Chapter 11

Fundamentals of Thermodynamics

Learning Objectives

Syllabus: **Teaching Hour (TH): 2**

Concepts and definition; Applications of thermodynamics; Properties and state of a substance; Thermodynamics properties and types; Thermodynamics processes (definition, characteristics and examples); Reversible and irreversible processes.

After studying this chapter, you will learn:

- To understand the concept and definition of thermodynamics.
- To understand the applications of thermodynamics.
- To understand the concept of properties and thermodynamic state of a substance.
- To understand the types of thermodynamic properties.
- To understand the definition, characteristics and examples of various thermodynamics processes.
- To understand the concept of reversible and irreversible processes.
- To solve the numerical problems related to the fundamentals of thermodynamics.

A Chapter Opening Question

What are the applications of thermodynamics in engineering?

11.1 Introduction

Thermodynamics is a branch of physics that deals with the relationship between heat, energy, and work. It provides a scientific framework for understanding and analyzing the behavior of energy and its interactions with matter, specifically in thermal processes and energy transformations. The laws of thermodynamics state the principles governing energy transfer and the relationship between heat, work, and internal energy of a system. In this chapter, we will study the concepts and definitions of thermodynamics, applications of thermodynamics, properties and state of a substance, properties and types of thermodynamics; definition, characteristics and examples of thermodynamical processes, and reversible and irreversible processes.

11.2 Concepts of Thermodynamics

In engineering, thermodynamics is an essential component of the design and analysis of energy systems and equipment, including power plants, engines, refrigeration systems, and heat exchangers. It is used to determine the efficiency of energy conversion processes, predict the performance of engines and power plants, and design systems for maximum efficiency and cost-effectiveness. The first and second laws of thermodynamics form the foundation of engineering thermodynamics, which also encompasses concepts such as entropy, enthalpy, and thermodynamic cycles.

Thermodynamics is the study of the relationships between heat, energy, and work in a physical system. It is concerned with understanding how energy is transformed from one form to another and how it affects the physical properties of a system, such as temperature, pressure, and volume. The central principles of thermodynamics are described by the first and second laws, which describe the conservation of energy and the direction of energy flow in a system. The study of thermodynamics is essential in various fields, including mechanical, electrical, chemical, and materials engineering, for the design and analysis of energy systems and equipment.

11.3 Applications of Thermodynamics

Thermodynamics has a wide range of *applications* in various fields. Some of them are

(a) The study of thermodynamics is fundamental in *mechanical engineering* to the design and analysis of engines and power plants, as well as heating and cooling systems.

(b) The principles of thermodynamics are used in *electrical engineering* to design and analyze power generators, transformers, and other electrical equipment.

(c) Thermodynamics is used in *chemical engineering* in the design and optimization of chemical processes, such as refining, petrochemical, and pharmaceutical processes.

(d) Thermodynamics is used in *materials science and engineering* to study the behavior of materials at high temperatures and pressures and to design materials with improved thermal properties.

(e) The principles of thermodynamics are used in *environmental engineering* to analyze and design energy-efficient systems for heating and cooling, as well as to minimize waste and pollution.

(f) Thermodynamics is used in *aerospace engineering* to design and analyze the performance of rocket engines and propulsion systems.

(g) The principles of thermodynamics are used in *biomedical engineering* to understand the metabolism of living organisms and to design medical equipment, such as artificial organs and thermal management systems.

11.4 Properties and State of a Substance

In thermodynamics, understanding the properties and state of a substance is important for analyzing and predicting its behavior in a given situation.

The properties of a substance are the characteristics that describe its behavior and characteristics, such as temperature, pressure, volume, and internal energy. These properties can be either intensive, meaning they do not depend on the amount of the substance, or extensive, meaning they do depend on the amount of the substance.

The state of a substance refers to the condition of the substance at a particular moment and is defined by its properties. The state of a substance can change as a result of external or internal factors, such as a change in temperature or pressure.

To describe the state of a substance, a state function is used. A state function is a property of a substance that depends only on its current state, and not on its history or how it got to that state. Examples of state functions include enthalpy, entropy, and internal energy.

11.5 Properties and types of Thermodynamics

Properties: There are several *properties* in thermodynamics. Some of them are

(a) **Temperature**: The measure of the average kinetic energy of the particles in a substance is called the *temperature*. It is also the *measure* of the heat energy in a system.

(b) **Pressure**: The force per unit area exerted on the boundaries of a substance is called the *pressure*. It is a measure of the compressive forces in a system.

(c) **Volume**: The amount of space occupied by a substance is called the *volume*. It is a measure of the size of a system.

(d) **Internal energy**: The total energy of a system, including the kinetic and potential energy of its particles is called *internal energy*.

(e) **Enthalpy**: The sum of the internal energy of a substance and the product of its pressure and volume is called *enthalpy*.

(f) **Entropy**: A measure of the disorder or randomness of a system is called *entropy*. It is a measure of the availability of energy in a system.

Types: Thermodynamics can be divided into *three* main branches: classical thermodynamics, statistical thermodynamics, and quantum thermodynamics.

(a) **Classical thermodynamics**: Classical thermodynamics deals with macroscopic systems and the first and second laws of thermodynamics. It is based on macroscopic observations and measurements of thermodynamic properties.

(b) **Statistical thermodynamics**: *Statistical thermodynamics* deals with the behavior of large numbers of particles and the distribution of their energy levels. It is based on the statistical analysis of molecular behavior and interactions.

(c) **Quantum thermodynamics**: *Quantum thermodynamics* deals with the thermodynamics of quantum systems and the behavior of particles at very small scales. It is based on quantum mechanics and the principles of quantum theory.

11.6 Thermodynamics Processes

In thermodynamics, a process refers to a change in the state of a system that occurs as a result of heat and/or works exchange with the surroundings. In thermodynamics, understanding the nature of thermodynamic processes is important for analyzing and predicting the behavior of energy systems and equipment.

There are *four* types of thermodynamic processes as discussed below

(a) **Isothermal process**: The thermodynamic process in which the temperature of a system remains constant is called the *isothermal process*. During an isothermal process, heat is exchanged between the system and its surroundings in such a way that the temperature of the system does not change.

Isothermal processes are important in thermodynamics because they provide a way to study the behavior of systems at a constant temperature. It is also an important part of understanding the behavior of systems and the exchange of heat and work. For example, by studying an isothermal expansion or compression of a gas, we can determine its relationship between pressure, volume and temperature.

In practice, isothermal processes are not always possible because the temperature of a system is not always constant. However, in some cases, it is possible to approximate an isothermal process by making the system exchange heat with a heat bath at a constant temperature.

The process in which the pressure and volume of a system change without any changes in its temperature is called an *isothermal process*. In such a process, there is a free exchange of heat between the system and its surroundings.

Gas equation: The *gas equation* for an isothermal process is

$$PV = \text{constant} \qquad \text{……… (i)}$$

If gas expands from initial state P_1 and V_1 to final state P_2 and V_2, then

$$P_1V_1 = P_2V_2$$

The variation of pressure P with volume V of an ideal gas in an isothermal process is as shown in the graph.

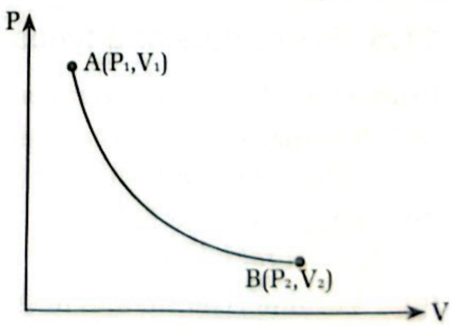

Fig: P-V graph of an isothermal curve

The equation of the first law of thermodynamics for the isothermal change is $dQ = dW$. i.e. work done by the gas during isothermal expansion is at the cost of heat supplied and during isothermal compression, heat is lost to the surrounding. A gas undergoing an isothermal process obeys Boyle's law.

Work done: For an isothermal process, the *work done* during an isothermal process is given by

$$W = RT \ln \frac{V_2}{V_1} \qquad \text{... ... ... (ii)}$$

For n mole of gas, eq^n (ii) can be expressed as

$$W = nRT \ln \frac{V_2}{V_1}$$

In terms of pressure change, the *work done* during an isothermal process is given by

$$W = RT \ln \frac{P_1}{P_2} \qquad \text{... ... ... (iii)}$$

For n mole of gas, eq^n (iii) can be expressed as

$$W = nRT \ln \frac{P_1}{P_2}$$

Thus, work done in an isothermal expansion of gas depends on both compression and expansion ratio.

Example: Some *examples* of isothermal processes in thermodynamics are

(i) An ideal gas that is allowed to expand or compress while in contact with a heat bath at a constant temperature.

(ii) A liquid is heated or cooled slowly, allowing it to exchange heat with its surroundings at a constant temperature.

(iii) A thermally insulated container that contains a gas at a constant temperature. When the gas expands or contracts, the process is isothermal because the temperature does not change.

(iv) The process of melting or solidifying a substance at its melting or freezing point. The temperature remains constant during the process, making it an isothermal process.

(v) An exothermic chemical reaction is conducted in a constant-temperature bath. The reaction occurs at a constant temperature, making it an isothermal process.

These are just a few examples of isothermal processes in thermodynamics. In practice, isothermal processes are often approximated to better understand the behavior of systems and the exchange of heat and work.

Adiabatic process: The thermodynamic process in which there is no heat exchange between the system and its surroundings is known as the *adiabatic process*. During an adiabatic process, the temperature of a system may change as work is done on or by the system, but the total amount of heat remains constant.

Adiabatic processes are important in thermodynamics because they provide a way to study the behavior of systems without the influence of heat exchange. It is also used to analyze and predict the performance of equipment and energy systems, such as gas turbines and refrigeration systems. For example, by studying an adiabatic expansion or compression of a gas, we can determine its relationship between pressure, volume, and temperature without the influence of heat exchange.

In practice, adiabatic processes are not always possible because heat is always exchanged between a system and its surroundings. However, in some cases, it is possible to approximate an adiabatic process by making the system insulated so that heat exchange is minimized.

Gas equation: The *gas equation* between P and V of an adiabatic process is

$$PV^{\gamma} = \text{constant} \qquad \dots\dots\dots (i)$$

Thus, the adiabatic equation describes the relationship between the pressure (P) of an ideal gas with its volume (V).

If P_1 and P_2 are the initial and final pressure of a gas with respective volumes V_1 and V_2, then

$$P_1 V_1^{\gamma} = P_2 V_2^{\gamma}$$

Relation between V and T: The relation to the adiabatic process between temperature and volume is

$$TV^{\gamma-1} = \text{constant} \qquad \dots\dots\dots (ii)$$

If T_1 and T_2 are the initial and final temperatures of gas with respective volumes V_1 and V_2, then

$$T_1 V_1^{\gamma-1} = T_2 V_2^{\gamma-1}$$

Relation between P and T: The *adiabatic process* between temperature and pressure is

$$P^{1-\gamma} T^{\gamma} = \text{constant} \qquad \dots\dots\dots (iii)$$

If P_1 and P_2 are the initial and final pressure of a gas with respective temperatures T_1 and T_2, then

$$P_1^{1-\gamma} T_1^{\gamma} = P_2^{1-\gamma} T_2^{\gamma}$$

Work done: The *work done* by the gas during an adiabatic process is

$$W = \frac{R}{\gamma - 1} (T_1 - T_2) \qquad \dots\dots\dots (iv)$$

Thus, the work done in an adiabatic change in a particular gas depends only on the change in temperature of the gas.

- During the adiabatic expansion, the gas does positive work and its internal energy decreases due to a fall in temperature.
- During adiabatic compression, the gas does negative work, and its internal energy increases due to a temperature rise.

Example: Some *examples* of adiabatic processes in thermodynamics are

(i) An insulated cylinder containing a gas that is compressed or expanded by a piston. The cylinder is insulated to minimize heat exchange, making the process adiabatic.

(iii) An explosion in a closed container. The container acts as insulation, preventing heat exchange with the surroundings, making the explosion an adiabatic process.

(iv) The adiabatic compression of air in a turbocharger of an internal combustion engine. The compression is performed without exchanging heat with the surroundings, making it an adiabatic process.

(v) An adiabatic expansion of gas in a refrigeration cycle. The gas is expanded without exchanging heat with the surroundings, causing its temperature to drop and making it useful for cooling.

(vi) An adiabatic process in a thermally insulated thermometer. The thermometer is insulated to minimize heat exchange, making the change in temperature an adiabatic process.

These are just a few examples of adiabatic processes in thermodynamics. Adiabatic processes play a crucial role in many energy systems and equipment, and a good understanding of them is important for analyzing and predicting their performance.

Isobaric process: The thermodynamic process in which the pressure of a system remains constant is known as the *isobaric process*. During an isobaric process, heat may be exchanged between the system and its surroundings, causing the temperature and volume of the system to change.

Isobaric processes are important in thermodynamics because they provide a way to study the behavior of systems and the exchange of heat and work at constant pressure. It is also used to analyze and predict the performance of equipment and energy systems at constant pressure, such as gas turbines and refrigeration systems.

For example, by studying an isobaric expansion or compression of a gas, we can determine its relationship between pressure, volume, and temperature.

Gas equation: The *equation* of the first law of thermodynamics for isobaric change is

$$dQ = dU + dW = dU + P\,dV$$

Work done: The *work done* during isobaric change is

$$W = P\,\Delta V = P\,(V_2 - V_1)$$

In practice, isobaric processes are not always possible because the pressure of a system is not always constant. However, in some cases, it is possible to approximate an isobaric process by making the system exchange heat with a heat bath at a constant pressure.

Example: Some *examples* of isobaric processes in thermodynamics are

(i) A gas that is allowed to expand or compress while in contact with a constant-pressure bath. As the gas expands or compresses, it exchanges heat with the bath, keeping the pressure constant.

(ii) A liquid that is heated or cooled while in a sealed container, keeping the pressure constant. As the temperature of the liquid changes, the pressure of the container remains constant.

(iii) An isobaric process in a pressure cooker. The pressure inside the cooker is kept constant by the valve, allowing the temperature to increase, cooking the food faster.

(iv) An isobaric process in a diving cylinder. The pressure inside the cylinder remains constant as the air is consumed, allowing the diver to breathe at the same pressure as the surrounding water.

(v) An isobaric process in a weather balloon. The pressure inside the balloon remains constant as it rises, allowing the temperature and volume of the gas inside to change.

These are just a few examples of isobaric processes in thermodynamics. In practice, isobaric processes are often approximated to better understand the behavior of systems and the exchange of heat and work.

Isochoric process: The thermodynamic process in which the volume of a system remains constant is known as the *isochoric process*. During an isochoric process, the temperature and pressure of the system may change as heat is exchanged with the surroundings. It is also called an *isometric process*.

Isochoric processes are important in thermodynamics because they provide a way to study the behavior of systems at constant volume and the exchange of heat and work. It is also used to analyze and predict the performance of equipment and energy systems, such as heat engines and refrigeration systems. For example, by studying the isochoric heating or cooling of gas, we can determine its relationship between pressure, volume, and temperature.

Gas equation: The *equation* of the first law of thermodynamics for isochoric change is

$$\Delta Q = \Delta U \qquad (\because \Delta V = 0)$$

Work done: Work done during isochoric change is zero. i.e. $\Delta W = 0$.

In practice, isochoric processes are not always possible because the volume of a system is not always constant. However, in some cases, it is possible to approximate an isochoric process by making the system exchange heat with a heat bath at constant volume.

Example: Some *examples* of isochoric processes in thermodynamics are

(i) A gas that is confined in a rigid container, allowing it to exchange heat with the surroundings while its volume remains constant.

(ii) An isochoric process in a sealed, rigid container filled with a gas. The gas is heated or cooled, causing its temperature and pressure to change, but its volume remains constant.

(iii) An isochoric process in a sealed, rigid bottle of soda. The pressure inside the bottle increases as the temperature rises, but its volume remains constant.

(iv) An isochoric process in a sealed, insulated container filled with a liquid. The temperature of the liquid changes as heat is exchanged with the surroundings, but its volume remains constant.

(v) An isochoric process in a sealed, rigid container filled with a solid. The temperature of the solid changes as heat is exchanged with the surroundings, but its volume remains constant.

For More Knowledge

Work done by the gas in different process

1. **Isothermals process:** $\Delta W = nRT\, ln\left(\frac{V_2}{V_1}\right) = nRT\, ln\left(\frac{P_1}{P_2}\right)$
2. **Adiabatic process:** $\Delta W = \frac{P_1V_1 - P_2V_2}{\gamma - 1} = \frac{nR}{\gamma - 1}(T_1 - T_2)$
3. **Isochoric process:** $\Delta W = 0$
4. **Isobaric process:** $\Delta W = P\, dV = P\,(V_2 - V_1)$

11.7 Reversible and Irreversible Processes

(a) Reversible process: The thermodynamic process that can be reversed without leaving any trace of its occurrence is known as the *reversible process*. In other words, the reversible process can be reversed, step by step, back to its original state with no change in the system or the surroundings. In a reversible process, the system and its surroundings are in thermal equilibrium, meaning that the temperature of the system is equal to the temperature of its surroundings.

Conditions: The *essential conditions* for the reversible process are

- All the processes taking place in the cycle of operation must be infinitely *slow*.
- There should *not* be any loss of energy due to conduction or radiation during the cycle of operation.

Example: Some *examples* of reversible processes in thermodynamics are

(i) A gas expanding into a vacuum, reversibly, meaning that the gas can be compressed back into its original state without any change in the system or the surroundings.

(ii) A Carnot heat engine, which operates between two temperature reservoirs and performs work in a reversible manner.

(iii) The adiabatic compression of an ideal gas, which can be reversed to its original state by an adiabatic expansion.

(b) **Irreversible process**: The thermodynamic process that cannot be reversed without leaving a trace of its occurrence is known as the *irreversible process*. In an irreversible process, the system and its surroundings are not in thermal equilibrium, meaning that the temperature of the system is not equal to the temperature of its surroundings.

Example: Some *examples* of irreversible processes in thermodynamics are

(i) A gas expanding into a vacuum, irreversibly, meaning that the gas cannot be compressed back into its original state without some change in the system or the surroundings.

(ii) Frictional heating, which generates heat due to friction between two surfaces and cannot be reversed without some change in the system or the surroundings.

(iii) A gas leak in a pipe is irreversible because the gas cannot be retrieved without some change in the system or the surroundings.

Difference: The distinction between reversible and irreversible processes is important in thermodynamics because it helps to quantify the maximum amount of work that can be extracted from a system and to determine the efficiency of thermodynamic systems. For example, the maximum amount of work that can be extracted from a system is equal to the amount of work that would be extracted in a reversible process.

In practice, almost all real-world processes are irreversible, meaning that they cannot be reversed without leaving a trace of their occurrence. However, the study of reversible processes is important in thermodynamics because it provides a theoretical limit on the performance of real-world systems and helps to understand the behavior of systems in idealized conditions.

Answer to Chapter Opening Question

Thermodynamics is a branch of physics that deals with the relationships between heat, energy and work. In engineering, thermodynamics is used in the design and analysis of a wide range of systems and devices, including power plants, engines, refrigeration systems, and heat exchangers. It is also used to study the behavior of gases and liquids, and to understand the properties of materials at high temperatures and pressures. Additionally, thermodynamics is used in the field of aerospace engineering to understand the behavior of rocket engines and other propulsion systems.

Review & Summary

1. Thermodynamics is a branch of physics that deals with the relationship between heat, energy, and work.
2. The properties of a substance are the characteristics that describe its behavior and characteristics, such as temperature, pressure, volume, and internal energy.
3. The state of a substance refers to the condition of the substance at a particular moment and is defined by its properties.
4. Thermodynamics can be divided into *three* main branches: classical thermodynamics, statistical thermodynamics, and quantum thermodynamics.
5. The thermodynamic process in which the temperature of a system remains constant is called the *isothermal process*.
6. The thermodynamic process in which there is no heat exchange between the system and its surroundings is known as the *adiabatic process*.
7. The thermodynamic process in which the pressure of a system remains constant is known as the *isobaric process*.

8. The thermodynamic process in which the volume of a system remains constant is known as the *isochoric process*.
9. The thermodynamic process that can be reversed without leaving any trace of its occurrence is known as the *reversible process*.
10. The thermodynamic process that cannot be reversed without leaving a trace of its occurrence is known as the *irreversible process*.

Key Formulae

1. **Gas equation for an isothermal process:** $PV = \text{constant} \Rightarrow P_1V_1 = P_2V_2$
2. **Work done during an isothermal process:** $W = nRT\ ln\frac{V_2}{V_1} = nRT\ ln\frac{P_1}{P_2}$
3. **Gas equation for an adiabatic process:**

   $PV^\gamma = \text{constant.} \qquad \Rightarrow P_1\ V_1^\gamma = P_2\ V_2^\gamma$

   $TV^{\gamma-1} = \text{constant.} \qquad \Rightarrow T_1\ V_1^{\gamma-1} = T_2\ V_2^{\gamma-1}$

   $P^{1-\gamma}\ T^\gamma = \text{constant.} \qquad \Rightarrow P_1^{1-\gamma}\ T_1^\gamma = P_2^{1-\gamma}\ T_2^\gamma$
4. **Work done by the gas during an adiabatic process:**

   $$W = \frac{P_1V_1 - P_2V_2}{\gamma - 1} = \frac{R}{\gamma - 1}(T_1 - T_2)$$
5. **Gas equation for isobaric change:** $dQ = dU + dW = dU + P\ dV$
6. **Work done during isobaric change:** $W = P\ \Delta V = P\ (V_2 - V_1)$
7. **Gas equation for isochoric change:** $\Delta Q = \Delta U$
8. **Work done for isochoric change:** $\Delta W = 0$.

Sample Conceptual Questions Answers

1. ***What is the role of thermodynamics in science and technology?***

✍ Thermodynamics is a branch of physics that deals with the study of heat and its relationship with other forms of energy. It plays a critical role in science and technology by providing a framework for understanding and manipulating energy, matter, and their interactions. It is essential for the design and optimization of energy systems, industrial processes, materials, environmental applications, and our fundamental understanding of the physical world.

2. ***Why is the reversible process not found in nature?***

✍ Reversible processes are not found in nature because natural processes involve some level of irreversibility due to factors such as friction, thermal gradients, and entropy production. While the concept of a reversible process is important in thermodynamics for defining theoretical limits on energy conversion processes, it is an idealization that cannot be achieved in practice.

3. ***Can you do any research project by studying thermodynamics?***

✍ Thermodynamics can be applied to a wide range of fields, from chemistry and physics to engineering and materials science. Combining thermodynamics with other disciplines can lead to research projects that address complex problems or develop new technologies. For example, research projects in this area could include developing new technologies for capturing and storing energy or designing systems that optimize energy use in buildings, transportation, or manufacturing.

Sample Examples

10 moles of an ideal gas in a cylinder are compressed isothermally at 27 °C showing that its pressure increases by 3 times. Find the amount of work done during this process.

ion: Given;

Initial pressure (P_1) = P

Temperature (T) = 27 °C = 300 K

Ideal gas constant (R) = 8.31 J mol^{-1} K^{-1}

Final pressure (P_2) = 3P

Number of moles (n) = 10

Work done (W) = ?

For an *isothermal process*, we have

$$W = nRT\, ln\frac{P_1}{P_2} = 10 \times 8.31 \times 300\, ln\frac{P}{3P} = -27{,}388.40\text{ J}$$

Hence, the amount of work done during the given isothermal process is –27,388.40 J.

A mass of air occupying initially a volume of 2 ×10^{-3} m^3 at a pressure of 760 mm of mercury and a temperature of 20 °C is expanded adiabatically and reversibly to twice its volume, and then compressed isothermally and reversibly to a volume of 3 × 10^{-3}. Find the final pressure assuming the ratio of the specific heat capacities of air to be 1.4.

ion: Given;

For an adiabatic expansion, we have

Initial volume (V_1) = 2 × 10^{-3} m^3

Second stage volume (V_2) = 2 V_1

Initial pressure (P_1) = 760 mm of Hg

Second stage pressure (P_2) = ?

Initial temperature (T_1) = 20 °C = (20 + 273) K = 293 K

For an *adiabatic process*, we have

$$PV^\gamma = \text{constant} \qquad \Rightarrow P_1V_1^\gamma = P_2V_2^\gamma$$

$$\therefore \quad P_2 = \left(\frac{V_1}{V_2}\right)^\gamma \times P_1 = \left(\frac{V_1}{2V_2}\right)^\gamma \times P_1 = \left(\frac{1}{2}\right)^{1.4} \times 760 = 287.99 \text{ mm of Hg}$$

For *isothermal compression*, we have

Final volume (V_3) = 3 × 10^{-3} m^3

Final pressure (P_3) = ?

For *isothermal compression*, we have

$$PV = \text{constant} \qquad \Rightarrow P_2V_2 = P_3V_3$$

$$\text{or,} \quad P_3 = \frac{P_2V_2}{V_3} = \frac{287.99 \times 2 \times 2 \times 10^{-3}}{3 \times 10^{-3}} \qquad (\because V_2 = 2V_1)$$

$$\therefore \quad P_3 = 383.99 \text{ mm of Hg}$$

Hence, the *final pressure* of the given mass of air is 383.99 mm of Hg.

Air is compressed adiabatically to half its volume at 0 °C. Calculate the change in its temperature.

tion: Given;

Initial volume (V_1) = V

Initial temperature (T_1) = 0 °C = 273 K

Change in temperature (ΔT) = ?

Final volume (V_2) = V/2

Final temperature (T_2) = ?

For an *adiabatic process*, we have

$TV^{\gamma-1} = \text{constant}$

or, $T_1 V_1^{\gamma-1} = T_2 V_2^{\gamma-1}$

$\therefore \quad T_2 = T_1 \times \left(\frac{V_1}{V_2}\right)^{\gamma-1} = 273\left(\frac{V}{V/2}\right)^{1.4-1} = 273\,(2)^{0.4} = 360.2\text{ K}$

So, the *change in temperature* of the air is

$\Delta T = T_2 - T_1 = 360.2 - 273 = 87.2\text{ K}$

Thus the temperature of given air is increased on compressing adiabatically by 87.2 K.

4. ***A gasoline engine takes in air at 25 °C and one atmospheric pressure and compresses adiabatically to one-tenth of its original volume. Find the final temperature and final pressure. (γ= 1.4)***

Solution: Given;

Initial volume $(V_1) = V$ (say)

Initial temperature $(T_1) = 25°C = 298$ K

Initial pressure $(P_1) = 1$ atm. $= 1.01 \times 10^5\text{ Nm}^{-2}$

Final volume $(V_2) = \frac{V}{10}$

Final temperature $(T_2) = ?$

Final pressure $(P_2) = ?$

For an *adiabatic process*, we have

$PV^{\gamma} = \text{constant} \quad \Rightarrow P_1V_1^{\gamma} = P_2V_2^{\gamma}$

$\therefore \quad P_2 = P_1\left(\frac{V_1}{V_2}\right)^{\gamma} = 1.01 \times 10^5 \left(\frac{V}{V/10}\right)^{1.4} = 1.01 \times 10^5 \times (10)^{1.4} = 2.54 \times 10^5\text{ Nm}^{-2}$

For the *adiabatic process*, we have

$TV^{\gamma-1} = \text{constant} \quad \Rightarrow T_1V_1^{\gamma-1} = T_2V_2^{\gamma-1}$

or, $T_2 = T_1\left(\frac{V_1}{V_2}\right)^{\gamma-1} = 298 \times \left(\frac{V}{V/10}\right)^{1.4-1} = 298 \times (10)^{0.4} = 748.54\text{ K}$

$\therefore \quad T_2 = (748.54 - 273)\text{ °C} = 475.54\text{ °C}$

Hence, the final pressure and final temperature of the air in the gasoline engine are $2.54 \times 10^5\text{ Nm}^{-2}$ and 475.54 °C respectively.

5. ***A liter of air initially at 20 °C and at 760 mm of Hg pressure is heated at constant pressure until its volume is doubled. Find the final temperature and the external work done by the gas in expanding.***

Solution: Given;

Initial Volume $(V_1) = 1$ liter $= 10^{-3}\text{ m}^3$

Initial Temperature $(T_1) = 20\text{ °C} = 293$ K

Initial Pressure $(P_1) = 760$ mm of Hg $= 1.01\times10^5\text{ Nm}^{-2}$

External work done (dW) =?

Final Volume $(V_2) = 2$ V

Final Temperature $(T_2) = ?$

Final pressure $(P_2) = P_1$

At constant pressure, we have

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

$\therefore \quad T_2 = \frac{V_2}{V_1} \times T_1 = \frac{2V}{V} \times 293 = 586\text{ K}$

The *external work done* by the gas in expansion is

$dW = P\,dV = P_1 (V_2 - V_1) = P_1 (2V - V) = P_1 \times V$

$dW = 1.01 \times 10^5 \times 10^{-3} = 101$ J

Thus, the final temperature and external work done by the gas during expansion are 586 K and 101 J.

Calculate the change in internal energy of 1 gm of water when boiled at 100 °C at 1 atmospheric pressure. The volume of steam at 100 °C is 1671 cc and the latent heat of vaporization is 540 cal/gm.

Soln: Given;

Latent heat of vaporzation (L_V) = 540 cal/gm = 2.268×10^6 J/kg

Mass of water (m) = 1 gm = 10^{-3} kg

$$\text{Initial volume } (V_1) = \frac{\text{mass of water}}{\text{density of water}} = \frac{10^{-3}}{1000} = 10^{-6}\ m^3$$

Pressure (P) = 1 atm = 1.01×10^5 N/m^2

Final volume (V_2) = 1671 cc = 1671×10^{-6} m^3

Change in internal energy (dU) = ?

Here, the *change in volume* is

$dV = V_2 - V_1 = 1671 \times 10^{-6} - 10^{-6} = 1670 \times 10^{-6}\ m^3$

The amount of *heat supplied* to boil water is

$dQ = m\,Lv = 10^{-3} \times 2.268 \times 10^6 = 2.27 \times 10^3$ J

Using the *first law of thermodynamics*, we have

$dQ = dU + P\,dV$

$dU = dQ - P\,dV = 2.27 \times 10^3 - 1.01 \times 10^5 \times 1670 \times 10^{-6} = 2270$ J

At constant temperature, the change in internal energy is zero. But in this case, the change in internal energy is due to a change in the state of water into the steam.

Exercise and Problems

Short Answer Questions

Define thermodynamics with main applications.

What are the properties and thermodynamic state of a substance?

Distinguish between reversible and irreversible processes.

Long Answer Questions

Describe the types of thermodynamical properties.

Write down definitions, characteristics and examples of various thermodynamic processes.

What are the differences between the isothermal process and the adiabatic process? Describe with suitable examples.