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
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EDITIONS

First Edition : 2020
Second Edition : 2021
Third Edition : 2022
Fourth Edition : 2023
Fifth Edition : 2024

Sixth Edition : 2025

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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 liquification 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 focused 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)?

Student's Assignments 1

Q.1 Which of the following is not a pure substance?
(a) Atmospheric air
(b) Steam-water mixture
(c) Combustion products of a fuel
(d) A mixture of air and liquid air

Q.2 What is the value of degree of freedom at critical point?
(a) 0 (b) 1
(c) 2 (d) 3

Q.3 Steady flow occurs when
(a) Fluid properties doesn't change with time at any point.
(b) Fluid properties are same at adjacent points at any instant.
(c) Fluid properties change steadily with time.
(d) None of these

Q.4 A sample of an ideal gas having an internal energy *U*, is then compressed to one half of its original volume, while the temperature remains same. What is the new internal energy of the ideal gas in terms of *U*?
(a) U (b) $\frac{1}{2}U$
(c) $\frac{1}{4}U$ (d) $2U$

Q.5 When a current flows through a resistor, taken as a system, across a potential difference, the energy flowing into the system is
(a) Work transfer
(b) Heat transfer
(c) Work and heat transfer
(d) Elasticity

Q.6 In an oil cooler, oil flows steadily through a bundle of metal tubes submerged in steady stream of cooling water. Under steady conditions oil enters at 90°C and leaves at 30°C. Water enters at 25°C and leaves at 70°C. Enthalpy of oil $h = 1.68t + 10.5 \times 10^{-4} t^2$ kJ/kg. What is cooling water required for cooling 3 kg/s of oil?
(a) 2 kg/s (b) 1.73 kg/s
(c) 1.9 kg/s (d) 2.3 kg/s

Q.7 A certain gas has c_p = 1.968 kJ/kgK and c_v =1.507 kJ/kgK, then molecular weight of gas is _____ g/gmol.

Q.8 An ideal gas at 30°C is heated at constant pressure till the volume becomes four times, the temperature of the gas will be ________°C.

Q.9 A paddle wheel is installed in a rigid insulated tank containing 10 kg air (C_V = 0.718 kJ/kgK). A torque of 100 N.m is applied on the paddle wheel to rotate it at 60 rpm for 2 minutes. At the end of the process, the increase in temperature of air is ________°C

Q.10 A gas is compressed by a steady flow compression process. The mass flow rate of gas is 3 kg/s, increase in the specific enthalpy is 18 kJ/kg and decrease in the kinetic energy is 3 kJ/kg. If the rate of heat rejection to the environment is 3 kW, then the power needed to drive the compressor is ________ kW. (only magnitude)

Q.11 In a thermal power plant, power production is 1200 MW. If the energy given by coal is 900×10^7 kJ/h, then the rate at which heat is rejected from the power plant is ________ MW.

Q.12 For a steady process, the conditions at stage 1 and stage 2 are respectively, h_1 = 300 kJ/kg, h_2 = 150 kJ/kg, s_1 = 1.25 kJ/kg and s_2 = 0.8 kJ/kg-K, the change in availability will be ________ kJ/kg. (Take surrounding temperature = 300 K)

Q.13 As a closed system undergoes an internally reversible process, its entropy can
(a) increase (b) decrease
(c) remain constant (d) any of the above

Q.14 A manufacturer claims to have developed a table fan that consumes 25 W of electrical power to discharge 0.8 kg/s of air at velocity of 8 m/s. His claim is
(a) justified
(b) not possible
(c) highly cost intensive
(d) possible with advance technology

2°C, respectively. It delivers 70 kJ of work. This heat engine,

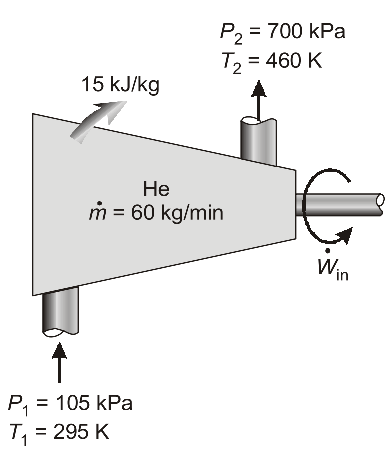
(a) violates the first law of thermodynamics only
(b) violates the 2nd law of thermodynamics but satisfy the first law
(c) satisfy the first law but violates the 2nd law of thermodynamics
(d) satisfy both the laws

Q.26 A body of mass 2.5 kg and c_p = 1.00 kJ/kgK is available at 600 K. If the atmosphere is at 300 K. The maximum work obtainable from the body by interacting with atmosphere is________ kJ.

Q.27 A heat engine receives half of its heat supply at 1000 K and half at 500 K, while rejecting heat to the sink at 300 K. The maximum thermal efficiency of the engine is ________%

Q.28 Block *A* of mass 5 kg and temperature 300°C. Block *B* of mass 10 kg and temperature –50°C. These two blocks consist of an isolated system. Heat capacities of block *A* and *B* be 1.0 and 0.4 kJ/kgK. The irreversibility of the system is________kJ.

Q.29 Helium is to be compressed from 105 kPa and 295 K to 700 kPa and 460K. A heat loss of 15 kJ/kg occurs during the compression process. Neglecting kinetic energy changes, the power input (in kW) required for a mass flow rate of 60 kg/min _______. (Correct up to two decimal places) Assume specific heat at constant pressure for helium as 5.1926 kJ/kgK.



ANSWERS

1. (d)	**2.** (a)	**3.** (a)	**4.** (a)	**5.** (a)
6. (b)	**7.** (18.04)	**8.** (939)	**9.** 10.5	**10.** (48)
11. (1300)	**12.** (15)	**13.** (d)	**14.** (b)	**15.** (b)
16. (207.4)	**17.** (19.08)	**18.** (a)	**19.** (c)	**20.** (b)
21. (b)	**22.** (d)	**23.** (d)	**24.** (a)	**25.** (c)
26. (230.14)	**27.** (55)	**28.** (276)	**29.** (871.78)	

HINTS

1. (d)

The mixture of air and liquid air is not a pure substance, because the relative proportions of oxygen and nitrogen differ in gas and liquid phases in equilibrium.

2. (a)

$$DOF = 0$$

Gibbs phase rule fails at critical point.

3. (a)

At steady state fluid properties doesn't change with respect to time at any given point.

4. (a)

If temperature is constant, *U* will remain unchanged as internal energy for an ideal gas is the function of temperature only.

6. (b)

Now, $\Delta H_{oil} = \Delta H_{water}$

$$\Rightarrow \dot{m}_{oil}\left[1.68(T_1 - T_2) + 10.5 \times 10^{-4} \times \left(T_1^2 - T_2^2\right)\right]$$

$$= \dot{m}_{water} \times c_{p_w}\,[T_1 - T_2]_{water}$$

$$\Rightarrow 3\left[1.68(90 - 30) + 10.5 \times 10^{-4}\left(90^2 - 30^2\right)\right]$$

$$= \dot{m}_{water} \times 4.18 \times (70 - 25)$$

$$\Rightarrow \dot{m}_{water} = 1.73 \text{ kg/s}$$

7. 18.04 (17.0 to 19.0)

Gas constant, $R = c_p - c_v$

$= 1.968 - 1.507$

$= 0.461$ kJ/kgK

Molecular weight,

$$\mu = \frac{\bar{R}}{R} = \frac{8.314}{0.461} = 18.04 \text{ g/gmol}$$

8. (939)

Pressure, P = Constant