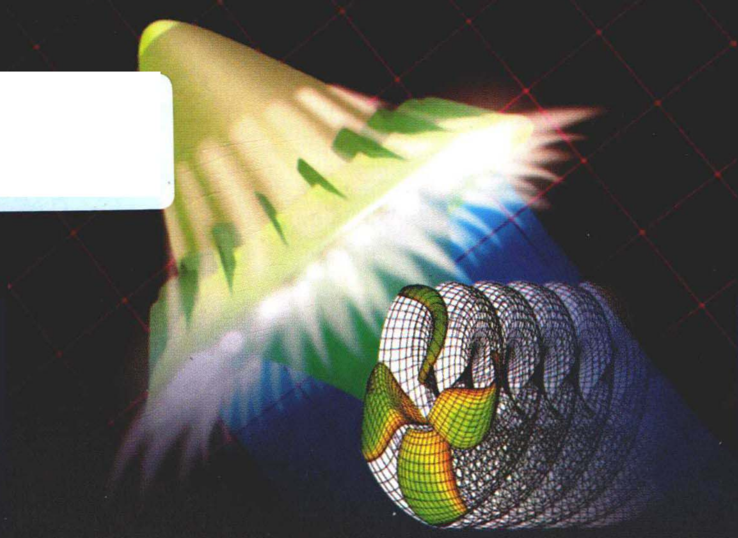

Aircraft and Automobile Propulsion

A Textbook

Himanshu Shekhar

Alpha Science

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Aircraft and Automobile Propulsion

A Textbook

Dedicated to

MY PARENTS

DR. KIRAN SHANKAR PRASAD (FATHER)
DR. KRISHNA PRASAD (MOTHER)

Preface

'Aircraft and Automobile Propulsion' is restricted to chemical propulsion, where a working fluid is burnt to produce large amount of gases, which gives propulsive force for execution of motion. Propulsion is a multi-disciplinary science and the main theme of this book is basically chemical propulsion, which needs simultaneous understanding of chemistry of molecules, heat transfer processes, combustion mechanisms, mechanical engineering, mathematics and all gamut of science.

This book has three aspects in general. First is discussion on internal combustion (IC) engines. This part encompasses discussions on both theoretical cycles and operational engines simultaneously. Second aspect is introduction and deliberations on aircraft power plants, where specific requirements of air-worthiness are debated. Third aspect is exhaustive discussion on modes of heat transfer. Three modes of heat transfer namely conduction; convection and radiation are deliberated in detail in this book.

Overall, this book covers theoretical and practical aspects of internal combustion engines. This book is very useful for graduation in mechanical engineering courses and other engineering streams where propulsion, internal combustion engine, heat transfer and thermodynamics are essential part of curriculum. This book serves the requirements of multi-dimensional domain of students, teachers, librarians, researchers and industries.

Himanshu Shekhar

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CHAPTER

1

Cycles and Processes

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- Summary
- Questions

1.1 INTRODUCTION

In the internal combustion engines, the chemical energy of fuel is first converted into heat through combustion process and then this generated heat is converted into work. The working fluid for air standard cycle is air mixed with fuel, which may be petrol or diesel. Invariably, the air standard cycles are constituted by minimum four processes. It has heat rejection and heat addition processes. Other two processes are work consumed and work produced. Depending on nature of these processes, various cycles are prevalent. This chapter gives a brief description of various cycles and their control terms.

The chapter deals with the reciprocating engine where piston-cylinder arrangement is prevalent. The piston slides inside the cylinder executing compression stroke. At the end of compression heat addition takes place by combustion of fuel and useful work is extract during outward movement of piston executed by hot combustion gases. Once piston moves out of the cylinder, some part of useful work is stored in a flywheel, which releases work for the compression stroke of the piston. This chapter gives details of various air-standard cycles for reciprocating engines.

Objective

After studying this Chapter, you should be able to :

- Understand different air standard cycles
- Evaluate Otto, Diesel and Dual cycles
- Realize various types of efficiencies used in Internal Combustion Engines
- Know power output in terms of torque
- Calculate mean effective pressure and specific fuel consumption

1.2 THERMODYNAMIC PROCESSES AND CYCLES

Thermodynamics is a physical science and is based on observation of nature. It is made of Greek words *therme* meaning heat and *dynamis* means force; so it is study of energy conversion between heat and mechanical work. Then how it is different from heat transfer? If heat moves from one place to other, the thermodynamics only gives conditions responsible for movement of heat and at most how much heat can be transferred. However, heat transfer gives rate of transfer of heat also and ultimately it gives idea about time taken to heat an object. Heat transfer gives temperature at various points in the system, while thermodynamics only gives total amount of heat transferred and assumes entire system at a uniform temperature. **Thermodynamics gives quantity of heat while heat transfer gives rate of energy transfer.** There are certain other rate processes like mass transfer, momentum transfer, chemical kinetics etc.

In thermodynamics formulation of intuitive and primitive concepts has a major role. For example, if heat is given to a system, temperature will rise. Mathematical formulation of this intuitive idea is subject matter of thermodynamics. It involves several terms like energy, equilibrium, property, system, process, work, heat *etc.* All of them have a precise definition in thermodynamics. Before anything else, definition of thermodynamics is to be understood.

'Best way to study a subject is to understand it before you start'

Hotsopoulos and Keenan : Thermodynamics is the science of states and change of state of physical systems and the interaction between systems, which may accompany changes of states.

Callen : Thermodynamics is the study of the macroscopic consequence of myriads of atomic coordinates, which by virtue of the statistical averaging; do not appear explicitly in a macroscopic description of a system.

Epstein : Thermodynamics deals with systems, which, in addition to mechanical and electromagnetic parameters, are described by a specifically thermal one, namely the temperature or some equivalent of it. Thermodynamics is essentially a science about the conditions of equilibrium of systems and about the processes, which can go in states little different from the state of equilibrium.

Kestin : The science of thermodynamics is a branch of physics. It describes natural processes in which changes in temperature play an important part. Such processes involve the transformation of energy from one form to another. Consequently thermodynamics deals with the laws, which govern such transformation of energy.

Van Wylen and Sonntag : Thermodynamics is a science of energy and entropy.

In general, thermodynamics is (*i*) study of three 'E's namely energy, entropy and enthalpy (*ii*) study of heat and work interactions (*iii*) study of thermal effects on system (*iv*) study of energy, matter and the law governing their interactions. Whenever thermodynamic study is conducted, a region in space or a fixed mass or volume of material is considered. The constant volume or mass or control volume on which attention is focused for a given study is called '**system**'. Anything outside system is called '**surrounding**' and the demarcation of system is called '**boundary**'. Boundary is basically a hypothetical dividing line between system and surrounding. A diathermal boundary is one, which allows heat transfer, while adiabatic boundary means prevention of any heat transfer across the boundary.

Once system is defined, then it undergoes two types of interaction with surrounding. First type is called energy transfer. This energy transfer is also divided into two parts namely work transfer and heat transfer. **Heat transfer is basically all the energy transfers between the system and surrounding due to temperature difference.** Heat flow out of the system is negative heat transfer. **Work transfer** is all other forms of energy transfer and is defined in thermodynamics as **those energy transfers in which sole effect external to the system can be reduced to raising or lowering of weight.** Work transfer associated with raising of weight is taken positive as convention. This definition of work is different from work defined in mechanics. In mechanics, work is associated with displacement due applied force and is defined as product of force and displacement. However, in many energy conversion systems displacement is not easily available. Another form of interaction is called mass transfer. Mass transfer is associated with change in mass of the system and is always associated with the energy transfer. Mass transfer in absence of energy transfer is not possible.

Depending on these two forms of system-surrounding interactions, namely energy transfer and mass transfer, systems are classified in three different modules. First form is called **closed system**, in which mass transfer is prohibited and only energy transfer is permitted through boundary of the system. The mass of the system remains constant. Another form is called **open system**, which permits both mass and energy interactions. To study open system, generally closed volume concept is utilized, which is a fixed space, through which working fluids pass. Almost all the real systems are open system. Third type of system is called **isolated system**, which prevents interaction of both the types through their boundaries. Combination of both system and surrounding is an isolated system.

For each system, there are certain fixed properties on which attention is focused. Suppose in a class, each student possesses several unique characteristics like name, roll number, sex, religion, age, date of birth, father's name, height, marks obtained *etc.* Rather than specifying name, a number of these characteristics can help us in identification of a particular set of students. Male student with 5 feet 9 inch height born on 20 July may result in identification of a single student. There are different ways in which students in a class can be studied. It may be their sex-ratio, height profile; date of birth dispersion etc and for each study one particular property is considered. For a system, these set of characteristics are called '**property**'. Pressure is a property, volume is a property, and temperature is a property and so on.

Properties of a system may be classified as (*i*) **Intrinsic properties**, which are independent of mass of the system like pressure, temperature, internal energy, density *etc.* They are not additive. They are also called **thermostatic properties**. They arise due to mass and are evaluated by considering mass inside a system and without considering surrounding. They do not require any external datum point for their measurement. (*ii*) **Extrinsic properties** increase with increase in mass of the system like volume, energy *etc.* Ratio of two extrinsic properties is always intrinsic property. Properties acquire a definite value only at the state of equilibrium. The concept of thermodynamic equilibrium needs little explanation.

Thermodynamic equilibrium of a system is basically a combination of three forms of equilibrium – **mechanical equilibrium, thermal equilibrium and chemical equilibrium**. A system is said to be in mechanical equilibrium, if there is no unbalanced force or moment acting on the system. This ensures that system does not change position. Thermal equilibrium ensures that temperature of system and surrounding are same. There is no heat transfer across the diathermal boundary of the system and surrounding. There is no temperature change in the system. Existence of thermal equilibrium and no thermal interaction at equality of temperature is, in fact, derived from **zeroth law of thermodynamics**, which states – **'If a body is in thermal equilibrium separately with another two bodies, the other two bodies will also be in thermal equilibrium with each other'**. This law of thermodynamics can be expressed in several other forms. **'Energy can neither be created nor be destroyed'** is the statement of **first law of thermodynamics**. This indirectly indicates that energy can only change form. Another way to express this law is – **'Work cannot be executed without some form of equivalent amount of heat getting absorbed by the system'**. SI unit of work is joule (J), while for heat it is calories (cal) and 1 cal = 4.187 J. The conversion factor of heat to work is called **mechanical equivalent of heat**. Chemical equilibrium is another from of equilibrium, which ensures absence of any unaided spontaneous chemical reaction. The material, working fluid or content of the system should not undergo any chemical reaction of its own and bring any change in the composition of the system. Thermodynamic equilibrium is basically a hypothetical concept to understand and ensure that system properties are fixed and it does not change of its own. It also indirectly indicates that all the systems will lead to thermodynamic equilibrium, if left undisturbed. At thermodynamic equilibrium, properties of the system have a fixed value.

The distinguishing characteristics of the system are called properties of the system. Physical description of each system is characterized by certain quantities like pressure, volume, temperature *etc.* They are called properties of the system. These are all macroscopic in nature. Properties may be directly or indirectly observable characteristic of the system. Any combination of such characteristics is also a property. For example product of pressure and volume is property of a system. New properties can be defined in terms of already known properties. Such derived properties include enthalpy, Gibb's free energy, Helmholtz Function. Properties of a system are always called a state function or a point function and change of properties is dependent on end properties only.

For the system in thermodynamics, some of the unique properties of the systems need special attention. Properties of the system can be stated to exist in **conjugate pairs**. These pair in combination gives value of work. For example, in mechanics product of force and displacement gives work and they form a conjugate pair. Out of the elements of a conjugate pair, one is cause (force) and other is effect (displacement). For thermodynamics systems, one conjugate pair is pressure-volume, while another is temperature-entropy. Pressure is cause and it results in change in volume. Area under the curve on a pressure volume thermodynamic plane is equal to work interaction in the system. Similarly temperature is a cause, which results in change of entropy. As their product gives heat interaction during any change in the system, they form a conjugate pair. Here it must be noted that as per first law of thermodynamics, heat and work are mutually convertible. One interaction can be replaced totally by the other form of energy interaction. These four properties are important for understanding various energy transfer processes. So, each one is defined below.

Pressure (P) is derived from force directly. Force acting perpendicular to a surface is called thrust and thrust per unit area is called pressure. Force is a vector quantity, area is also a vector quantity, but pressure is a scalar quantity. It only indicates amplification of vector area to denote force acting on the surface. The scalar behaviour of pressure can be understood from the fact that hydraulic pressure at certain depth from free surface of water remains same and is independent of direction of considered plane at given depth. This makes it different from stress, which has identical units as pressure, but has tensor properties. Stress is force of resistance generated inside the body against an externally applied force, while pressure is constituted by the external forces directly. The application of pressure is seen in real life. A knife can cut vegetables with manual efforts. This is because, due to small area at the sharp edges of the knife, value of pressure becomes so high that vegetables get cut. However applying same force with a blunt knife or opposite edge of the knife require much higher force for execution of same operation. Similarly putting nail on wall, ease of movement for camels in desert, *etc.*, are some direct applications of pressure in real life.

Pressure is expressed in Pascal (Pa = N/m^2). Atmospheric pressure is measured by barometer. However, there are several other auxiliary units prevalent for indicating pressure. Their relations are given below.

1 atmospheric pressure = 1.0332 kg/cm^2 = 1.0332 ata = 1.01325 bar = 101.325 kPa = 1.01325 × 10^5 N/m^2 = 1.01325 × 10^5 Pa = 14.696 psi = 760 mm Hg = 10.26 m of water.

Pressure at a given point is called absolute pressure. This is used only when equation of state is to be used. In most of the real systems, it is change of pressure, which is important. So instead of absolute pressure, some relative variation of pressure is important. In real systems, value of pressure over atmospheric pressure is desirable. Such excess overpressure is called gauge pressure. In automobile tires, the pressure is expressed as 220 kPa/32 psi. These values are, in fact, gauge pressures and atmospheric pressure (101.325 kPa/14.696 psi) should be added to express the values correctly in absolute pressure. The absolute pressure in tires is 321.325 kPa/46.696 psi.

For pressure of gases, it needs a little more discussion. As per kinetic theory of gases, molecules of gases are in continuous motion inside a container. They collide amongst themselves and with the wall of the container in elastic manner and rebounds without any loss of energy. The net interactions of these molecules with wall of the container cause pressure.

EXAMPLE 1.1

A manometer has two limbs. One limb is open to atmosphere and other is connected to a pipe. If mercury (density 13.6 g/cc) is filled in manometer and open limb is 300 mm above the height of mercury in other limb of the manometer, find pressure in the pipe.

SOLUTION

Gage pressure in the open limb of the pipe

= Pressure due to difference in mercury column

= Density of mercury × Height of mercury column

= 13.6×30 g/cm^2 = $4.08/1000$ kg/cm^2

= $0.408 \times 101.325/1.0332$ kPa

= 40.0 kPa.

As limb connected to pipe has on lower side, pressure in pipe is higher than atmosphere. So, absolute pressure in the pipe = atmospheric pressure + gage pressure

= 101.325 kPa + 40 kPa = 141.325 kPa.

EXAMPLE 1.2

In example 1.1, if height of mercury in open limb is 300 mm below the height of mercury in the other limb, find pressure in the pipe.

SOLUTION

Gage pressure remains same as 40.0 kPa as calculated in the previous solution. However, absolute pressure in the pipe will be lower than atmospheric pressure by the pressure equal to gage pressure.

So, absolute pressure in the pipe = atmospheric pressure – gage pressure = 101.325 kPa – 40 kPa = 61.325 kPa.

Volume (V) is another significant property for a system and is derived from the geometry of the system. Volume is how much three-dimensional space a substance (solid, liquid, gas, or plasma) or shape occupies or contains, often quantified numerically using the SI derived unit, the cubic meter. The volume of a container is generally understood to be the capacity of the container, *i.e.* the amount of fluid (gas or liquid) that the container could hold, rather than the amount of space the container itself displaces. Three dimensional mathematical shapes are also assigned volumes. Volumes of some simple shapes, such as regular, straight-edged, and circular shapes can be easily calculated using arithmetic formulas. The volumes of more complicated shapes can be calculated by integral calculus if a formula exists for the shape's boundary. One-dimensional figures (such as lines) and two-dimensional shapes (such as squares) are assigned zero volume in the three-dimensional space. The volume of a solid (whether regularly or irregularly shaped) can be determined by fluid displacement. Displacement of liquid can also be used to determine the volume of a gas. The combined volume of two substances is usually greater than the volume of one of the substances. However, sometimes one substance dissolves in the other. In that case, the combined volume is not obtained by addition of volumes of solvent and solute. In thermodynamics, volume is a fundamental parameter, and is a conjugate variable to pressure.

EXAMPLE 1.3

Find volume of a figure made by a hemisphere placed over a cylinder of diameter of 30 mm and height of 50 mm. radius of hemi-sphere is same as that of cylinder and bottom end of the cylinder is flat.

SOLUTION

Given, Diameter, $D = 30$ mm,

Height of the cylinder, $H = 50$ mm.

$$\text{Volume of the cylinder} = \pi D^2 H/4 = \pi \times 302 \times 50/4$$

$$= 35342.9 \text{ mm}^3 = 35.3429 \text{ cc.}$$

$$\text{Volume of the hemi-sphere} = \pi D^3/12 = \pi \times 303/12$$

$$= 7068.58 \text{ mm}^3 = 7.06858 \text{ cc.}$$

$$\text{Total volume of the figure} = 35.3429 \text{ cc} + 7.06858 \text{ cc} = 42.4115 \text{ cc.}$$

EXAMPLE 1.4

Find work interaction in the process, which takes place in such a way that product of pressure and volume is constant. Pressure of the system changes from atmospheric pressure to 600 kPa and initial volume is 400 cc.

SOLUTION

Since pressure and volume are conjugate process, product of both can give work. For a given process, work interaction is given by area under the pressure volume curve. Here it is given that product of pressure and volume is the same. If first condition is expressed as subscript 1 and final condition by subscript 2, then