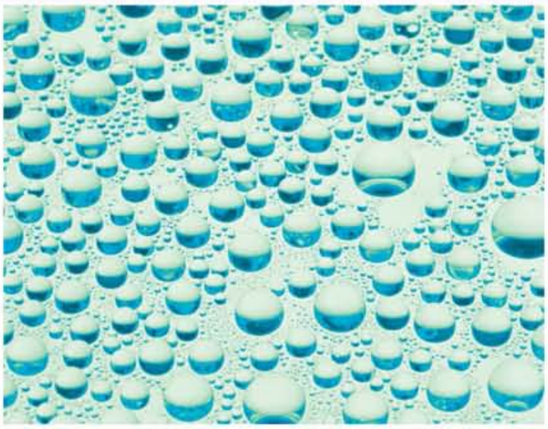
THERMODYNAMICS



Dr. D.S. Kumar

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THERMODYNAMICS

by

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Preface to the First Edition

The author has been teaching the subject of Applied Thermodynamics and Heat Engines for the last several years. Based on his class notes, experience gained through useful class discussions and feedback, he prepared two books namely **Heat Engineering** and **Thermal Science and Engineering**. These books have served and continue to serve as useful texts for the students of engineering curriculum, AMIE and other professional examinations in the subjects of heat engines and basic thermodynamics. While these books will continue to remain in circulation, the present book will provide an edited and reorganized version to cater to specific needs of the course in **Thermodynamics** offered to 3rd semester mechanical engineering students of UP Technical University. The subject is important as it covers the basic principles of engineering thermodynamics which are essential for the analysis of practical problems relating to heat and work and their mutual interconversions. The text presents an amalgam of numerous ideas and influences and is the outcome of the distillation of the available text books written by distinguished authors.

The key features of this edited and reorganized version of the book are :

- Concise covering of each topic in a simple, lucid and easily understandable language.
- Full use of line diagrams made to supplement the text and explain a particular phenomenon as clearly as possible.
- Solutions provided to a wide variety of problems of standard comparable to those set for engineering degree, AMIE, GATE and Engineering Service Examinations.
- Consistent use of SI units and notations throughout the text
- Inclusion of sections on multiple choice questions and short answer questions keeping in view the recent trend of such questions being asked in the various University and competitive examinations.

The author expresses his gratitude to his departmental colleagues with whom he had hours of useful discussion during the revising, updating writing and editing of the text. The author thanks the publishers also for their considerable patience and good co-operation throughout. Further, the author would be extremely thankful to the readers for their constructive suggestions and healthy criticism with a view to enhance the usefulness of the book. Author and the publishers would gratefully acknowledge if misprints and errors discovered are brought to their notice.

Finally, the author wishes to place on record his apologies and sincere thanks to his near and dear ones who willingly endured certain hardships which resulted from his preoccupation with this work.

MREI, Faridabad D.S. Kumar
July, 2009

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CHAPTER 1

Basic Concepts and Definitions

1.1. THERMODYNAMICS: WHAT IS IT?

Thermodynamics: heat-force-action

Thermodynamics is the fascinating branch of science which deals with energy transfer and its effect on the state or condition of a system. Essentially, thermodynamics pertains to the study of :

- Interaction of system and surroundings; it relates the changes which the system undergoes to the influences to which it is put.
- Energy and its transformation; energy inter-conversions in the form of heat and work. James Joule had proved with his well-known experiments with churner that mechanical work can be converted into heat energy. The credit for using heat by converting into mechanical work goes to James Watt who produced the first steam engine and paved the way for industrial revolution.
- Relationship between heat, work and physical properties such as pressure, volume and temperature of the working substance employed to obtain energy conversion.
- Feasibility of a process and the concept of equilibrium processes.

Thermodynamics has been excellently defined as the science of three "Es" namely energy, entropy and equilibrium.

The laws, principles and concepts of 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. Notable applications of engineering thermodynamics in the field of energy technology are:

- power producing devices, *e.g.*, internal combustion engines and gas turbines, steam and nuclear power plants.
- power consuming devices, *e.g.*, fans, blowers and compressors, refrigeration and air-conditioning plants.
- chemical process plants and direct energy conversion devices.

A large number of processes in various fields such as agriculture, textiles, dairy, drugs and pharmaceutical industry are also governed by thermodynamic principles.

Thermodynamics is essentially based upon experimental results and observations of common experience; there is no mathematical proof to the zeroth, 1st and 2nd laws of thermodynamics.

The evidence of their validity stems from the fact that not in a single case these principles have been violated. The laws, however, lay down the general restrictions within which energy transformations are observed to occur.

- **Zeroth law** deals with thermal equilibrium, relates to the concept of equality of temperature and provides a means for measuring temperature.
- **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, dictates limits on the conversion of heat into work and provides a yardstick to evaluate the performance of various processes. It also tells us whether a particular change is feasible or not and introduces the concept of entropy. It will be shown later that first law denies the possibility of creating or destroying energy, the second law denies the possibility of utilizing energy in a particular way.
- Third law defines the absolute zero of entropy.

Carnot (1792-1832), Joule (1818-1889), Kelvin (1824-1907) and Clausius (1822-1888) were the main scientists who developed and formalized thermodynamics as a science in the nineteenth century. Later, Gibbs (1839-1903) developed and broadened the scope of thermodynamics to such an extent that its principles could be applied to analyse almost any physical and chemical phenomenon.

1.2. MACROSCOPIC AND MICROSCOPIC APPROACH : CLASSICAL AND STATISTICAL THERMODYNAMICS

There are two approaches for investigating the behaviour of a system. In the ***macroscopic approach*** which is followed in classical thermodynamics

- structure of the matter is not considered; no attention is focussed on the behaviour of individual particles constituting the matter.
- the volumes considered are very large compared to molecular dimensions and the system is regarded as continuum devoid of any voids and cavities.
- study is made of overall effect of several molecules; the behaviour and activities of the molecules are averaged, *i.e.*, their effect integrated.

Only a few variables are needed to describe the state or condition of matter under consideration and these time-averaged characteristics or variables can be perceived by our senses and measured directly by instruments. For example, in the piston-cylinder assembly of an I.C. engine, the volume occupied by the gas for each position of the piston can be determined by measuring the cylinder diameter and the piston travel. The pressure exerted by the gas and its temperature can be measured by means of a pressure gauge and a themocouple respectively. The state or condition of the system (gas in the cylinder) can then be completely described by specifying the measured values of pressure, temperature and volume. These few large scale characteristics/properties, known as ***macroscopic co-ordinates***, are considered sufficient to provide complete description of the system under consideration at a particular instant. Further, it is possible to set-up or deduce many relations among their time-averaged characteristics. However, the particular form of relationship cannot be explained. The macroscopic approach, however, offers results of sufficient accuracy and validity.

Statistical thermodynamics adopts ***microscopic approach*** in which the matter is considered to be comprised of a large number of tiny particles called molecules (1 cm^3 of a monoatomic gas at atmospheric pressure and temperature contains 6×10^5 atoms) which move randomly in chaotic fashion. At a particular instant each particle has a definite position, velocity and energy and these characteristics change very frequently due to collision between the particles. The overall behaviour of the matter is then predicted by statistically averaging the behaviour of individual particles. The salient aspects of microscopic approach may be summed up as:

(*i*) necessity of complete knowledge of the structure of matter,

(*ii*) requirement of a large number of variables for complete specification of the state of matter,

(*iii*) easy and precise measurement is not possible of the variables used to describe the state of matter.

Microscopic view does help to explain certain phenomenon which cannot be analysed by macroscopic approach. However, the microscopic approach is rather complex, cumbersome and time consuming. The macroscopic approach is more practical and consequently the overwhelming majority of thermodynamic analysis is made by it. Engineering thermodynamic analysis is macroscopic and not microscopic.

Comparison of Macroscopic and Microscopic Approach

Macroscopic approach	*Microscopic approach*
1. Attention is focussed on a certain quantity of matter without taking into account the events occuring at molecular level.	1. Matter constituting the system is considered to comprise a large number of discrete particles called molecules. These molecules have different velocities and energies, and these parameters constantly change with time.
2. Analysis is concerned with gross or overall behaviour of the system, and this approach is adopted in the study of classical thermodynamics.	2. A knowledge of the structure of matter is essential in analysing the behaviour of the system, and this approch is adopted in the study of statistical thermodynamics.
3. A few properties are needed to describe the system.	3. Large number of variables are needed to describe the system.
4. The properties like pressure and temperature etc needed to describe the system can be easily measured, and felt by our senses.	4. The properties like velocity, momentum and kinetic energy which describe the behaviour of the molecules can neither be felt by our senses nor easily measured by instruments.
5. The properties of the system are their average values.	5. The properties are defined for each molecule individually.
6. The macroscopic approach requires simple mathematical formulae for analysing the system.	6. Number of molecules is very large and as such the microscopic approach requires advanced statistical and mathematical methods to explain any change in the system.

Note: The relationship between macroscopic and microscopic point of view lies in the fact that macroscopic properties are in fact the average properties of a large number of microscopic characteristics. Obviously, when both the methods are applied to a practical system, they give the same result.

Thermodynamics, however, never explains how a process is executed, the time rate at which the process is in progress and time of completion. Such investigations are made through kinetic theory of gases, heat and mass transfer and chemical kinetics. Again, thermodynamics fails when the system is at high vacuum, *i.e.*, it has less number of particles.

1.3. THERMODYNAMIC SYSTEM, SURROUNDINGS AND BOUNDARY

A ***thermodynamic system*** represents a prescribed and identifiable (fixed) quantity of matter under consideration to analyse a problem; to study the changes in its properties due to exchange of energy in the form of heat and work. The system may be a quantity of steam, a mixture of vapour and gas or a piston-cylinder assembly of an I.C. engine and its contents.

For the description of a thermodynamic system, some of the following quantities need to be specified:

(*i*) quantity as well as composition of the matter
(*ii*) measurable properties such as pressure, temperature and volume of the system
(*iii*) energy of the system.

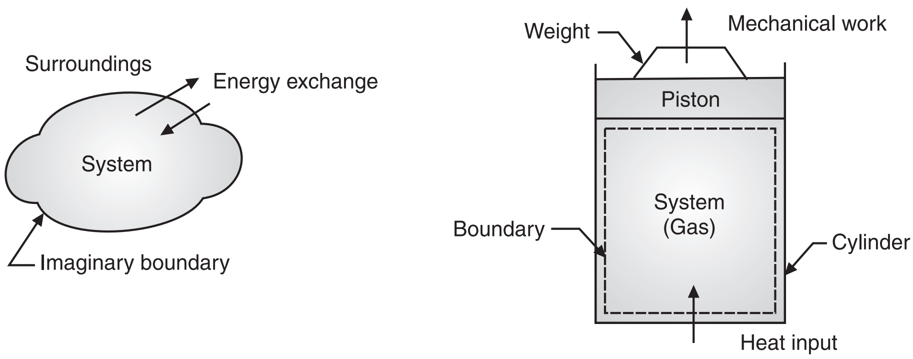


Fig. 1.1. Representation of system, boundary and surroundings

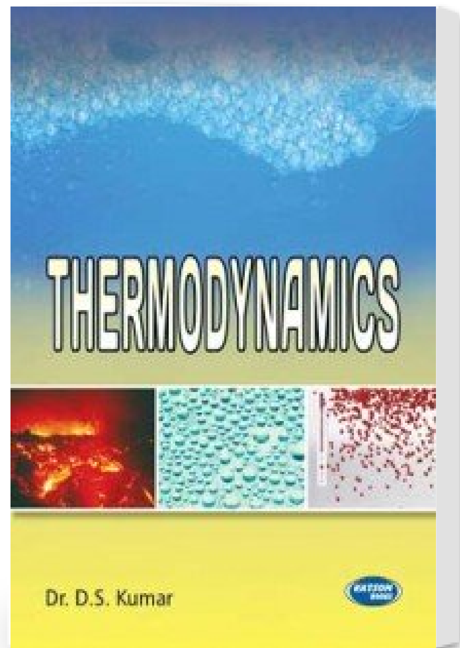
The combination of matter and space, external to the system, that may be influenced by changes in the system is called *surroundings* or *environment*. The thermodynamic system and surroundings are separated by an envelope called *boundary* of the system. The boundary represents the limit of the system and may be either real or imaginary, and may change shape, volume, position and/or orientation relative to the observer. For example, an elastic balloon which is initially spherical in shape may get deformed into a cylindrical shape or some other geometrical shape or it may get squeezed to a reduced volume during a certain process. As such the boundary of the gas enclosed in the balloon would not retain the same shape and size. Further, the boundary may be diathermal or adiabatic depending upon whether it allows or not exchange of energy in the form of heat. The walls or boundaries which do not allow heat transfer to take place across them are named *adiabatic*. In contrast, the walls that do allow heat interaction across them are called *diathermic*.

The surroundings can also be regarded as a system, and hence thermodynamics is largely concerned with interaction between systems.

Thermodynamic systems can be classified into:

(*a*) Closed System : A closed system can exchange energy in the form of heat and work with its environment but there is no mass transfer across the system boundary. The mass within the system remains the same and constant, though its volume can change against a flexible boundary. Further, the physical nature and chemical composition of the mass may change. Thus a liquid may evaporate, a gas may condense or a chemical reaction may occur between two or more components of the system.

Thermodynamics



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