Production & Industrial Engineering

General Engineering

Vol. V : Basic Thermodynamics

Comprehensive Theory

with **Solved Examples** and **Practice Questions**

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General Engineering : Vol. V – Basic Thermodynamics

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VOLUME V

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INTRODUCTION

The most of general sense of thermodynamics is the study of energy and its relationship to the properties of matter. All activities in nature involve some interaction between energy and matter. Thermodynamics is a science that governs the following:

- Energy and its transformation
- Feasibility of a process involving transformation of energy
- Feasibility of a process involving transfer of energy
- Equilibrium processes

More specifically, thermodynamics deals with energy conversion, energy exchange and the direction of exchange.

5.1 Application of Thermodynamics

All natural processes are governed by the principles of thermodynamics. However, the following engineering devices are typically designed based on the principles of thermodynamics.

Automotive engines, turbines, compressors, pumps, fossil and nuclear power plants, propulsion systems for the aircrafts, separation and liquefication plant, refrigeration, air-conditioning and heating devices.

The principles of thermodynamics are summarized in the form of set of axioms. These axioms are known as four thermodynamic laws :

- **The Zeroth Law** deals with thermal equilibrium and provides a means for measuring temperatures.
- **The First Law** deals with the conservation of energy and introduces the concept of internal energy.
- **The Second Law** of thermodynamics provides with the guidelines on the conversion of internal energy of matter into work. It also introduces the concept of entropy.
- **The Third Law** of thermodynamics defines the absolute zero of entropy. The entropy of a pure crystalline substance at absolute zero temperature is zero.

5.2 Different Approaches in the Study of Thermodynamics

Thermodynamics can be studied through two different approaches:

(1) Macroscopic approach and

(2) Microscopic approach

1. **Macroscopic Approach :** Consider a certain amount of gas in a cylindrical container. The volume (V) can be measured by measuring the diameter and the height of the cylinder. The pressure (P) of the gas can be measured by a pressure gauge. The temperature (T) of the gas can be measured using a thermometer. The state of the gas can be specified by the measured P, V and T. The values of these variables are space averaged characteristics of the properties of the gas under consideration. In classical thermodynamics, we often use this macroscopic approach. The macroscopic approach has the following features.
   - The structure of the matter is not considered.
   - A few variables are used to describe the state of the matter under consideration.
   - The values of these variables are measurable following the available techniques of experimental physics.
2. **Microscopic Approach :** On the other hand, the gas can be considered as assemblage of a large number of particles each of which moves randomly with independent velocity. The state of each particle can be specified in terms of position coordinates (x_i, y_i, z_i) and the momentum components (p_{xi}, p_{yi}, p_{zi}). If we consider a gas occupying a volume of 1 cm^3 at ambient temperature and pressure, the number of particles present in it is of the order of 10^{20} . The same number of position coordinates and momentum components are needed to specify the state of the gas. The microscopic approach can be summarized as :
   - A knowledge of the molecular structure of matter under consideration is essential.
   - A large number of variables are needed for a complete specification of the state of the matter.

5.3 Concept of System and Surrounding

5.3.1 System

A thermodynamic system is defined as a definite quantity of matter or a region in space upon which attention is focussed in the analysis of a problem. We may want to study a quantity of matter contained with in a closed rigid walled chambers, or we may want to consider something such as gas pipeline through which the matter flows. The composition of the matter inside the system may be fixed or may change through chemical and nuclear reactions. A system may be arbitrarily defined. It becomes important when exchange of energy between the system and the everything else outside the system is considered. The judgement on the energetics of this exchange is very important.

5.3.2 Surroundings

Everything external to the system is surroundings. The system is distinguished from its surroundings by a specified boundary which may be at rest or in motion. The interactions between a system and its surroundings, which take place across the boundary, play an important role in thermodynamics. A system and its surroundings together comprise a universe.

Types of Systems

Two types of systems can be distinguished. These are referred to, respectively, as closed systems and open systems or control volumes. A closed system or a control mass refers to a fixed quantity of matter, whereas a control volume is a region in space through which mass may flow. A special type of closed system that does not interact with its surroundings is called an **Isolated system** .

Two types of exchange can occur between the system and its surroundings :

1. energy exchange (heat or work) and
2. exchange of matter (movement of molecules across the boundary of the system and surroundings).

Based on the types of exchange, one can define :

- **isolated systems :** no exchange of matter and energy
- **closed systems :** no exchange of matter but some exchange of energy
- **open systems :** exchange of both matter and energy

If the boundary does not allow heat (energy) exchange to take place it is called adiabatic boundary otherwise it is diathermal boundary.

5.4 Property

To describe a system and predict its behaviour requires a knowledge of its properties and how those properties are related. Properties are macroscopic characteristics of a system such as mass, volume, energy, pressure and temperature to which numerical values can be assigned at a given time without knowledge of the past history of the system. Many other properties are considered during the course of our study.

- The value of a property of a system is independent of the process or the path followed by the system in reaching a particular state.
- The change in the value of the property depends only on the initial and the final states.

The word state refers to the condition of a system as described by its properties.

Mathematically, if p is a property of the system, then the change in the property in going from the initial state 1 to the final state 2 is given by

$$\int_1^2 dp = p_2 - p_1$$

If $p = p(x, y)$ then,

$$dp = \left(\frac{\partial p}{\partial x}\right)_y dx + \left(\frac{\partial p}{\partial y}\right)_x dy = adx + bdy$$

where, $$a = \left(\frac{\partial p}{\partial x}\right)_y \text{ and } b = \left(\frac{\partial p}{\partial y}\right)_x$$

If $$\left(\frac{\partial a}{\partial y}\right)_x = \left(\frac{\partial b}{\partial y}\right)_x$$

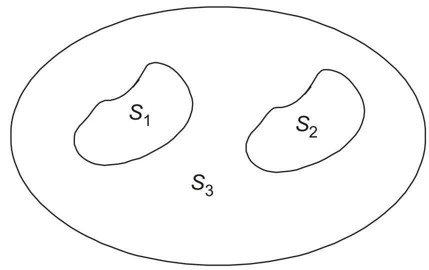
then dp is said to be an exact differential, and p is a point function. A thermodynamic property is a point function and not a path function. Pressure, temperature, volume or molar volume are some of the quantities which satisfy these requirements.

5.4.1 Intensive and Extensive Properties

There are certain properties which depend on the size or extent of the system, and there are certain properties which are independent of the size or extent of the system. The properties like volume, which depend on the size of the system are called extensive properties. The properties, like temperature and pressure which are independent of the mass of the system are called **intensive properties**. The test for an intensive property is to observe how it is affected when a given system is combined with some fraction of exact replica of itself to create a new system differing only by size. Intensive properties are those which are unchanged by this process, whereas those properties whose values are increased or decreased in proportion to the enlargement or reduction of the system are called extensive properties.

Assume two identical systems S_1 and S_2 as shown in figure. Both the systems are in identical states.

Let S_3 be the combined system. Is the value of property for S_3 same as that for S_1 (and S_2)?



- If the answer is yes, then the property is intensive.
- If the answer is no, then the property is extensive.

The ratio of the extensive property to the mass is called the specific value of that property

Specific volume, $v = \frac{V}{m} = \frac{1}{\rho}$ (ρ is the density)

Specific internal energy, $u = \frac{U}{m}$

Similarly, the molar properties are defined as the ratios of the properties to the mole number (N) of the substance

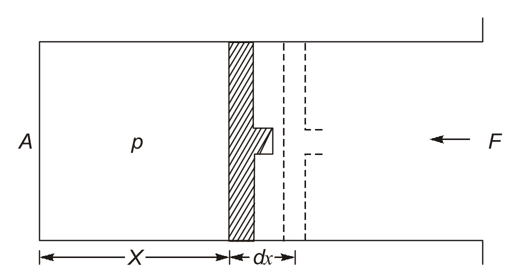
$$\text{Molar volume} = \hat{v} = \frac{V}{N}$$

$$\text{Molar internal energy} = \hat{u} = \frac{U}{N}$$

5.5 Concept of Heat and Work

5.5.1 Work

Work is one of the basic modes of energy transfer. The work done by a system is a path function, and not a point function. Therefore, work is not a property of the system, and it cannot be said that the work is possessed by the system. It is an interaction across the boundary. What is stored in the system is energy, but not work. A decrease in energy of the system appears as work done. Therefore, work is energy in transit and it can be identified only when the system undergoes a process.



Work must be regarded only as a type of energy in transition across a well defined, zero thickness, boundary of a system. Consequently work, is never a property or any quantity contained within a system. Work is energy driven across by differences in the driving forces on either side of it. Various kinds of work are identified by the kind of driving force involved and the characteristic extensive property change which accompanied it. Work is measured quantitatively in the following way. Any driving force other than temperature, located outside the system on its external boundary, is multiplied by a transported extensive property change within the system which was transferred across the system boundary in response to this force. The result is the numerical value of the work associated with this system and driving force. In static Equilibrium, $F = pA$ (see fig). The dX is small so that P does not change. The change in volume of the gas = AdX. The elemental work,

$$dW = FdX = pAdX = pdV$$

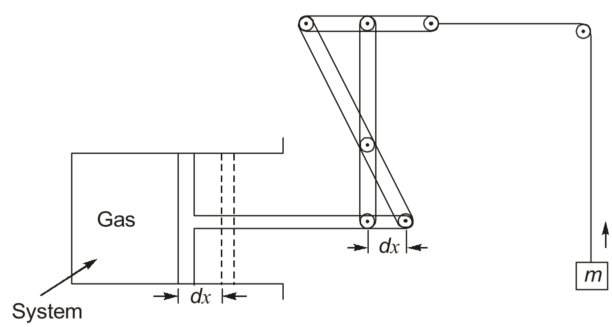
Thermodynamic Definition of Work

In thermodynamics, work done by a system on its surroundings during a process is defined as that interaction whose sole effect, external to the system, could be reduced as the raising of a mass through a distance against gravitational force. Let us consider the raising of mass *m* from an initial elevation z_1 to final elevation z_2 against gravitational force. To raise this mass, the force acting on the mass is given by $F = mg$. The work done on the body *is* $W = mg(z_2 - z_1)$

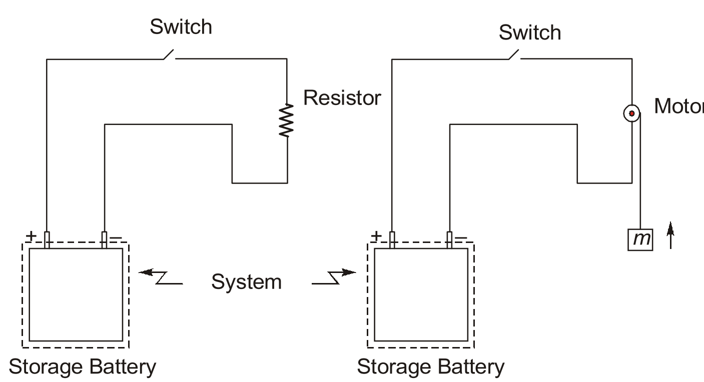
- An external agency is needed to act on the system
- It can be seen that expansion of the gas gets reduced to raising a mass against gravitational force

$$dW = Fdx = pA\,dx = pdV$$

$$W = \int_1^2 pdV$$



During this expansion process, the external pressure is always infinitesimally smaller than the gas pressure.



Compare two systems shown in the figure. Let the resistor be replaced by a motor drawing the same amount of current as the resistor. The motor can wind a string and thereby raise the mass which is suspended. As far as the battery is concerned, the situations are identical. So, according to thermodynamic definition of work, the interaction of a battery with a resistor is called work. By manipulating the environment, that is external to the battery (system), the effect can be reduced to raising of a mass against the gravitational force and that is the only effect on the surroundings. We can see that the thermodynamic definition of work is more general than that used in mechanics.

- Situation in which $W \neq pdV$
- Let the initial volume be V_1 and pressure p_1.
- Let the final volume be V_2 and pressure p_2.
- $\int PdV$ = area under the curve indicating the process on P-V diagram.