

ENGINEERING THERMODYNAMICS

P K NAG

Engineering Thermodynamics

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Indian Institute of Technology
Kharagpur



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To
My Parents

Preface

The purpose of this book is to provide a mature approach to the basic principles of classical thermodynamics which is one of the few core subjects for the undergraduate students of almost all branches of engineering. The system-surroundings interactions involving work and heat transfer with associated property changes, and the system-control volume approaches of the first law have been emphasized. The second law has been elaborated upon in considerable detail. Except for some physical explanations, a statistical or microscopic analysis of the subject has not been made.

The first eight chapters of the book are devoted to a thorough treatment of the basic principles and concepts of classical thermodynamics. The second law and entropy have been introduced using the concept of heat engine. Chapters 9 and 10 present the properties of substances. Chapter 11 gives the general thermodynamic relationships among properties. A detailed analysis of power and refrigeration cycles is given in Chapters 12 to 14. Chapter 15 deals with air-water vapour mixtures, and reactive systems are analyzed in Chapter 16. To increase the utility of the book, Chapters 17 and 18 dealing with compressible fluid flow and heat transfer respectively, have been added.

Many illustrative examples are solved and many problems are provided in each chapter to aid comprehension and to stimulate the interest of the students.

Throughout the text SI units have been used. Tables and charts given in the Appendix are also in SI units.

This book is based mainly on the lecture notes prepared for classes on the subject at IIT, Kharagpur. I am grateful to all the authors of the books I had used in preparing the notes, a list of which is given in the bibliography. I am thankful to my colleagues in the mechanical engineering department of IIT, Kharagpur, for many stimulating discussions, and for encouragement. I am indebted to all those who have helped in the preparation of the book.

I would very much appreciate criticisms, suggestions for improvement, and detection of errors from my readers, which will be gratefully acknowledged.

P K NAG

It is a remarkable illustration of the ranging power of the human intellect that a principle first detected in connection with the clumsy puffing of the early steam engines should be found to apply to the whole world, and possibly, even to the whole cosmic universe.

A.R. Ubbelohde, *Man and Energy*
(Hutchinson, London, 1954)

List of Symbols

| | |
|----------------|--|
| A | Area, availability |
| AE | Available energy |
| a | Acceleration, specific availability |
| B | Virial coefficient, Keenan function |
| b | Specific Keenan function |
| C | Heat capacity, number of components, virial coefficient |
| c | Specific heat, velocity of sound |
| $^{\circ}C$ | Degree Celsius |
| D | Diameter, virial coefficient |
| d | An infinitesimal increase in a point function |
| E | Energy |
| e | Specific energy |
| F | Helmholtz function, force, impulse function, configuration factor for gray bodies, tension |
| f | Degree of freedom or variance, fugacity, specific Helmholtz function |
| G | Gibbs function, mass of dry air |
| ΔG | Gibbs function change |
| g | Acceleration due to gravity, specific Gibbs function |
| g_0 | Constant of proportionality in Newton's law |
| Gr | Grashof number |
| H | Enthalpy, magnetic field strength |
| ΔH | Heat of reaction |
| h | Specific enthalpy, heat transfer coefficient |
| \bar{h}_{RP} | Enthalpy of combustion |
| I | Electric current, irreversibility, moment of inertia, impulse pressure |
| J | Joule's equivalent |
| K | Boltzmann constant, equilibrium constant, thermal conductivity, |
| K | Degree Kelvin |
| $K.E.$ | Kinetic energy |
| kgf | Kilogram force (in MKS) |
| kgm | Kilogram mass (in MKS) |
| kg | Kilogram (in SI) |
| L | Length, amount of liquid |
| l | Latent heat |
| M | Mach number |
| μ | Molecular weight |
| m | Mass, mass of water vapour |
| \dot{m} | Mass flow rate |

| | |
|----------------|--|
| N | RPM, number of molecules |
| Nu | Nusselt number |
| n | Number of moles, number of cylinders, polytropic exponent |
| P.E. | Potential energy |
| Pr | Prandtl number |
| p | Pressure, partial pressure |
| Q | Heat transfer, rate of heat transfer |
| q | Rate of heat flux |
| R | Characteristic gas constant, thermal resistance, electrical resistance |
| \bar{R} | Universal gas constant |
| Re | Reynolds number |
| r | Radius |
| r_c | Cut-off ratio |
| r_k | Compression ratio |
| r_e | Expansion ratio |
| S | Entropy |
| s | Specific entropy |
| T | Absolute temperature, torque |
| t | Temperature |
| t_{db} | Dry bulb temperature |
| t_{dp} | Dew point temperature |
| t_{wb} | Wet bulb temperature |
| U | Internal energy, overall heat transfer coefficient |
| U.E. | Unavailable energy |
| u | Specific internal energy |
| \bar{u}_{RP} | Internal energy of combustion |
| V | Volume |
| \mathbf{V} | Velocity |
| v | Specific volume |
| W | Work transfer, specific humidity |
| w | Mass flow rate, angular velocity |
| X | Value of thermometric property |
| x | Quality, mole fraction, thickness, Cartesian co-ordinate |
| y | Cartesian co-ordinate |
| Z | Compressibility factor, elevation, height |
| z | Cartesian co-ordinate |

Greek symbols and special notations

| | |
|----------|--|
| α | Absorptivity |
| β | Coefficient of volume expansion |
| γ | Specific heat ratio |
| Δ | A finite increase in a point function or property |
| d | An infinitesimal amount of work or heat transfer (a path function) |

| | |
|---------------|--|
| δ | A small change in a property |
| ϵ | Degree of reaction, energy of a particle |
| ε | Thermal emf |
| η | Efficiency |
| θ | Angle, temperature |
| μ | Joule-Kelvin coefficient, chemical potential, degree of saturation, coefficient of viscosity |
| ν | Kinematic viscosity, stoichiometric coefficient |
| ρ | Density, reflectivity |
| σ | Control surface, surface tension, Stefan-Boltzmann constant |
| τ | Time, transmissivity |
| ϕ | Availability function for a closed system, number of phases, relative humidity |
| Ψ | Availability function for a steady flow system |

Subscripts and superscripts

| | |
|-------|---|
| c | Critical state, cold fluid |
| f | Saturated liquid |
| f_g | Change in property between saturated vapour and saturated liquid phases |
| g | Saturated vapour |
| i | Fluid at initial state, initial phase |
| f | Fluid at final state; final phase |
| h | Hot fluid |
| m | Mixture value |
| o | Surrounding state |
| p | Constant pressure |
| R | Reversible |
| r | Reduced value |
| s | Constant entropy |
| t | Triple point |
| v | Constant volume |

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1

Introduction : Basic Concepts, Definitions and Units

Thermodynamics is the science of energy transfer and its effect on the physical properties of substances. It is based upon observations of common experience which have been formulated into thermodynamic laws. These laws govern the principles of energy conversion. The applications of the thermodynamic laws and principles are found in all fields of energy technology, notably in steam and nuclear power plants, internal combustion engines, gas turbines, air conditioning, refrigeration, gas dynamics, jet propulsion, compressors, chemical process plants, and direct energy conversion devices.

1.1 MACROSCOPIC vs MICROSCOPIC

There are two points of view from which the behaviour of matter can be studied: the macroscopic and the microscopic. In the macroscopic approach, a certain quantity of matter is considered, without the events occurring at the molecular level being taken into account. From the microscopic point of view, matter is composed of myriads of molecules. If it is a gas, each molecule at a given instant has a certain position, velocity, and energy, and for each molecule these change very frequently as a result of collisions. The behaviour of the gas is described by summing up the behaviour of each molecule. Such a study is made in *microscopic or statistical thermodynamics*. *Macroscopic thermodynamics* is only concerned with the effects of the action of many molecules, and these effects can be perceived by human senses. For example, the macroscopic quantity, pressure, is the average rate of change of momentum due to all the molecular collisions made on a unit area. The effects of pressure can be felt. The macroscopic point of view is not concerned with the action of individual molecules, and the force on a given unit area can be measured by using, e.g., a pressure gauge. These macroscopic observations are completely independent of the assumptions regarding the nature of matter. All the results of classical or macroscopic thermodynamics can, however, be derived from the microscopic and statistical study of matter.

1.2 THERMODYNAMIC SYSTEM AND CONTROL VOLUME

A thermodynamic *system* is defined as a quantity of matter or a region in space upon which attention is concentrated in the analysis of a problem. Everything external to the system is called the *surroundings* or the *environment*. The system is separated from the surroundings by the system boundary (Fig. 1.1). The boundary may be either *fixed* or *moving*. A system and its surroundings together comprise a *universe*.

There are three classes of systems: (a) closed system, (b) open system, and (c) isolated system. The *closed system* (Fig. 1.2) is a system of fixed

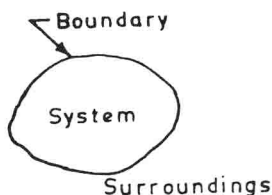


Fig. 1.1 A thermodynamic system

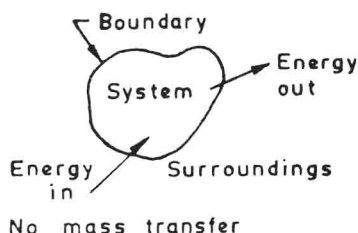


Fig. 1.2 A closed system

mass. There is no mass transfer across the system boundary. There may be energy transfer into or out of the system. A certain quantity of fluid in a cylinder bounded by a piston constitutes a closed system. The *open system* (Fig. 1.3) is one in which matter crosses the boundary of the system. There may be energy transfer also. Most of the engineering devices are generally open systems, e.g., an air compressor in which air enters at low pressure and leaves at high pressure and there are energy transfers across the system boundary. The *isolated system* (Fig. 1.4) is one in which there is no in-

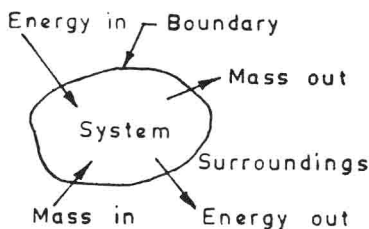


Fig. 1.3 An open system

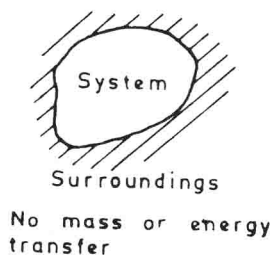


Fig. 1.4 An isolated system

teraction between the system and the surroundings. It is of fixed mass and energy, and there is no mass or energy transfer across the system boundary.

For thermodynamic analysis of an open system, such as an air compressor, in which there is a flow of mass into and out of the system (Fig. 1.5), attention is focussed on a certain volume in space surrounding the compressor, known as the *control volume*, bounded by a surface called the *control surface*. Matter as well as energy can cross the control surface.

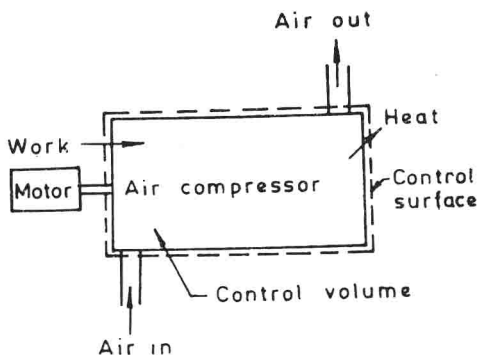


Fig. 1.5 Control volume and control surface

While dealing with a fixed quantity of mass, a system is defined, and in the case of a device involving a flow of mass a control volume is specified. The system approach concentrates on a fixed mass and the control volume approach focusses on the mass (and energy) flowing across the control surface. These are equivalent to the closed system and the open system respectively. The difference in these two approaches is elaborated in Chapter 5.

1.3 THERMODYNAMIC PROPERTIES, PROCESSES, AND CYCLES

Every system has certain characteristics by which its physical condition may be described, e.g., volume, temperature, pressure, etc. Such characteristics are called *properties* of the system. These are all *macroscopic* in nature. When all the properties of a system have definite values, the system is said

to exist at a definite *state*. Properties are the coordinates to describe the state of a system. They are the state variables of the system. Any operation in which one or more of the properties of a system changes is called a *change of state*. The succession of states passed through during a change of state is called the *path* of the change of state. When the path is completely specified, the change of state is called a *process*, e.g., a constant pressure process. A thermodynamic *cycle* is defined as a series of state changes such that the final state is identical with the initial state (Fig. 1.6).

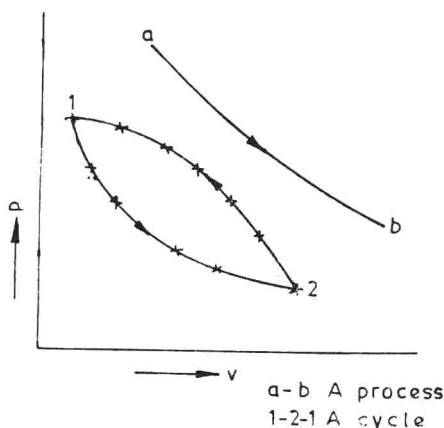


Fig. 1.6 A process and a cycle