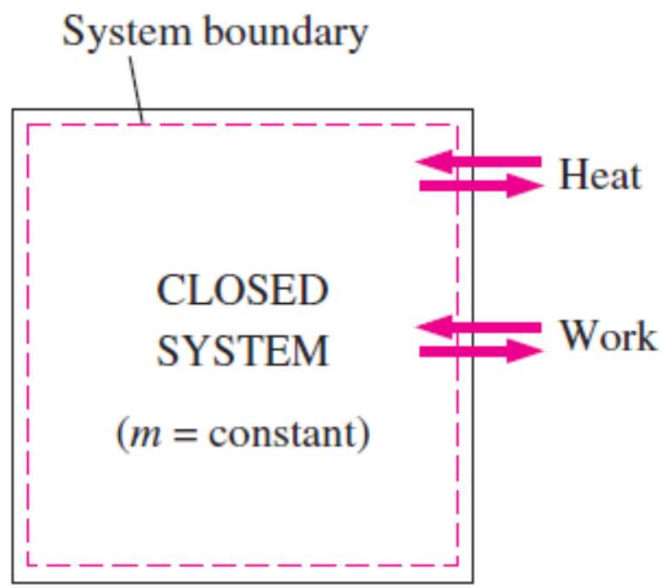
- Then the energy flow rate associated with a fluid flowing at a rate of $\dot{m}$ is:

- *Energy flow rate:* $\dot{E} = \dot{m} \times e \quad$ (kJ/s or kW)

Energy Transfer by Heat in Closed System

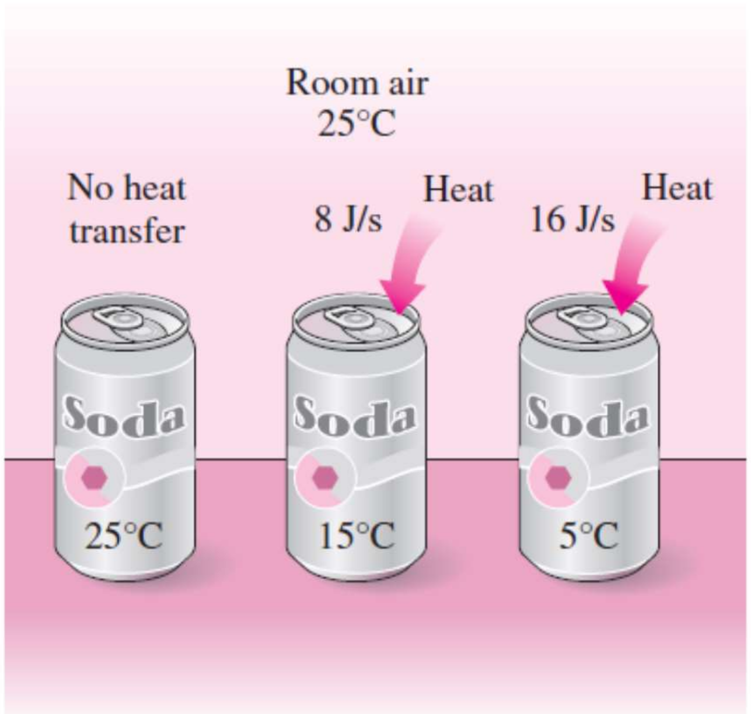
- Energy can cross the boundary of a closed system in two distinct forms:
  - *Heat,* and
  - *Work*.

- It is important to distinguish between these two forms of energy.

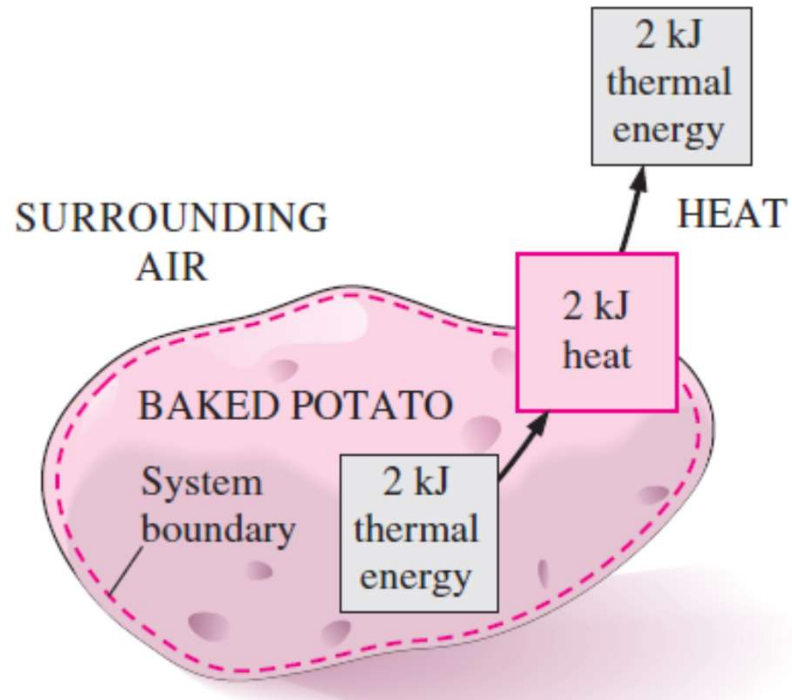


Energy can cross the boundaries of a closed system in the form of heat and work.

Closed systems



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



Energy is recognized as heat transfer only as it crosses the system boundary.

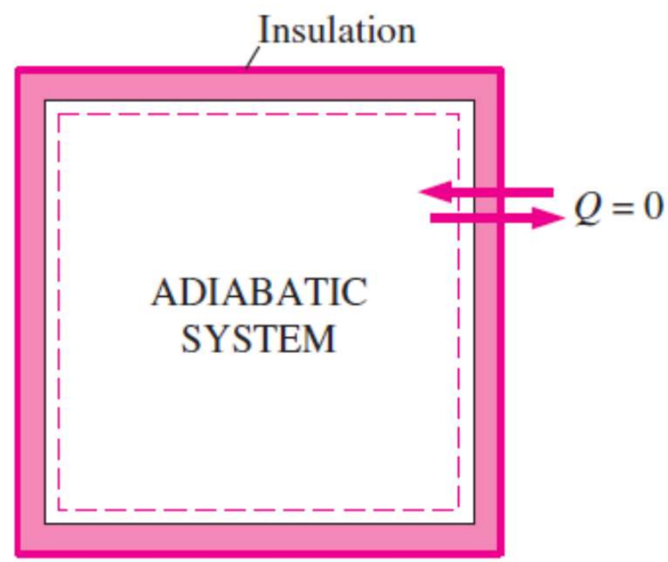
Adiabatic Process

- A process during which there is no heat transfer is called an ***adiabatic process*** (see Fig.).

- 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.



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

- 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 of energy, i.e.
    * such as work.

- That means:
  - Isothermal system = Temperature of the system is constant.
  - Adiabatic system = Temperature of system and surrounding are same.

Heat (Units)

- 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 ${}_1Q_2$, Q_{12}, or simply just Q *(kJ)*.
- Heat transfer *per unit mass* of a system is denoted q and is determined from:

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

Energy Transfer by Work

- Work, like heat, is an energy interaction between a system and its surroundings.

- As mentioned earlier, energy can cross the boundary of a closed system in the form of (1) heat or (2) work. Example: Refrigerator.

- Therefore, *if the energy crossing the boundary of a closed system is not heat, then it must be work*.

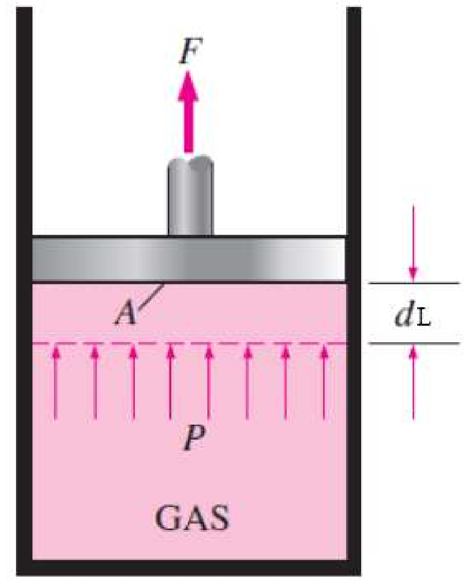
- Heat is easy to recognize:
  - Its driving force is a temperature difference between the system and its surroundings.

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.

- More specifically,
  - *Work is the energy transfer associated with a force acting through a distance.*
  - $\delta W = F \times ds = F \times dL$
  - $\delta W = p \times A \times dL = p \times dV \quad \because p = \frac{F}{A} \quad or \quad F = p \times A$
  - $W = p \times \Delta V = p \times A \times \Delta L = F \times \Delta L$

- A rising piston and a rotating shaft crossing the system boundaries are all associated with work interactions.



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

Work (Units)

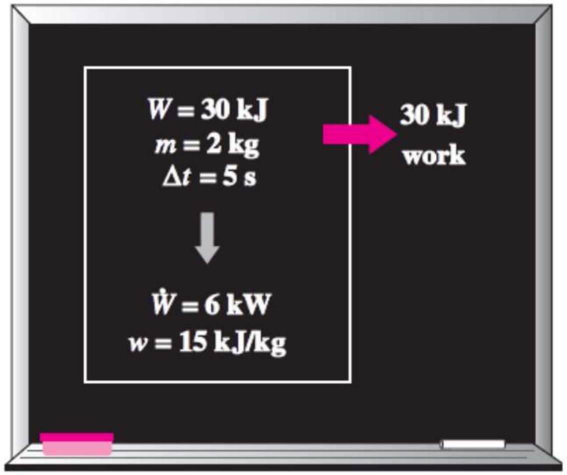
- Work is also a form of energy transferred like heat and, therefore, has energy units such as kJ.

- The work done during a process between states 1 and 2 is denoted by $_1W_2$, W_{12}, or simply W.

- The work done *per unit mass* of a system is denoted by w and is expressed as:

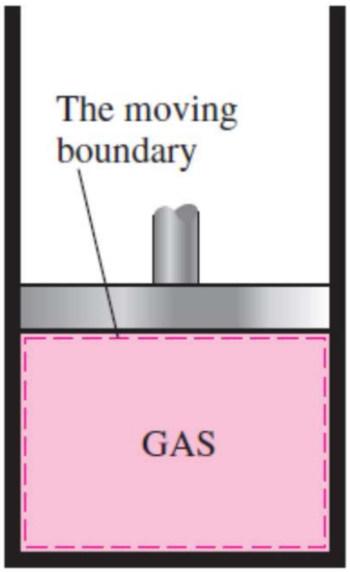
$$w = \frac{W}{m} \qquad (kJ/kg)$$

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



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

Moving Boundary Work



The work associated with a Moving boundary is called *boundary work.*

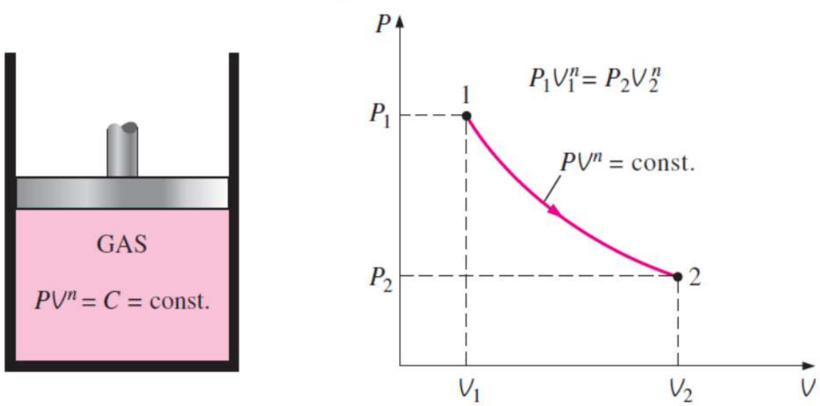
- One form of mechanical work frequently encountered in practice is associated with the ***expansion*** or ***compression*** of a gas in a piston–cylinder device.
- During this process, part of the boundary (the inner face of the piston) moves back and forth.
- Therefore, the expansion and compression work is often called **moving boundary work,** or simply **boundary work** (Fig.).

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.

$$pV^n = C \quad or \quad p = C\,V^{-n}$$



$$p_1V_1^n = p_2V_2^n = C$$

$$p_1V_1^n = mRT_1 \quad and \quad p_2V_2^n = mRT_2$$

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} \quad \text{and} \quad \frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{n-1}$$

Schematic and *p-V* diagram for a polytropic process.

Work done during a polytropic process: $pV^n = C, or\ p = \frac{C}{V^n}, or\ p = CV^{-n}$

$$W_b = \int_1^2 pdV = \int_1^2 CV^{-n}dV = \left[\frac{CV^{-n+1}}{-n+1}\right]_2 - \left[\frac{CV^{-n+1}}{-n+1}\right]_1$$

$$W_b = \frac{CV_2^{1-n} - CV_1^{1-n}}{1-n}$$

Where as, $p_1V_1^n = p_1V_2^n = C$, therefore

$$W_b = \frac{CV_2^{1-n} - CV_1^{1-n}}{1-n} = \frac{p_2V_2^nV_2^{1-n} - p_1V_1^nV_1^{1-n}}{1-n} = \frac{p_2V_2^{n+1-n} - p_1V_1^{n+1-n}}{1-n}$$

$$\frac{(p_2V_2 - p_1V_1)}{1-n}, or\ \frac{(p_1V_1 - p_2V_2)}{n-1}$$

For ideal gas, $pV = mRT$

$$W_b = \frac{mRT_2 - mRT_1}{1-n} = mR\frac{(T_2 - T_1)}{1-n}, \qquad or \quad wb = R\frac{(T_2 - T_1)}{1-n}$$

Isentropic process

Isentropic process:

1. An ideal **process** in which frictional or irreversible factors are absent.
2. For example, a fluid passing through frictionless nozzle.

Polytropic process

1. A **Polytropic process** is a general **process** for which $pV^n = constant$.
2. All **processes** other than **isentropic process** are **polytropic** in nature.

Adiabatic Process

- Work done during a adiabatic process:
- Process: pv^{γ} = constant,
  - where the γ is the index of ***adiabatic expansion*** or ***compression***.
- The quasi-equilibrium adiabatic process is a special case of the quasi-equilibrium polytropic process, where, $n = \gamma$.
  - Where, $\gamma = cp \div cv$ or c_p/c_v or $\gamma = \frac{c_p}{c_v}$
- Heat capacity ratio, γ is varies with temperature, but the variation is small.
- For monatomic gases, $\gamma = 1.667$.
  - Example: helium (He), neon (Ne), argon (Ar), etc.
- For diatomic gases including air, $\gamma = 1.4$
  - Example: hydrogen (H_2), nitrogen (N_2), oxygen (O_2), fluorine (F_2), chlorine (Cl_2), iodine (I_2), bromine (Br_2), air

- Process: pv^{γ} = constant, $p_1V_1^{\gamma} = p_2V_2^{\gamma} = C$

$$p_1V_1^{\gamma} = mRT_1 \quad and \quad p_2V_2^{\gamma} = mRT_2$$

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} \qquad \text{and} \qquad \frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$$

Follow the same methodology for the derivation of relation for work done as in the case of ***Polytropic process***.

$$W_b = \frac{(p_2V_2 - p_1V_1)}{1-\gamma} = \frac{(p_1V_1 - p_2V_2)}{\gamma - 1}$$

The derivation is given in next slide.

Due to, $pV = mRT$

$$W_b = \frac{mR(T_1 - T_2)}{\gamma - 1}$$

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

Work done during a adiabatic process: $pV^{\gamma} = C, or\ p = \frac{C}{V^{\gamma}}, or\ p = CV^{-\gamma}$

$$W_b = \int_1^2 pdV = \int_1^2 CV^{-\gamma}dV = \left[\frac{CV^{-\gamma+1}}{-\gamma+1}\right]_2 - \left[\frac{CV^{-\gamma+1}}{-\gamma+1}\right]_1$$

$$W_b = \frac{CV_2^{1-\gamma} - CV_1^{1-\gamma}}{1-\gamma}$$

Where as, $p_1V_1^{\gamma} = p_1V_2^{\gamma} = C$, therefore

$$W_b = \frac{CV_2^{1-\gamma} - CV_1^{1-\gamma}}{1-\gamma} = \frac{p_2V_2^{\gamma}V_2^{1-\gamma} - p_1V_1^{\gamma}V_1^{1-\gamma}}{1-\gamma} = \frac{p_2V_2^{\gamma+1-\gamma} - p_1V_1^{\gamma+1-\gamma}}{1-\gamma}$$

$$\frac{(p_2V_2 - p_1V_1)}{1-\gamma}, or\ \frac{(p_1V_1 - p_2V_2)}{\gamma-1}$$

For ideal gas, $pV = mRT$

$$W_b = \frac{mRT_2 - mRT_1}{1-\gamma} = mR\frac{(T_2 - T_1)}{1-\gamma}, \qquad or \quad wb = R\frac{(T_2 - T_1)}{1-\gamma}$$

- As we know:

$$c_p - c_v = R$$

$$\frac{c_p}{c_v} - 1 = \frac{R}{c_v}$$

$$\gamma - 1 = \frac{R}{c_v} \qquad \because \frac{c_p}{c_v} = \gamma$$

$$c_v = \frac{R}{\gamma - 1}$$

$$\overline{R} = 8314 \frac{J}{kmol.K}$$

$$R = \frac{\overline{R}}{M}$$

$$For\ air, R = \frac{8314}{29} \frac{J}{kg.K}$$

Energy Balance - General

- The conservation of energy principle (First law of thermodynamics) 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.

- That is:

  (Total energy entering the system) – (Total energy leaving the system) = (Change in the total energy of the system)

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

Energy Change of a System, ΔE_{system}

- The determination of the energy change of a system, ΔE_{system}, during a process involves the evaluation of the energy of the system:
  - at the beginning or initial condition, and
  - at the end or final condition of the process, and
  - taking their difference.

- That is:

Energy change of system = (Energy at final state – Energy at initial state).

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

- Change in the ***total energy of a system*** (ΔE_{system}) during a process is the sum of the changes in its internal, kinetic, and potential energies.

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

- Where

$\Delta U = m\,(u_2 - u_1)$ or $\Delta u = \Delta U/m = (u_2 - u_1)$

$\Delta KE = \frac{1}{2} m\left(v_2^2 - v_1^2\right)$ or $\Delta ke = \dfrac{\Delta KE}{m} = \frac{1}{2}\left(v_2^2 - v_1^2\right)$

$\Delta PE = mg(z_2 - z_1)$ or $\Delta pe = \Delta PE/m = g(z_2 - z_1)$

- Noting that energy can be transferred in the forms of heat, work, and mass.

- 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:

$$= (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out})$$

$$= (E_{in} - E_{out})$$
$$= \Delta E_{system}$$

- 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,
- The energy transport with mass E_{mass} is zero for systems that involve no mass flow across their boundaries (i.e., closed systems).

Open system

- Energy balance for **any system** undergoing any kind of process can be expressed more compactly as:

$$\begin{bmatrix}\text{Net energy transfer}\\ \text{by heat, work, and mass}\end{bmatrix} = \begin{bmatrix}\text{Change in internal, kinetic,}\\ \text{potential, etc., energies}\end{bmatrix}$$

$$E_{in} - E_{out} = \Delta E_{system} \qquad \text{(kJ)}$$

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

$$\begin{bmatrix}\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}\end{bmatrix} = \begin{bmatrix}\text{Rate of change in internal, kinetic,}\\ \text{potential, etc., energies}\end{bmatrix}$$

$$\dot{E}_{in} - \dot{E}_{out} = \frac{dE_{system}}{dt} = \frac{\Delta Esystem}{\Delta t} \qquad \text{(kW)}$$

- For constant rates, the total quantities during a time interval Δt are related to the quantities per unit time as:

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

$$W = \dot{W} \times \Delta t, \quad \text{and} \qquad \text{(kJ)}$$

$$\Delta E = (dE/dt) \times \Delta t \qquad \text{(kJ)}$$

Energy Conversion Efficiencies

- *Efficiency* indicates how well an energy conversion or transfer process is accomplished.

- Performance or efficiency can be expressed in terms of the desired output and the required input as:

$$Performance = \frac{Desired\ output}{Required\ input} = Efficiency, \eta$$

  - The range of efficiency = from 0 to 1,

    Since, the Desired output < Required input.

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