

## **Course Title:**

# **Fundamental of Thermodynamics and Heat Transfer**

## **Chapter 1:**

### **Introduction**

#### **Lecture 1:**

### **Basic Concepts of Thermodynamics**

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#### **Learning Objective of Lecture:**

To impart a great deal of knowledge to undergraduate students on the topics:

- ✓ Definition of Engineering Thermodynamics
- ✓ Scope of Engineering Thermodynamics
- ✓ Macroscopic and Microscopic Approach
- ✓ Value of Energy to the Society
- ✓ Concepts and Definitions: Thermodynamic System, Boundary and Surroundings
- ✓ Thermodynamic Properties: Intensive Properties, Extensive Properties, Specific Properties
- ✓ Thermodynamic Equilibrium: Thermal Equilibrium, Mechanical Equilibrium, Chemical Equilibrium

## 1.1. Definition and Scope of Engineering Thermodynamics

Engineering thermodynamics is the branch of applied science which deals with energy, its conversions and effect on the state or condition of a system. The name *thermodynamics* originates from the Greek words *therme* (heat) and *dynamis* (power), which is most descriptive of the early efforts to convert heat into power. Today the same name is broadly interpreted to include all aspects of energy and energy transformations, including power generation, refrigeration, and relationships among the properties of matter. Thus, basic engineering thermodynamics is concerned with the study of:

- Interaction of system and surroundings which relates the changes in the system due to the interaction in the form of mass and energy transfer (heat and work transfer).
- Energy and its conversion from one form to another to produce certain useful effects.
- Fundamental thermodynamic laws which govern the energy conversion processes.
- Physical properties (pressure, temperature and volume) of the working substances which can be used to obtain energy conversion.
- The concept of an equilibrium condition and feasibility of a process.

With reference to above mentioned features, engineering thermodynamics is also defined as the science of three “E”s namely energy, equilibrium and entropy.

Thermodynamic devices are designed using laws of thermodynamics which are based on experimental results and observations of common experiences. There are four laws of thermodynamics namely zeroth, first, second and third law but there is no mathematical proof to them.

Zeroth law deals with thermal equilibrium, relates to the concept of equality of temperature and provides a basis for temperature measurements.

- First law pertains to the conservation of energy i.e. energy can neither be created nor destroyed and introduces the concept of internal energy.

- Second law relates the direction of flow of heat, and dictates limits on the conversion of heat into work. It also tells us whether a particular change is feasible or not and introduces the concept of entropy.
- Third law defines the entropy of all homogeneous crystalline substances in an equilibrium state which becomes zero at absolute zero temperature.

The zeroth law was recognized long time after the formulation of the first and the second laws of thermodynamics. It was named the zeroth law since it should have preceded the first and the second laws of thermodynamics. The first and second laws of thermodynamics emerged simultaneously in the 1850s, primarily out of the works of the scientists Rankine, Clausius, and Kelvin, who after Carnot and Joule developed and formalized thermodynamics as a science in the nineteenth century.

The laws, principles and concepts of engineering thermodynamics are important and indispensable tools in the innovation, design, development and improvement of engineering processes, equipment and devices which deal with effective utilization of energy. The remarkable applications of engineering thermodynamics are power producing devices (heat engines, gas and steam turbines etc), power consuming devices (compressors, refrigerators, heat pumps, fans etc) as well as flow devices (nozzles, diffusers, heat exchangers etc) [1].

Engineering thermodynamics has great scope and finds extremely wide range of applications in diverse areas of different engineering disciplines. For example, it is used by mechanical engineers in the design of energy converting and transferring devices whenever there is combustion of fuels, heating or cooling of desired space, heat exchanger for heat exchange between hot and cold fluids, conversion of heat into work by heat engine for producing mechanical or electrical power etc. Similarly, it is used by civil engineers while choosing the layout of a building on a provided land space such that energy requirement for heating and lighting is minimum. Electrical, electronics and computer engineers may have its application while selecting the proper cooling system for the different electrical and electronic appliances [2].

## **1.2. Value of Energy to Society**

Energy plays a unique and critical role in the human society as no activity can take place without the transfer or conversion of energy from one form to another. The use of energy has been significant in the development of the human society by helping it to control and adapt to the environment. Managing the use of energy is unavoidable in any functional society.

The availability of energy “sources” and ability of people to harness that energy in useful ways have transformed our society and the energy requirements of almost all countries are ascending up inexorably. It is very hard to imagine the present life without electricity and other forms of energy. The energy available and consumed data exhibit the perspective picture of the economic condition and the level of living standard of people of a country.

In the old days, the greatest fraction of the population struggled to live by producing food for their consumption and therefore much of the population was not freed for other activities. Now, we are able to travel great distance in short times by using a choice of conveyances; we can communicate instantaneously with persons anywhere on earth; and we control large amount of energy at our personal whim in the form of automobiles, electric tools and appliances, and comfort conditioning in our accommodations. All these changes are as results of the development of the science and application of engineering thermodynamics, our ability to obtain energy, transform it, and apply it to society’s needs [3].

## **1.3. Macroscopic and Microscopic Approach**

Thermodynamic studies or analysis of a system are undertaken by the following two different approaches:

- Microscopic approach (Micro means small)
- Macroscopic approach (Macro means big)

When a system is analyzed from the microscopic point of view, the subject is called *statistical thermodynamics*. Hence, the statistical thermodynamics adopts the microscopic approach which is based on kinetic theory. The matter consists of a large number of molecules, which move randomly in chaotic fashion. At a particular moment, each molecule has a definite position, velocity and energy. The characteristics change very frequently due to collision between molecules. The overall behavior of the matter is predicted by statistically averaging the behavior of individual molecules. Microscopic view helps to gain deeper understanding of the laws of thermodynamics. However, it is rather complex, cumbersome and time consuming.

When a system is analyzed from the macroscopic point of view, the subject is called *classical thermodynamics*. Hence, the macroscopic approach is followed in the classical thermodynamics. The state or condition of a system can be completely described by measured values of pressure, temperature and volume which are called macroscopic or time-averaged variables. The results obtained are of sufficient accuracy and validity. Engineering thermodynamic analysis is macroscopic and most of the analysis is done by using it.

For example, let us consider pressure of a system e. g. the gas in a piston cylinder device which is assumed to contain a large number of molecules each having same mass but having different positions and velocities independent of each other. In microscopic approach, the pressure of the system is determined by calculating force exerted by the individual molecule on the container wall per unit area and finally by summing up this quantity due to each molecule. But, in case of macroscopic approach, the pressure of the system is determined by measuring its value for a particular mass of the gas with the help of a standard calibrated pressure measuring device e. g. a pressure gauge or manometer.

Thus, the main features of the microscopic and macroscopic approaches are listed below:

### **1.3.1. Microscopic Approach**

- The approach considers that the system is made up of a very large number of discrete particles known as molecules. These molecules have different

velocities and energies. The values of these energies are constantly changing with time. This approach to thermodynamics is concerned directly with the structure of the matter so called statistical thermodynamics.

- The behavior of the system is found by using statistical methods, as the number of molecules is very large. So advanced statistical and mathematical methods are needed to explain the changes in the system.
- The properties like velocity, momentum, impulse, kinetic energy and force of impact etc. that describe the molecule can neither be felt by our senses nor easily measured by instruments.
- Large numbers of variables are needed to describe a system. So the approach is complicated.

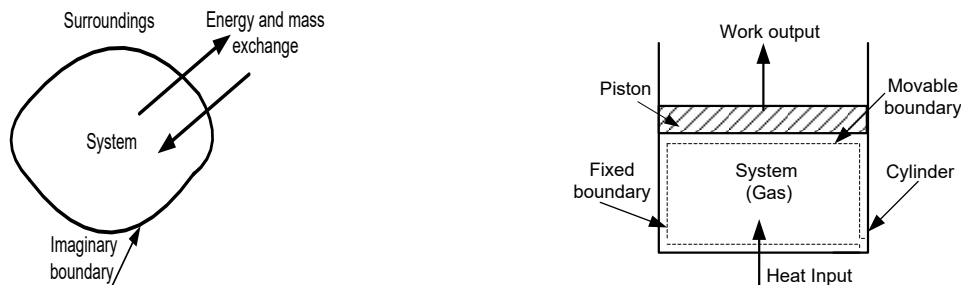
### **1.3.2. Macroscopic Approach**

- In this approach a certain quantity of matter is considered without taking into account the events occurring at molecular level. In other words, this approach to thermodynamics is concerned with gross or overall behavior so called classical thermodynamics.
- The analysis of macroscopic system requires simple mathematical formula.
- The values of the properties of the system are their average values. For example, let us consider a sample of gas in a closed container. The pressure of the gas is the average value of the pressure exerted by millions of individual molecules. They can be easily measured and felt by our senses.
- In order to describe a system only a few properties are needed. So the approach is fast and simple.

## **1.4. Concepts and Definitions - Thermodynamic System, Boundary and Surroundings**

A *thermodynamic system* is defined as a quantity of matter or a region in space under consideration which is selected for the analysis of a thermodynamic problem or for the study of the changes in its properties due to exchange of energy (heat and work) and mass. A piston – cylinder device of an engine and its contents as shown in figure 1.1(b) is an example of a system.

The mass or region outside the system is called *surroundings*. The *real* or *imaginary* surfaces which separates the system and surroundings is called *boundary*. The boundary of a system can be *fixed* or *movable* as shown in figure 1.1 (b). The boundary can also be *rigid* so that there is no exchange of work between system and surroundings. The *deformable (flexible)* boundary may change shape or size and then volume like in case of an elastic balloon. Further, the boundary may be *diathermic* or *adiabatic* depending upon whether it allows or not exchange of energy in the form of heat.



(a) Schematic diagram of a system      (b) Piston cylinder device as a system

Figure 1.1. System, Boundary, and Surroundings

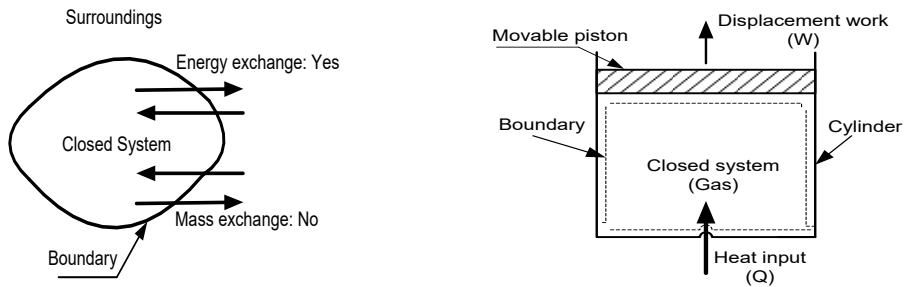
To understand the system, surroundings and the boundary in a better way let us take an example. Consider a closed vessel on which we are going to do our study. Since we are doing our study on the vessel so it is the system and the region excluding the closed vessel is called as surroundings. The surface of the closed vessel that separates the vessel and surroundings is called boundary. Finally, anything on which we pay our attention for the study or analysis is called system. When a system and its surroundings are taken together, they constitute a *universe* which can be considered as an isolated system.

On the basis of mass and energy interactions between system and surroundings the thermodynamic system is divided into three types, namely closed system, open system and isolated system.

### 1.4.1. Closed System

A system in which the transfer of energy but not mass can take place across the boundary is called *closed system* as shown in figure 1.2(a). The mass inside the closed system remains constant. Hence, this system is also known as *control mass*. However, its volume can change against a flexible boundary. Further, the physical nature and chemical composition of the mass may change, i.e., a liquid may evaporate, a gas may condense, even a chemical reaction may take place within the system.

For example, boiling of water in a closed vessel is a closed system. Since the water is boiled in closed vessel, so the mass of water cannot escapes out of the boundary of the system, but heat energy continuously entering and leaving the boundary of the vessel. The other examples of a closed system are a battery, a pressure cooker, a cylinder fitted with a movable piston containing a fixed mass of a gas as shown in figure 1.2(b) etc.



(a) Schematic diagram of a closed system arrangement

(b) Piston-cylinder

Figure 1.2. Closed system (control mass) with example

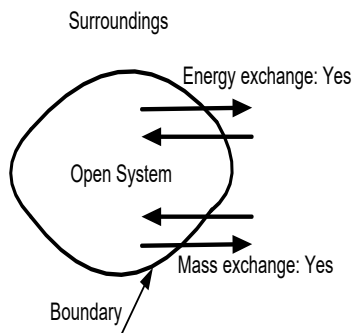
### 1.4.2. Open System

A system in which the transfer of both mass and energy takes place is called an open system shown in figure 1.3(a). An open system is also known as *control volume* whenever it has a constant volume with a fixed shape and size, i.e., its

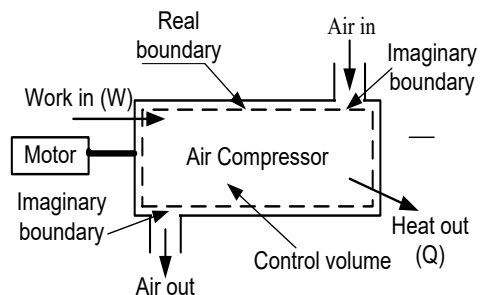
boundary neither expands nor contracts as in the case of an air compressor shown in figure 1.3(b). But the mass within the system does not necessarily remain constant. However, an open system may not be a control volume when its boundary itself expands or contracts, i.e., it changes its shape and then volume. An example for this is piston cylinder arrangement of a petrol engine shown in figure 1.3(c). When the piston moves downwards the air and fuel mixture is sucked in through the inlet valve during suction stroke and the burnt gases are discharged out through the outlet valve during upward motion of the piston in exhaust stroke. Since the system boundary itself expands or contracts, a piston cylinder arrangement of a petrol engine forms an open system but not a control volume due to change in its shape and size.

A control volume is defined as any region in space which is separated from its surroundings by boundaries called a *control surface*, and they can be *real* or *imaginary*. In the case of an air compressor shown in figure 1.3 (b), the inner surface of the compressor forms the real part of the boundary, and the entrance and exit areas form the imaginary part, since there are no physical surfaces present.

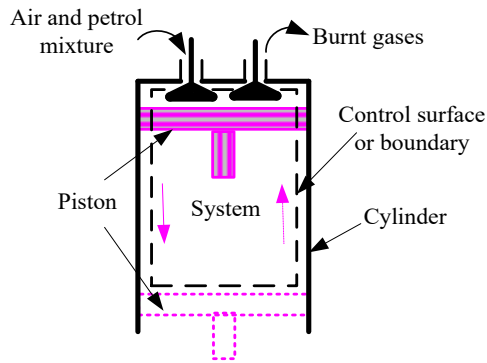
Boiling of water in an open vessel is an example of open system. This is because the water and heat energy both enters and leaves the boundary of the vessel. The other examples of an open system are car engine, air compressor, turbine, fan, pump, nozzle, diffuser, heat exchanger, condenser etc.



(a) Schematic of an open system



(b) An open system and control volume



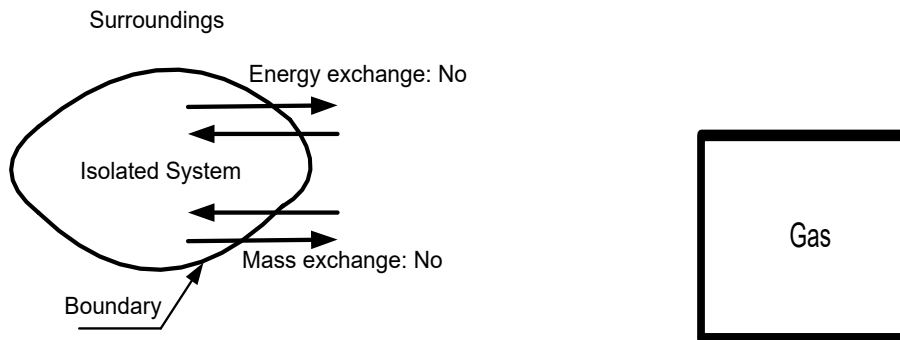
(c) An open system but not a control volume

Figure 1.3. Representation of open systems

### 1.4.3. Isolated System

A system in which the transfer of both mass and energy cannot take place is called an isolated system. An isolated system has therefore fixed mass and energy.

For example, tea present in a perfectly insulated closed vessel, e.g., a thermos flask can be considered as an isolated system. In this case the heat and the mass of the tea cannot cross the boundary of the thermos flask. Hence, the thermos flask is an isolated system. The other example of an isolated system is a closed rigid insulated box containing a gas as shown in figure 1.4.



(a) Schematic diagram  
Figure 1.4. Isolated system

(b) Closed rigid insulated box

Based on phase change, a system may be classified as a homogeneous system and a heterogeneous system. A *phase* is a quantity of matter that is uniform throughout in chemical composition and physical structure. Uniformity in chemical composition implies that the chemical composition does not vary from one part of the system to another. Whereas uniformity in physical structure means that the matter is all gas, or all liquid or all solid.

## 1.5. Thermodynamic Property and Thermodynamic Equilibrium

### 1.5.1. Thermodynamic Property

A thermodynamic property defined as a variable or characteristic which can be used to describe the condition or state of a system. For example, mass, temperature, pressure, volume, energy, entropy, enthalpy etc. It is a directly or indirectly measurable characteristic describing a system, and helps to distinguish one system from another. It has an exact differential.

A differential is taken to be exact if its integration between two end states can be carried out without requiring any information on the variation of variables. For example, If  $P$  is a thermodynamic property with  $dP$  denoting its differential change, then the integral between initial state 1 to final state 2 of the system will have only value given by

$$\int_1^2 dP = (P_2 - P_1) \quad \text{.....(1.1)}$$

But  $PdV$  is not an exact differential and hence not a thermodynamic property. Because the integration of  $PdV$  can be determined only if a relationship between variation of  $P$  and  $V$  is known. In contrary to this, the integration of  $d(PV)$  is  $PV$  which has been obtained without requiring any additional information as to how  $P$  and  $V$  are related. The quantity  $d(PV)$  is thus an exact differential and hence a thermodynamic property of a system.

Since a thermodynamic property is a function of the state of a system, it is also called a *point function* or a *state function*.

According to their nature, the thermodynamic properties of a system may be divided into two classes namely an intensive property and an extensive property.

### 1.5.1.1. Intensive Property

*Intensive property* is defined as the property of a system whose value is independent of the extent or mass of the system. Its value remains the same whether one considers the whole system or only a part of it. Intensive property is not additive by nature. Examples are pressure, temperature, density, velocity, viscosity, thermal conductivity, electrical potentials etc.

### 1.5.1.2. Extensive Property

*Extensive property* is defined as the property of a system whose value depends on or proportional to mass or extent of the system. Its value depends on how big a portion of the system is being considered. Extensive property is additive by nature. Examples are mass, volume, energy, enthalpy, entropy, surface area etc.

Let a system having a certain property  $P$  be divided into a number of parts or sub-systems. If  $P_1, P_2, P_3$  etc denote the value of that property for various parts of the system, then

For an intensive property:  $P = P_1 = P_2 = P_3 = \dots\dots$

For an extensive property:  $P = P_1 + P_2 + P_3 + \dots\dots$

### 1.5.1.3. Specific Property

Since extensive properties are proportional to mass they can be converted into intensive form by dividing its value by mass of the system. An extensive property expressed per unit mass of the system is defined as *specific property*. Examples are specific volume, specific total energy, specific entropy, specific enthalpy etc. Hence, specific volume,  $v = V/m$  and specific total energy,  $e = E/m$  where  $m, V$  and  $E$  are mass, volume and total energy of the system respectively. In general, capital letters will denote extensive properties and small letters will be used to represent the specific properties.

## 1.5.2. Thermodynamic Equilibrium

A system is said to exist in a condition of thermodynamic equilibrium if there is no change in any macroscopic property of the system when it is isolated from its surroundings. The condition of a thermodynamic system can be described with the help of the values of different thermodynamic properties, e.g. temperature, pressure, volume etc. To describe a system with the values of certain thermodynamic properties it should have same values of those properties throughout the system. Therefore, there can be no spontaneous change in any macroscopic properties for the system to be in a condition of thermodynamic equilibrium. Hence, thermodynamics is a study of mainly the properties of physical systems that are found in equilibrium condition.

In other words, a thermodynamic system will be in a condition of thermodynamic equilibrium, if it satisfies the following three types of equilibrium conditions namely mechanical equilibrium, thermal equilibrium and chemical equilibrium at a time.

### 1.5.2.1. Mechanical Equilibrium

A system is said to exist in a condition of *mechanical equilibrium* if there is uniformity of pressure throughout the system, i.e. there is only one value of pressure for the entire system. This is also known as equality of pressure. This condition exists in the system only when there is no unbalanced force within the system or at its boundaries. For example, if the weight on the piston from the piston - cylinder arrangement is removed, the system boundary will expand until the mechanical equilibrium is attained.

### 1.5.2.2. Thermal Equilibrium

A system is said to be in a condition of *thermal equilibrium* if there exists uniformity of temperature throughout the system or between the system and surroundings. In other words, there is only one value of temperature for the whole system. This is also called equality of temperature. For example, when a system having low temperature and surroundings having high temperature are at physical contact to each other, then heat will flow towards system from the surroundings. After some time both will attain the same temperature. In this condition there is no more heat interaction between system and surroundings,

i.e. there is no change taking place in the condition of the system and surroundings. So, they are said to be in the thermal equilibrium with each other.

### 1.5.2.3. Chemical Equilibrium

A system is said to be in a condition of *chemical equilibrium* if there is no chemical reaction or transfer of matter (diffusion) from one part of the system to another. In other words, there exists uniformity of chemical potential throughout the system. Hence, this condition of the system is also defined as equality of chemical potential. For example, in a petrol engine there will be spontaneous change in the properties or internal structure of a system composed of a mixture of oxygen and petrol once it is ignited (exothermic reaction). Chemical equilibrium represents that condition of the system when all chemical reactions and mass diffusion in it have ceased.

### Lecture Highlights:

- *Definition of engineering thermodynamics:* It deals with the study of energy, its forms and transformations and its interactions with matters. It basically entails four laws namely Zeroth, First, Second and Third law of thermodynamics.
- *Scope of engineering thermodynamics:* It has wide range of applications in diverse areas of different engineering disciplines. It is important and indispensable tools in the innovation, design and development of engineering processes, equipment and devices. Its utilities are in power producing devices (heat engine, turbine etc) and consuming devices (refrigerator, heat pump etc) as well as flow devices (heat exchanger, nozzle etc).
- *Value of energy to the society:* It is the basic necessity of the human life. Its uses simplify our life style and make the human life comfortable. The rate of energy consumption of a country reflects the life style of the people of that country i.e. living standard of people. As no activity can take place without the conversion of one energy form to another, it plays a unique and crucial role in the human society.

- Thermodynamic systems can be studied by adopting either a *macroscopic (classical)* or a *microscopic (statistical)* approach. The differences between these approaches are:

<b>Microscopic Approach</b>	<b>Macroscopic Approach</b>
<ol style="list-style-type: none"> <li>1. System is analyzed with reference to its molecular behaviors.</li> <li>2. It needs large numbers of properties to describe a system.</li> <li>3. Properties that describe the behavior of the molecules can neither be felt by our senses nor easily measured by instruments.</li> <li>4. It requires advanced statistical mathematics for analysis of the system and calculation is time consuming and tedious.</li> <li>5. It is usually used in the study of statistical thermodynamics and preferred by pure scientists.</li> <li>6. For example: Volume of air inside a room = number of air molecules inside room x volume of single air molecule.</li> </ol>	<ol style="list-style-type: none"> <li>1. System is analyzed with reference to certain measurable or observable bulk properties.</li> <li>2. It needs few numbers of properties to describe a system.</li> <li>3. Properties needed to describe the system can be felt by our senses and easily measured by instruments.</li> <li>4. It requires simple mathematics for analysis of the system and calculation is relatively faster and simpler.</li> <li>5. It is used in the study of classical thermodynamics and preferred by engineers.</li> <li>6. For example: Volume of air inside a room = Volume of room = length x width x height.</li> </ol>

- *Thermodynamic System:* It is defined as a quantity of matter or a region in space that is under study with respect to thermodynamic parameters. According to the type of interaction a system may be closed, open or isolated.
- *Surroundings:* Everything (mass or region) outside the system is called its surroundings.
- *Boundary:* Any medium that separates system from its surroundings is called boundary. The boundary may change its shape or size. It may be real or imaginary, fixed or movable, rigid or deformable and diathermic or adiabatic.

- *Closed system*: System in which energy (heat and work) transfer can take place but no mass transfer across the boundary is called closed system, e.g. piston cylinder device. A closed system can be completely described by the fixed amount of mass inside the system. Therefore, a closed system is also known as *control mass* (CM).
- *Open system*: System in which both mass and energy (heat and work) transfer can take place across the boundary is called open system, e.g. turbine, compressor. Any open system can be analyzed with reference to a certain specified region in space. Therefore, an open system is also known as *control volume* (CV).
- Differences between control mass and control volume are:

Control mass	Control volume
1. Mass of the system remains constant. 2. Only energy transfer but no mass transfer takes place between system and surroundings. 3. It is also called closed system. 4. For examples: piston cylinder device, a pressure cooker, a battery etc.	1. Volume of the system remains constant. 2. Both the energy and mass transfers take place between system and surroundings. 3. It is also called open system. 4. For examples: Turbine, pump, nozzle, diffuser etc.

- *Isolated system*: System in which neither mass nor energy (heat and work) transfer can take place is called isolated system, e.g. a closed rigid insulated container, thermo flask, universe.
- *Thermodynamic property*: Any variable that is used to define the state or condition of a system, e.g. pressure, temperature, volume, internal energy, enthalpy, entropy. According to its nature a property may be extensive or intensive.
- Differences between *extensive* and *intensive properties* are:

Extensive property	Intensive property
1. It depends on mass or extent of the system. 2. Its value depends on how large a portion of the system is being considered. 3. They are additive when a system is divided into a number of parts, i.e., $P = P_1 + P_2 + P_3 + \dots$ 4. For examples: Mass, volume, energy, enthalpy, entropy etc.	1. It does not depend on mass or extent of the system. 2. Its value remains the same whether one considers the whole system or only a part of it. 3. They are not additive, i.e., $P = P_1 = P_2 = P_3 = \dots$ Here, P means any property. 4. For examples: temperature, pressure, density etc.

- *Specific property*: Extensive property per unit mass is called specific property and is an intensive property.
- *Thermodynamic equilibrium*: A system is said to be in thermodynamic equilibrium, if it is in the state of thermal, mechanical, and chemical equilibrium at a time.
- *Thermal equilibrium*: There should not be any temperature difference within the system for a system to be in a thermal equilibrium.
- *Mechanical equilibrium*: There should not be any pressure difference or unbalanced forces within the system for a system to be in a mechanical equilibrium.
- *Chemical equilibrium*: There should not be any chemical reaction during the observation period for a system to be in a chemical equilibrium.

### References:

- [1] *Thermal Science and Engineering*: Kumar D.S., S. K. Kataria & Sons, India, 2009.
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- [3] *Fundamentals of Thermodynamics and Heat Transfer*: Lecture Manual published by Department of Mechanical Engineering, Institute of Engineering, Pulchowk Campus, Nepal, 2016.