

# Mechanical Engineering

## Thermodynamics

Comprehensive Theory

*with* Solved Examples and Practice Questions



**MADE EASY**  
Publications



## **MADE EASY Publications**

Corporate Office: 44-A/4, Kalu Sarai (Near Hauz Khas Metro Station), New Delhi-110016

E-mail: [infomep@madeeasy.in](mailto:infomep@madeeasy.in)

Contact: 011-45124660, 8860378007

Visit us at: [www.madeeasypublications.org](http://www.madeeasypublications.org)

## **Thermodynamics**

© Copyright by MADE EASY Publications.

All rights are reserved. No part of this publication may be reproduced, stored in or introduced into a retrieval system, or transmitted in any form or by any means (electronic, mechanical, photo-copying, recording or otherwise), without the prior written permission of the above mentioned publisher of this book.

First Edition: 2015

Second Edition: 2016

Third Edition: 2017

**Fourth Edition: 2018**

# Contents

## Thermodynamics

### Chapter 1

#### Basic Concepts & Zeroth Law of Thermodynamics ..... 1

- 1.1 Introduction..... 1
- 1.2 System, Surroundings and Properties..... 1
- 1.3 State of the System & Process ..... 3
- 1.4 Pure Substances ..... 4
- 1.5 Zeroth Law of Thermodynamics ..... 5
- Objective Brain Teasers* ..... 9
- Student Assignments* ..... 10

### Chapter 2

#### Energy and Energy Interactions ..... 11

- 2.2 Work ..... 12
- 2.3 Closed System Analysis ..... 13
- 2.4 Ideal Gas..... 23
- 2.5 Heat ..... 26
- Objective Brain Teasers* ..... 30
- Student Assignments* ..... 34

### Chapter 3

#### First Law of Thermodynamics ..... 35

- 3.2 First Law of Thermodynamics ..... 35
- 3.3 Enthalpy ..... 40
- 3.4 Heat-Transfer in Various Processes ..... 40
- 3.5 Free Expansion ..... 54
- Objective Brain Teasers* ..... 62
- Student Assignments* ..... 67

### Chapter 4

#### Open System Analysis by First Law ..... 68

- 4.1 An Open System (or Control Volume) ..... 68
- 4.2 Steady Flow Systems ..... 68

- 4.3 Mass Balance and Energy Balance for Steady Flow Systems..... 69
- 4.4 SFEE Applied to Various Devices ..... 73
- 4.5 Comparison of SFEE with Euler and Bernoulli's Equation..... 83
- 4.6 Unsteady Flow Process ..... 84
- Objective Brain Teasers* ..... 104
- Student Assignments* ..... 108

### Chapter 5

#### Second Law of Thermodynamics..... 109

- 5.2 Thermal Energy Reservoir..... 110
- 5.3 Heat Engine ..... 110
- 5.4 Kelvin-Planck Statement of Second Law..... 112
- 5.5 Refrigerators and Heat Pumps..... 113
- 5.6 Clausius Statement of the Second Law ..... 116
- 5.7 Equivalence of Kelvin-Planck and Clausius Statement ..... 116
- 5.8 Reversible and Irreversible Processes ..... 117
- 5.9 The Carnot Cycle..... 122
- 5.10 The Carnot Principles..... 124
- 5.11 The Thermodynamic Temperature Scale ..... 127
- 5.12 Maximum Performance Measures for Cycles Operating between two Reservoirs..... 129
- Objective Brain Teasers* ..... 145
- Student Assignments* ..... 150

### Chapter 6

#### Entropy ..... 152

- 6.1 Introduction ..... 152
- 6.2 Clausius Inequality..... 152
- 6.3 The Property of Entropy..... 155
- 6.4 Principle of Entropy Increase ..... 157
- 6.5 Temperature-Entropy Diagram ..... 159

6.6	The T-dS Relations:.....	162
6.7	Entropy change for an Ideal Gas.....	164
6.8	Entropy Change of An Incompressible .....	172
6.9	Finite Body Analysis.....	173
6.10	Reversible Steady-Flow Work.....	179
6.11	Second Law Analysis of a Control Volume .....	183
6.12	Available Energy .....	190
6.13	Available Energy Referred to a Cycle.....	191
6.14	Heat Transfer Through a Finite Temperature Difference.....	192
6.15	Availability and Availability function .....	196
6.16	Irreversibility .....	197
6.17	Second Law Efficiency .....	198
	<i>Objective Brain Teasers</i> .....	216
	<i>Student Assignments</i> .....	222

## Chapter 7

### Properties of Pure Substances .....224

7.1	Introduction.....	224
7.2	Phase Change of a Pure Substance.....	224
7.3	Property Diagrams .....	226

7.4	Quality and Saturated Liquid Vapour .....	228
7.5	Enthalpy and Entropy of Pure Substances .....	231
7.6	Steam Tables.....	232
7.7	Reference State and Reference Values.....	237
	<i>Objective Brain Teasers</i> .....	247
	<i>Student Assignments</i> .....	250

## Chapter 8

### Thermodynamic Relations.....252

8.1	Mathematical Theorems .....	252
8.2	The Maxwell Relations .....	253
8.3	Tds Partial Differential Equations .....	254
8.4	Specific Heats $c_p$ and $c_v$ .....	255
8.5	Energy Equations.....	260
8.6	The Joule-Thomson Coefficient.....	263
8.7	Clausius-Clapeyron Equation .....	266
8.8	Compressibility Factor .....	269
8.9	Van der Waal's equation of State.....	270
	<i>Objective Brain Teasers</i> .....	282
	<i>Student Assignments</i> .....	286



# Basic Concepts & Zeroth Law of Thermodynamics

## 1.1 INTRODUCTION

Thermodynamics is the branch of science which deals with the energy and energy interactions. More specifically it deals with energy conversions, energy exchange and the direction of exchange.

### 1.1.1 Macroscopic and Microscopic Approach

- **Macroscopic Approach:** In this approach individual molecular behaviour of a gas is not taken into consideration and the average behaviour of all the molecules is studied. This approach is applied when the continuum concept is valid.



- Continuum hypothesis suggests that the matter is continuously distributed with no voids being present.
- In case of gases it is valid when mean free path (average distance travelled by a molecule between two successive collisions) is much smaller than the system dimensions.

- **Microscopic Approach:** In this the individual molecular behaviour is taken into consideration. For example It is used in space exploration.

**Remember :** For our use, in classical thermodynamics, we often use Macroscopic Approach.

## 1.2 System, Surroundings and Properties

### 1.2.1 System, Surroundings and Properties

- **System:** A thermodynamics system is defined as the fixed mass or fixed region in space (also called control volume) upon which our study is focussed.
- **Surroundings:** Everything external to the system is called surroundings.
- **Boundary:** It is a real or imaginary surface which separates system from the surroundings. A boundary can be fixed or movable. A boundary has zero thickness, no mass and no volume.

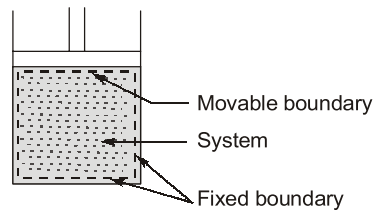


Figure 1.1 Fixed Mass System

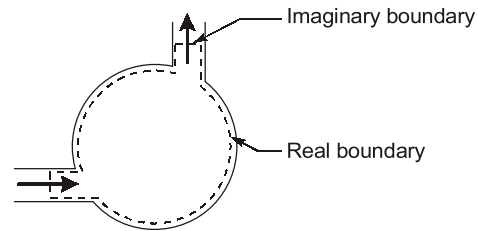


Figure 1.2 Fixed Region in Space (Control Volume)

## 1.2.2 Types of System

Based on energy-mass interaction with the surroundings the system has been categorized as given below.

Type of system	Energy transfer	Mass transfer	Example
Open	Yes	Yes	Piston cylinder arrangement with valves
Closed	Yes	No	Piston cylinder arrangement without valves
Isolated	No	No	Universe

**Remember :** Control volume is a volume surrounding an open system on which study is focussed. The boundaries of a Control Volume is called Control Surface.

## 1.2.3 Properties of a System

- 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. They have been classified as follows:

- Intensive (Intrinsic) Properties:** The properties which are independent of the mass of system under consideration.

For examples: Pressure, temperature, density, viscosity etc.

### Remember



- All specific properties are intensive properties, eg. specific volume, specific heat, specific internal energy etc.
- Density is an intensive property.

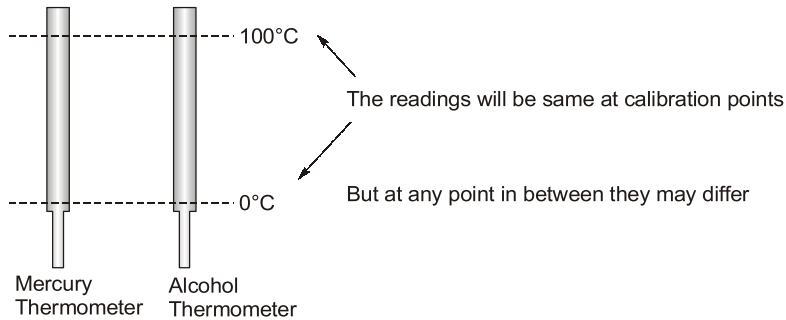
- Extensive (Extrinsic) Properties:** The properties which are dependent on the mass of system under consideration.

For examples: Mass, energy, volume etc.

**NOTE :** While deciding the type of property we should not change the system under consideration.

### 1.5.3 Calibration of Thermometers

- If two different thermometers using alcohol and mercury respectively, are calibrated at ice point and steam point and the distance between ice point and steam point is divided into 100 equal parts then they are not guaranteed to give the same reading anywhere between the calibration points, but they will always give the same readings at the calibration points itself.



#### Summary



- Thermodynamics is the science that primarily deals with energy.
- A system with fixed mass is called a closed system and a system that involves mass transfer across its boundary is called an open system.
- Mass dependent properties are called extensive properties and mass independent properties are called intensive properties.
- All temperature measurements are based on Zeroth law.
- Temperature scales are arbitrary/random in nature.



### Objective Brain Teasers

- Q.1** An open system is one in which
- Heat and work cross the boundary, but the mass does not
  - Mass crosses the boundary, but the heat and work do not
  - Heat, work and mass cross the boundary
  - None of heat, work and mass cross the boundary
- Q.2** Which of the following is not a point function?
- Temperature
  - Pressure
  - Energy
  - Power
- Q.3** Which of the following is an intensive property of a thermodynamics system?
- Volume
  - Temperature
  - Mass
  - Energy
- Q.4** Which of the following is the basis of temperature measurement?
- Zeroth law of thermodynamics
  - First law of thermodynamics
  - Second law of thermodynamics
  - Third law of thermodynamics
- Q.5** The absolute zero pressure will be
- When molecular momentum of the system becomes zero
  - at sea level
  - at a temperature of  $-273.15\text{ K}$
  - under vacuum conditions
- Q.6** The standard fixed point of thermometry is the
- ice point
  - triple point of water

- (c) boiling point of water
- (d) sulphur point

**Q.7** A system comprising of a single phase is called

- (a) Closed system
- (b) Open system
- (c) Heterogeneous system
- (d) Homogeneous system

**Q.8** A mixture of air and liquid air is

- (a) a pure substance
- (b) not a pure substance
- (c) homogeneous and invariable in chemical composition throughout its mass
- (d) one having relative proportions of oxygen and nitrogen constant in gas and liquid phases

**Q.9** When mean free path of the molecules of a gas approaches the order of magnitude of the dimensions of the vessel, which concept of the following loses its validity?

- (a) Continuum
- (b) Stability
- (c) Equilibrium
- (d) Entropy

**Q.10** Most of the real processes are

- (a) quasi-static
- (b) non-quasi-static
- (c) adiabatic
- (d) isothermal

### ANSWERS

1. (c)    2. (d)    3. (b)    4. (a)    5. (a)  
6. (b)    7. (d)    8. (b)    9. (a)    10. (b)



### STUDENT'S ASSIGNMENTS

1. A new temperature scale  $N$  is to be defined. The boiling and freezing points of water on this scale are  $100^\circ N$  and  $400^\circ N$  respectively. Then (a) What will be the reading on the new scale corresponding to  $60^\circ C$ ? (b) At what temperature both the Celsius and the new temperature scale reading would be same?

[Ans. (a)  $220^\circ N$ , (b)  $100^\circ$ ]

2. The reading  $t_A$  and  $t_B$  for centigrade thermometer  $A$  and  $B$  graded at ice point  $0^\circ C$  and steam point  $100^\circ C$  are related by the equation  $t_A = l + mt_B + nt_B^2$  where  $l, m, n$  are constants. When both are immersed in a liquid,  $A$  reads  $51^\circ C$  and  $B$  reads  $50^\circ C$ . Determine the reading of  $A$  when  $B$  reads  $25^\circ C$ ? Comment on which thermometer is correct.

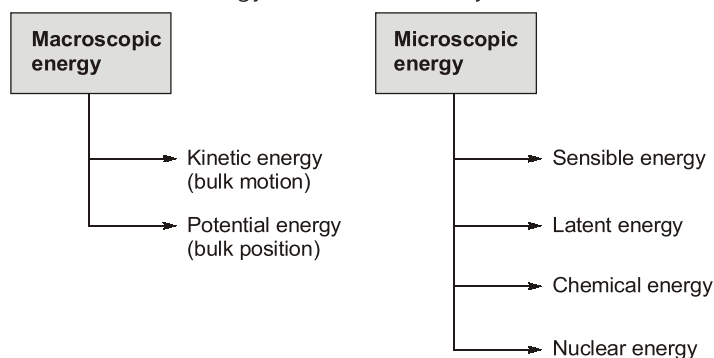
[Ans. (a)  $25.75^\circ C$ ; (b) not possible to say]



## Energy and Energy Interactions

### 2.1 INTRODUCTION

- Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electrical, magnetic, chemical and nuclear, and their sum constitutes total energy  $E$  of the system. Thermodynamics provides no information about the absolute value of the total energy. It deals only with the change of the total energy.
- In thermodynamics, the various forms of energy are considered in two groups, macroscopic and microscopic forms of energy.
- The energy possessed by the system as a whole with respect to an external reference frame constitute macroscopic forms of energy, such as kinetic and potential energies.
- The energy possessed by the system with respect to then molecular structure and molecular level interactions constitute microscopic forms of energy. The sum of all microscopic forms of energy of a system is called its internal energy and is denoted by  $U$ .



#### NOTE

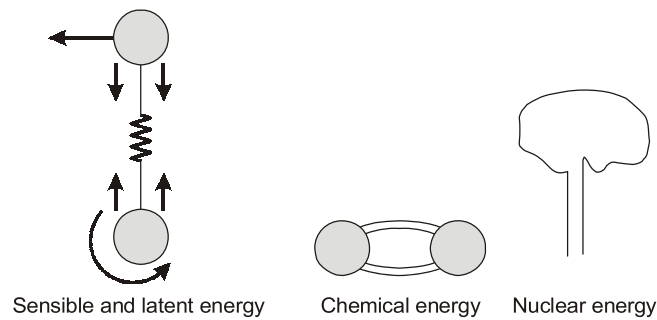


**Sensible energy** → due to molecular kinetic energy and is temperature dependent.

**Latent energy** → associated with phase of the system and comes into picture during phase change.

**Chemical energy** → associated with atomic bonds in a molecule.

**Nuclear energy** → associated with strong bonds within the nucleus.

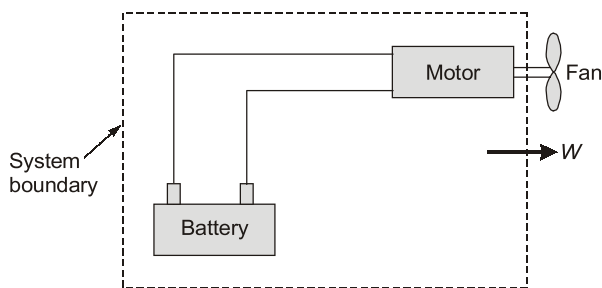


**Figure 2.1** Internal energy of a system is sum of all microscopic energies

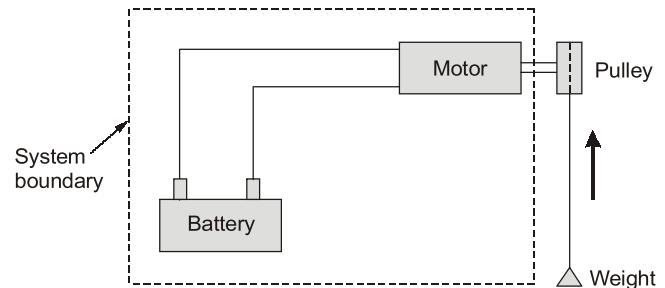
- Energy interaction for a closed system with its surroundings can take place in two ways:
  - (a) by work transfer
  - (b) by heat transfer
- Work and heat are modes of energy transfer. The discussion related to their quality will be done later in the second law of thermodynamics.

## 2.2 Work

- The work is said to be done by a force when it acts on a body moving in the direction of force. This definition of work is more suitable from mechanics point of view.
- In thermodynamics, work transfer is considered occurring between the system and the surroundings. Work is said to be done by the system if the sole effect on the things external to the system can be converted into raising of weights, though the weight may not be actually raised.
- In Fig. 2.2 (a), a battery is connected to a motor which is in turn driving a fan. The system is doing work on the surroundings. When the fan is replaced by a pulley and a weight as shown in Fig. 2.2 (b), the sole effect on things external to the system is then the raising of a weight.



**Figure 2.2 (a)**



**Figure 2.2 (b)**

**Remember :** Force should act on the system boundary and it should cause some displacement in the surroundings. Hence this is also called boundary work.

### Types of Work Interaction

- Expansion and compression work (Displacement work) – this has been dealt with in detail later.
- Stretching of wire: If a wire is stretched by length  $dL$  due to force  $F$ , then work done on the system.

$$\delta W = FdL$$

15. (d)

After the boiling temperature is reached water starts boiling off.

Heat required to boil dry

$$= (0.64 \times 10^{-3} \times 998) \times 2256$$

$$= 1440.95 \text{ kJ}$$

Power of kettle = 2.4 kW

$$\therefore \text{Time taken to boil} = \frac{1440.95}{2.4} \approx 600 \text{ s}$$

$$\therefore \text{Total time taken} = 117 + 600 = \mathbf{717 \text{ s}}$$

16. (d)

Clearly the area enclosed on the  $p$ - $V$  diagram under the path  $D$  is maximum

$\therefore$  Work done on that path is also maximum

17. (d)

For adiabatic reversible process

$$PV^\gamma = \text{constant}$$

Taking  $\log_e$ ,  $\log_e P + \gamma \log_e V = k$

$$\log_e P = -\gamma \log_e V + k$$

Which is equation of form,

$$y = mx + C$$

With  $m$  being  $-ve$

Q.3

An ideal gas is heated at constant volume until its temperature is 3 times the original temperature. It is then expanded isothermally till it reaches its original pressure. The gas is then cooled at constant pressure till it is restored to the original state. Represent this cycle on  $p$ - $V$  diagram and find the net work for 1 kg gas. Represent your answer in terms of gas constant  $R$  and take initial temperature as 350 K.

[Ans:  $453.5R$  kJ]

Q.4

A piston cylinder arrangement contains  $0.05 \text{ m}^3$  of a gas initially at 200 kPa. At this state a linear spring which has a spring constant of 150 kN/m is just touching the piston but exerting no force on it. Now heat is transferred to the gas causing the piston to rise and to compress the spring until the volume inside the cylinder doubles. If the cross section area of piston is  $0.25 \text{ m}^2$ . Find  
(i) The final pressure inside the cylinder  
(ii) Work done by the gas

[Ans: 320 kPa, 13 kJ]

Q.5

At the beginning of the compression stroke of a 2-cylinder internal combustion engine the air is at a pressure of 101.325 kPa. Compression reduces the volume to  $\left(\frac{1}{5}\right)^{th}$  of its original volume and the law of compression is given by  $pV^{1.2} = \text{constant}$ . If the bore and stroke of each cylinder is 0.15 m and 0.25 m respectively, determine the power absorbed in kW by compression strokes when the engine speed is such that each cylinder undergoes 500 compression strokes per minute.

[Ans:  $-17.7$  kW]

Q.6

A monatomic ideal gas ( $\gamma = 1.67$  and molecular weight = 40) is compressed adiabatically from 0.1 MPa, 300 K to 0.2 MPa. The universal gas constant is 8.314 kJ/kmol K. The work of compression of gas in kJ/kg will be?

[Ans:  $-29.86$  kJ/kg]



### STUDENT'S ASSIGNMENTS

**Q.1** An imaginary engine receives heat and performs work on a slowly moving piston at such a rate that the cycle of operation of 1 kg of fluid can be represented as a circle of 10 cm diameter on  $p$ - $V$  diagram. The scale is 1 cm = 300 kPa on  $y$ -axis and 1 cm =  $0.1 \text{ m}^3$  on  $x$ -axis. Find the net work done.

[Ans: 2356.2 kJ]

**Q.2** A spherical balloon of 1 m diameter contains a gas at 150 kPa. The gas inside balloon is heated until pressure reaches 450 kPa. During the process of heating the pressure of gas inside the balloon is proportional to cube of the diameter of the balloon. Find the work done by the gas.

[Ans: 314.16 kJ]

# First Law of Thermodynamics

## 3.1 INTRODUCTION

In the early part of nineteenth century the scientists developed the concept of energy and the hypothesis that it can neither be created nor destroyed; this came to be known as the law of conservation of energy. The first law of thermodynamics is merely one statement of this general law with particular reference to heat and work.

## 3.2 First Law of Thermodynamics

- When a closed system undergoes a complete cycle net work is done on or by the system. The only other energy involved in the cycle is heat which is supplied or rejected during various processes.
- The first law relates these two forms of energy in the following statement.

“For a closed system undergoing a cycle the net energy interaction in the form of heat is equal to the net energy interaction in the form of work”

$$(\Sigma W)_{\text{cycle}} = J(\Sigma Q)_{\text{cycle}}$$

$$J = 1 \text{ Nm/J}$$

i.e

$$\Sigma Q = \Sigma W$$

(for a closed system undergoing a cycle)

### NOTE



- There can be other statements which pertain to first law.
- The first law cannot be proved analytically, but experimental evidence have repeatedly confirmed its validity and it has never been violated. It is a law of nature.

### Example 3.1

In a certain steam plant the turbine develops 1100 kW. The heat supplied to the steam in the boiler is 2900 kJ/kg, the heat rejected by the steam to the cooling water in condenser is 2200 kJ/kg and the feed pump work required to pump the condensate back into the boiler is 5 kW. Calculate the steam flow rate.

**Solution :**

Refer to figure below for the mentioned cycle.

∴ For the given cycle,

Heat per unit mass flow rates,

$$\begin{aligned} \Sigma Q &= Q_{in} - Q_{out} \\ &= 2900 - 2200 = 700 \text{ kJ/kg} \end{aligned}$$

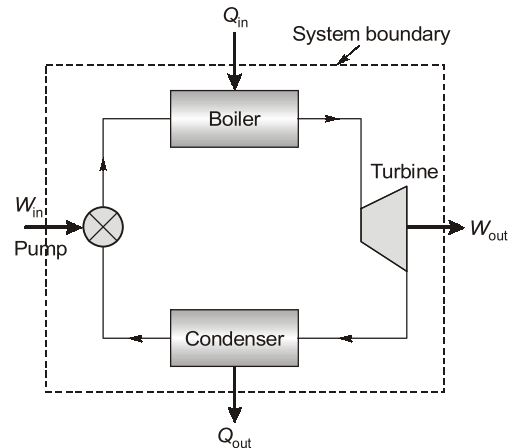
$$\begin{aligned} \Sigma W &= W_{out} - W_{in} \\ &= 1100 - 5 = 1095 \text{ kW} \end{aligned}$$

Assuming  $\dot{m}$  as steam flow rate in kg/s and by first law

$$\Sigma Q = \Sigma W$$

$$\therefore 700 \times \dot{m} = 1095$$

$$\therefore \dot{m} = 1.564 \text{ kg/s}$$



**3.2.1 Total Energy**

- A major consequence of the first law is the existence and the definition of the property called total energy  $E$ . It is to be noted that the value of total energy stored in a closed system at a state is not defined rather the change in total energy has been dealt with.
- Consider a system which changes its state from state (1) to state (2) by following path A and returned via path B from 2 to 1. (Fig. 2.1)

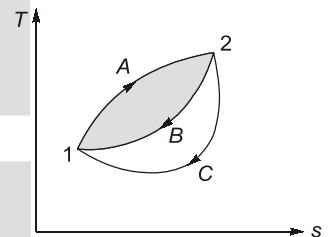


Figure 3.1

∴ Applying first law,  $\Sigma Q_{A-B} = \Sigma W_{A-B}$

$$Q_{1A2} + Q_{2B1} = W_{1A2} + W_{2B1} \quad \dots(i)$$

Now assume the same system returns via path C instead of B.

∴ Applying first law,  $\Sigma Q_{AC} = \Sigma W_{AC}$

$$Q_{1A2} + Q_{2C1} = W_{1A2} + W_{2C1} \quad \dots(ii)$$

Applying (i) - (ii),  $Q_{2B1} - Q_{2C1} = W_{2B1} - W_{2C1}$

$$\begin{aligned} Q_{2B1} - W_{2B1} &= Q_{2C1} - W_{2C1} \\ (Q - W)_{2B1} &= (Q - W)_{2C1} \quad \dots(iii) \end{aligned}$$

Equation (iii) implies that  $(Q - W)$  represents the change in quantity which is only dependent on initial and final states (1) and (2) respectively and not the path followed.

This property was named as energy  $E$

$$\therefore \delta Q - \delta W = dE$$

$$\text{or} \quad \delta Q = dE + \delta W$$

The above equation is the general statement of the first law of thermodynamics for a closed system.

**Remember**



- $\Sigma Q = \Sigma W$  is also a first law equation but is applicable only in a cycle, however  $\delta Q = dE + \delta W$  is applicable to a cycle as well as a process in a closed system.
- The energy  $E$  is a
  - (1) Property of the system (Extensive)
  - (2) Point function
  - (3) Exact differential
  - (4)  $\oint dE = 0$  as it is a point function

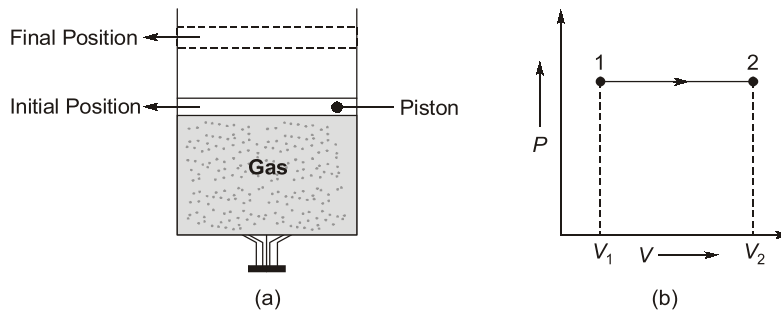


$\Delta U = mc_v \Delta T$  is applicable for

- (i) Constant volume process for any substance or
- (ii) Ideal gas and any process (as for ideal gas  $U = f(T)$  only)

### 3.4.2 Reversible Constant Pressure (or Isobaric) Process

- The boundary of the system is again the limits of volume occupied by the gas and it moves as piston moves to maintain constant pressure when heat is supplied (figure 3.4)



**Figure 3.4** Isobaric Process

From first law of thermodynamics for process 1 - 2

$$\delta Q = dU + \delta W$$

$$\delta Q = dU + pdV$$

(Assumption: (1) closed system, (2) Quasistatic, (3) Stationary)

or 
$$\delta Q = dU + d(PV) \quad (\text{as } P \text{ is constant})$$

$$\delta Q = d(U + PV)$$

$$(\delta Q)_P = dH \quad (\text{by definition, } H = U + PV)$$

but 
$$(\delta Q)_P = mc_p dT \quad (\text{by definition of } c_p)$$

$$\therefore dH = mc_p dT$$

or 
$$\Delta H = mc_p \Delta T$$

$$\therefore \text{Heat transfer at constant pressure, } Q_P = \Delta H = mc_p \Delta T$$



$\Delta H = mc_p \Delta T$  is applicable for

- (i) Constant pressure process for any substance or
- (ii) Ideal gas and any process (as for ideal gas  $H = f(T)$  only)

**Example 3.5**

A fluid system undergoes a non-flow frictionless process following the

pressure volume relation as  $P = \frac{10}{V} + 3$  where  $P$  is in bar and  $V$  is in  $m^3$ . During the process the volume

changes from  $0.2 m^3$  to  $0.05 m^3$  and the system rejects 200 kJ of heat. Determine:

- (i) Change in internal energy
- (ii) Change in enthalpy

**Solution :**

Given: Pressure volume relation,  $P = \left(\frac{10}{V} + 3\right)$  bar

Initial volume,  $V_1 = 0.2 \text{ m}^3$

Final volume,  $V_2 = 0.05 \text{ m}^3$

Heat rejected by the system,

$$\therefore Q = -200 \text{ kJ}$$

Assumption (i) The process is quasi-static, (ii)  $\Delta KE = \Delta PE = 0$

The thermodynamic work done,  $W = \int_1^2 P dV$

$$\therefore W = \int_1^2 \left(\frac{10}{V} + 3\right) dV$$

$$= \left[ 10 \ln \frac{V_2}{V_1} + 3(V_2 - V_1) \right]_{0.2}^{0.05} \times 10^2 \text{ kJ}$$

$$= -1431.29 \text{ kJ}$$

(i) Applying first law equation,

$$Q = \Delta U + W$$

i.e.

$$-200 = \Delta U + (-1431.29)$$

$\therefore$

$$\Delta U = 1231.29 \text{ kJ}$$

Hence the internal energy increases.

(ii) Change in enthalpy,

We know

$$H = U + PV$$

$\therefore$

$$\Delta H = \Delta U + \Delta(PV)$$

$$= \Delta U + (P_2 V_2 - P_1 V_1)$$

Now,

$$P_1 = \frac{10}{V_1} + 3 = \frac{10}{0.2} + 3 = 53 \text{ bar}$$

and

$$P_2 = \frac{10}{V_2} + 3 = \frac{10}{0.05} + 3 = 203 \text{ bar}$$

Substituting

$$\Delta H = 1231.29 + (203 \times 0.05 - 53 \times 0.2) \times 10^2$$

$$\Delta H = 1186.29 \text{ kJ}$$

**Example 3.6**

The properties of a system during a reversible constant pressure non flow process at  $P = 1.6 \text{ bar}$ , changed from  $v_1 = 0.3 \text{ m}^3/\text{kg}$ ,  $T_1 = 20^\circ\text{C}$  to  $v_2 = 0.55 \text{ m}^3/\text{kg}$ ,  $T_2 = 260^\circ\text{C}$ . The specific heat of the fluid is given by

$$c = \left( 1.5 + \frac{75}{T + 45} \right) \text{ kJ / kg}^\circ\text{C}, \text{ where } T \text{ is in } ^\circ\text{C}$$

Determine:

(i) Heat added per kg

(ii) Work done per kg

(iii) Change in internal energy per kg

(iv) Change in enthalpy per kg

**Solution :**

Given: Initial volume,  $v_1 = 0.3 \text{ m}^3/\text{kg}$   
 Initial temperature,  $T_1 = 20^\circ\text{C}$   
 Final volume,  $v_2 = 0.55 \text{ m}^3/\text{kg}$   
 Final temperature,  $T_2 = 260^\circ\text{C}$   
 Pressure (constant),  $P = 1.6 \text{ bar}$  and process is reversible  
 Also  $c = \left(1.5 + \frac{75}{T + 45}\right) \text{ kJ/kg}^\circ\text{C}$

**Assumptions:**

(i) **System is closed** (ii)  $\Delta KE = \Delta PE = 0$

(i) Heat added per kg is given by

$$q = \int_{T_1}^{T_2} c dT = \int_{20}^{260} \left(1.5 + \frac{75}{T + 45}\right) dT$$

$$= \left[1.5(260 - 20) + 75 \ln\left(\frac{260 + 45}{20 + 45}\right)\right] = 475.94 \text{ kJ/kg}$$

(ii) Work done per kg is given by

$$w = \int_1^2 P dv$$

As it is a constant pressure process

$$\therefore w = P(v_2 - v_1) = 1.6 \times 10^2 (0.55 - 0.3) \text{ kJ/kg} = 40 \text{ kJ/kg}$$

(iii) Change in internal energy

$$\text{Using first law for closed system, } \Delta u = q - w = 475.94 - 40 = 435.94 \text{ kJ/kg}$$

(iv) Change in enthalpy:

$$\delta q = dh - v dP$$

$$\therefore dP = 0$$

$$dh = \delta q$$

As it is a constant pressure process:

$$\therefore \Delta h = (q)_P$$

$$\text{i.e. } \Delta h = 475.94 \text{ kJ/kg}$$

**Example 3.7**

1.5 kg of a gas contained in a closed system undergoes a reversible isobaric process. During this process 45 kJ of internal energy is decreased. Determine the work during the process.

Take  $c_p = 850 \text{ J/kg}^\circ\text{C}$  and  $c_v = 620 \text{ J/kg}^\circ\text{C}$

**Solution :**

Given: Mass of gas,  $m = 1.5 \text{ kg}$   
 Change in internal energy,  $\Delta U = -45 \text{ kJ}$   
 $c_p = 850 \text{ J/kg}^\circ\text{C} = 0.85 \text{ kJ/kg}^\circ\text{C}$   
 $c_v = 620 \text{ J/kg}^\circ\text{C} = 0.62 \text{ kJ/kg}^\circ\text{C}$

Let the change in temperature of gas during the process =  $\Delta T$

**Assumptions:**

(i) Closed system (ii)  $\Delta KE = \Delta PE = 0$

(iii) Gas is an ideal gas





**STUDENT'S ASSIGNMENTS**

**Q.1** An insulated rigid pressure vessel is divided into two portions by a movable partition. One part of the vessel is occupied by the an ideal gas at a pressure  $P_1$ , volume  $V_1$  and temperature  $T_1$ . The other part is occupied by the same ideal gas but at a pressure  $P_2$ , volume  $V_2$  and temperature  $T_2$ . The partition is removed and two portions mix adiabatically. Show that the final pressure  $P_3$  and final temperature  $T_3$  as given by

$$P_3 = \frac{P_1V_1 + P_2V_2}{V_1 + V_2} \text{ and } T_3 = \frac{\frac{P_1V_1}{T_1} + \frac{P_2V_2}{T_2}}{\frac{P_1V_1}{T_1} + \frac{P_2V_2}{T_2}}$$

**Q.2** The following equation gives the internal energy of a certain substance  $u = 3.64 Pv + 90$  where  $u$  is in kJ/kg.  $P$  in kPa and  $v$  is in  $m^3/kg$ . A system composed of 3.5 kg of this substance expands from an initial pressure of 500 kPa and a volume of  $0.25 m^3$  to a final pressure of 100 kPa in a process in which the law followed is given by  $PV^{1.25} = \text{constant}$ .

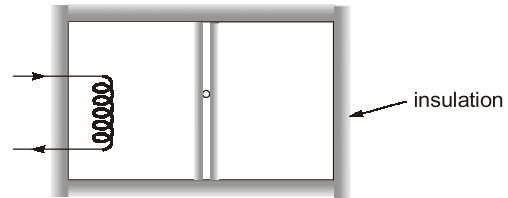
- (i) If the expansion is reversible find  $Q$ ,  $\Delta U$  and  $W$  for the process.
- (ii) In another process all conditions remains same except that the heat transfer in this case is 32 kJ. Find the work transfer for this process.
- (iii) Explain the difference in work transfer in parts (i) and (ii).

[Ans. (i)  $Q = 12.4 \text{ kJ}$ ,  $\Delta U = -125.2 \text{ kJ}$   
 $W = 137.6 \text{ kJ}$   
(ii)  $W = 157.2 \text{ kJ}$ ]

**Q.3** A rectangular box as shown in the figure has a partition which slides without friction along the length of the box. Initially the 2 chambers of the box have 1 kg each of an ideal gas ( $\gamma = 5/3$ ) at a pressure  $P_0$ , volume  $V_0$  and temperature  $T_0$ . The chamber on the left is slowly heated by an electric heater. The walls of the box and partition is thermally insulated. The gas in the left chamber expands pushing the partition until the final

pressure in both the chambers is  $\frac{243P_0}{32}$ .

Determine the final temperature of the gas in each chamber in terms of  $T_0$ ,  $P_0$ ,  $V_0$  and  $WD$  by the gas in the right chamber.



[Ans.  $T_R = 2.25 T_0$   
 $T_L = 12.397 T_0$   
 $W = -1.875 P_0 V_0$ ]

**Q.4**  $0.1 m^3$  of an ideal gas at 300 K and 1 bar is compressed adiabatically to 8 bar. It is cooled at constant volume and further expanded isothermally so as to reach back the initial condition.

- (i) Plot the  $P$ - $V$  diagram for the above cycle.
- (ii) Calculate pressure at the end of isochoric process.
- (iii)  $\Delta U$  during isochoric process
- (iv) Net work done and heat transferred during the cycle

Assume  $c_p = 14.3 \text{ kJ/kgK}$  and  $c_v = 10.2 \text{ kJ/kgK}$

[Ans. (ii)  $P_3 = 4.4 \text{ bar}$ ; (iii)  $\Delta U = -20.27 \text{ kJ}$   
(iv)  $W_{\text{net}} = Q_{\text{net}} = -5.45 \text{ kJ}$ ]

**Q.5** A stationary system consisting 2 kg of fluid with  $c_p = 1.005 \text{ kJ/kgK}$   
 $c_v = 0.718 \text{ kJ/kgK}$   
 $P_v = 0.287 (T + 273)$   
 $U = 196 + 0.718T$  ( $U$  is in kJ/kg)

expands in an adiabatic process according to  $Pv^{1.2} = \text{constant}$ . The initial conditions are 1 MPa and  $200^\circ\text{C}$  and the final pressure is 0.1 MPa. Find  $W$  and  $\Delta E$  for the process. Why is work transfer not equal to  $\int Pdv$  ?

[Ans.  $W = 216.66 \text{ kJ}$ ]

