Chapter 1

Basic Concepts of Thermodynamics and First Law of Thermodynamics

CHAPTER HIGHLIGHTS

- ☞ *Macroscopic and Microscopic Approach*
- ☞ *Intensive Properties and Extensive Properties*
- ☞ *Point Function and Path Function*
- ☞ *Continuum*
- ☞ *Gibbs Phase Rule*
- ☞ *Thermodynamic Equilibrium and Cycle*
- ☞ *Irreversible Process and Thermometry*
- ☞ *Various Forms of Pressure*
- ☞ *Energy Transfer and Work Transfer*
- ☞ *Quasi-static Process*
- ☞ *Heat Transfer*
- ☞ *Non-flow Process*
- ☞ *Universal Gas Equation*
- ☞ *First Law of Thermodynamics*
- ☞ *Steady Flow Energy Equation*
- ☞ *Transient Flow Processes*

INTRODUCTION

Thermodynamics is the transmission of heat to work originates from a Greek work 'Therme' means heat and dynamics means force or work. It is a science which deals with the energy transfer and its effect on the properties of the system. The application of thermodynamics is encountered in our daily life. It is applied in refrigeration, power generation, aircrafts and many more where heat exchange takes place.

One of the basic laws is 'Conservation of energy'. It states that energy can neither be created not be destroyed, it can only be transform from one to other form. This principle accounts the amount of energy transfer and asserts that the total amount of energy remains constant.

The first law of thermodynamics is same as the principle of conservation of energy. It says that when one form of energy (x) converts to another form of energy (y), then net energy transfer ($x - y$) will be stored in the system and it is a property of the system.

The second law of thermodynamics tells about the quality and quantity of the energy when a process is going on and a process always proceeds in the direction of decreasing quality of energy. It tells the feasibility of the process as well as gives the direction of the path on which any process takes place.

Example: Water always falls from high elevation to the low but the vice versa can never be possible without any external aid. So the process of falling of water from high altitude to the low altitude always follows a direction.

MACROSCOPIC AND MICROSCOPIC APPROACH

The behavior of matter can be studied by the macroscopic and the microscopic approach.

Macroscopic Approach (Classical Thermodynamics)

Study of average behavior of many atoms and molecules.

Example: the macroscopic quantity, pressure, is the average rate of change of momentum due to all the molecular collisions made on a unit area.

Microscopic Approach (Statical Thermodynamics)

Study of behavior of each atom and molecule.

Example: the pressure exerted by a gas at a given instant depends on the momentary behavior of the molecules in the neighborhood of the particular point.

The Microscopic point of view deals with the structure of the system and time average behavior.

BASIC DEFINITIONS

System

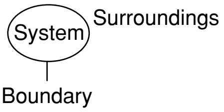
A specified space on which study or analysis is to be carried out is called as system.

Surroundings

The mass or region outside the system is called the surroundings.

Boundary

The real or imaginary surface that separates the system from its surroundings is called boundary. The Boundary of the system can be fixed or movable. Boundary may be real or imaginary.



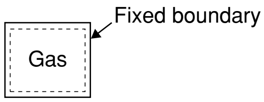


Figure 1 Closed container

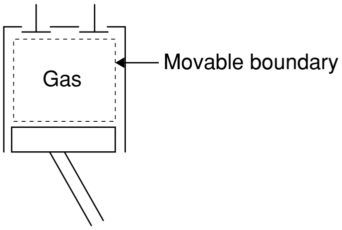
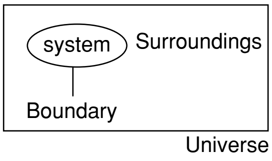


Figure 2 Piston and Cylinder arrangement

Universe

The system and surroundings together called as universe.



CLASSIFICATIONS OF THE SYSTEM

System is classified as:

1. Control mass system: Mass is fixed.
   - (i) Closed system
   - (ii) Isolated system
2. Control volume system: Volume is fixed.
   - (i) Open system

Closed System (Control Mass)

A closed system (control mass) consists of a fixed amount of mass and no mass can cross its boundary. That is no mass can enter or leave a closed system.

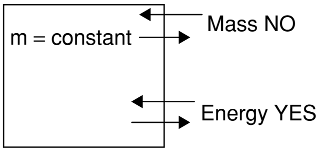


Figure 3 Closed system

Example: Gas contained in a closed vessel.

Open System (Control Volume)

An open system is a system in which both mass and energy can cross the boundary.

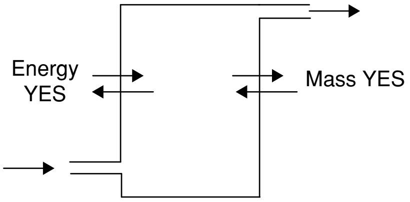


Figure 4 Open system

Example: Water heater, car radiators, turbine, and compressor nozzle.

Isolated System

An isolated system is a system in which mass as well as energy is not allowed to cross the boundary.

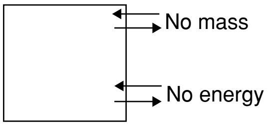


Figure 5 Isolated system

Example: Hot coffee left in thermo flask

Adiabatic System

An adiabatic system is one in which no heat transfer takes between the system and the surroundings however mass and work may transfer.

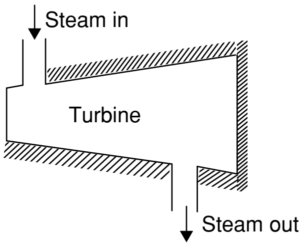


Figure 6 Adiabatic system

Example: Turbines, nottels, throttling valve etc

NOTE

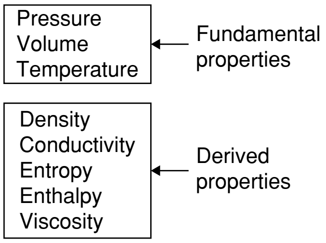
Types of system	Mass Transfer	Energy Transfer
Closed System	NO	YES
Open System	YES	YES
Isolated System	NO	NO
Adiabatic System	YES	YES (But $Q = 0$)

PROPERTIES OF A SYSTEM

Any measurable characteristic of a system is called property.

Example: Pressure, temperature, volume, mass, viscosity, density, modulus of elasticity, thermal conductivity, etc.

NOTE



Properties are classified into two types.

1. Intensive properties and
2. Extensive properties

Intensive Properties

Intensive properties are those that are independent of mass of a system.

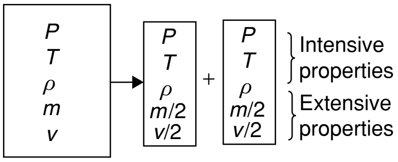
Example: Temperature, pressure, density, specific volume, specific mass

Extensive Properties

Extensive properties are those that are dependent of mass of a system.

Example: Volume, momentum, etc.

Consider a quantity of matter and divide into two equal parts as shown in figure.



The properties which do not change after dividing are called intensive properties.

Example: P, T, ρ.

Properties which changes in quantities are called extensive properties.

NOTES

1. A property is a characteristic that can be used to describe the state of a system.
2. The property is a state function and not a path function. Its differential must be exact.
3. The ratio of an extensive property to the mass of a system is called specific property.

   Example: Specific volume, $V = \frac{V}{m}$
4. The ratio of an extensive property to the mole number of the system is called molar property.

   Example: Molar volume, $= \frac{V}{N}$

NOTES

1. All specific properties are intensive *p* roperties.

   Example: Specific volume, Specific enthalpy, Specific entropy, etc.
2. Ratio of two extensive properties is called intensive property.

   Example: $\frac{\text{Volume}}{\text{Mass}}$ = Specific volume

Point Function and Path Function

Point Functions

The properties which can be represented by points on a coordinate system called point functions.

NOTES

1. Thermodynamic properties are point functions.
2. Point functions are exact differentials.

$$\therefore \int_{v_1}^{v_2} dv = v_2 - v_1$$

3. Path functions are inexact differentials.

$$\therefore \int_1^2 dw \neq W_2 - W_1$$

$$\int_1^2 dw = W_{1-2} \text{ or } {}_1W_2$$

Example: Pressure, Volume, Temperature, etc.

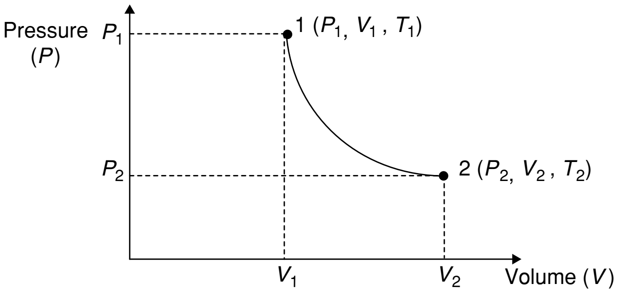
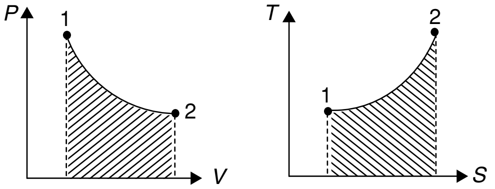


Figure 7 Point functions.

Path Functions

The entities which cannot be represented by point, can be represented by area on co-ordinate system.

Example: Heat and work



(*a*) (*b*)

Figure 8 (a) Area under *P–V* diagram = work transfer, (b) Area under *T–S* diagram = heat transfer

Continuum

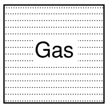
Matter is made up of atoms that are widely spaced in the gas phase. It is very convenient to disregard the atomic nature of a substance and view it as a continuous, homogeneous matter with no holes, that is a continuum. The continuum idealization allows us to treat properties as point function and to assume the properties vary continually in the space with no jump discontinuities.

Phase

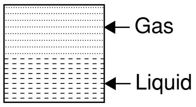
If a quantity of matter is homogeneous or uniform throughout in physical structure and chemical composition is termed as phase.

Example: Any matter exit in three phases. i.e., solid, liquid and gas.

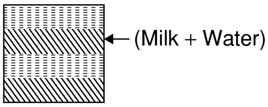
1. A mixture of gases is one phase



2. System has two phases i.e., liquid phase and gas phase

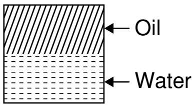


3.



A system consisting of two miscible liquid is said to be in a single liquid phase.

4.



A system consisting of two immiscible liquids form two liquid phases. On the basis of phases, the system is classified into

1. Homogenous system.
2. Heterogeneous system

Homogeneous System

It consists single phase.

Example:

1. Solution of NH_3 in water.
2. Mixture of air and water vapor.
3. Solution of water and nitric acid.

Heterogeneous System

It consists of two or more phases.

Gibbs Phase Rule

According to Gibbs phase rule

$P + F = C + 2$

Where

P = Number of phases

F = Degree of freedom or minimum number of independent variables require to fix the state condition.

C = number of components.

Example:

N_2	Solid CO_2 water	Steam water
$P = 1$	$P = 2$	$P = 2$
$C = 1$	$C = 2$	$C = 1$
$1 + F = 1 + 2$	$2 + F = 2 + 2$	$2 + F = 1 + 2$
$F = 2$	$F = 2$	$F = 1$

THERMODYNAMIC EQUILIBRIUM

A system is said to be in thermodynamic equilibrium, if it is in thermal equilibrium (equality of temperature), Mechanical equilibrium (equality of forces) and chemical equilibrium (equality of chemical potential)

Mechanical Equilibrium

It is related to pressure. A system will be in mechanical equilibrium if there is no change in pressure at any point of the system with time.

Example:

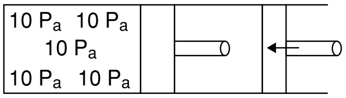
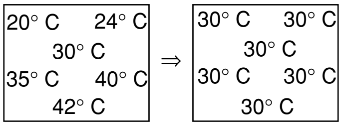


Figure 9 Slow compression, in mechanical equilibrium.

Thermal Equilibrium

A system will be in thermal equilibrium if the temperature is the same throughout the entire system.

Example:

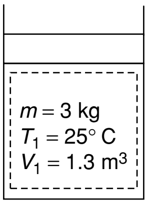


Chemical Equilibrium

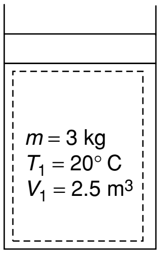
A system is in chemical equilibrium if its chemical composition does not change with time i.e., no chemical reaction occurs. A system will not be in equilibrium unless all the relevant equilibrium criteria are satisfied.

State

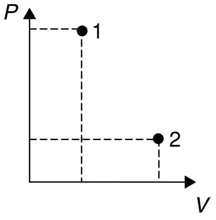
Each and unique condition of the system is called state. Let a system shown in figure exist at different states.



State 1



State 2

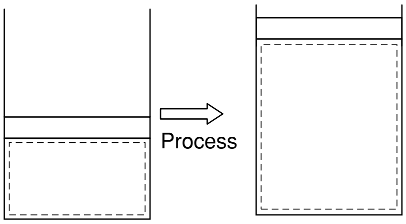


Representation of state

Process and Path

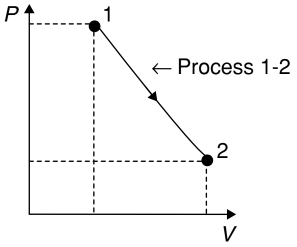
When an interaction between systems and surrounding takes place, the properties of that particular system changes from one equilibrium condition (state 1) to another equilibrium condition (state 2). This change in property of the system is termed as 'process' and the series of the equilibrium condition (state) which the systems is going through is termed as 'path'.

Example: Let a system, changes its state from (1) to state 2, as shown in figure



$m = 2$ kg
$T_1 = 20$ bar
$V_1 = 1.5$ m^3
State (1)

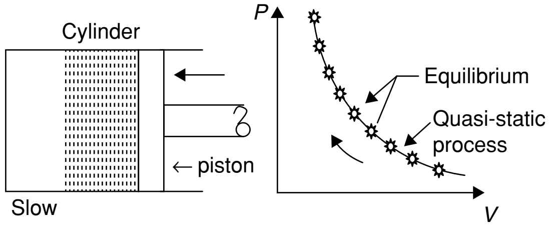
$m = 2$ kg
$T_1 = 5$ bar
$V_1 = 3.5$ m^3
State (2)



Quasi-equilibrium (Quasi-static) Process

If a process is followed by succession of equilibrium states, it is known as Quasti-static process.

Example: Let us consider a very slow compression process in which equilibrium is attained at any intermediate state.



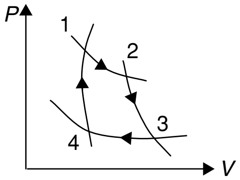
The locus of all the equilibrium points passed through by the system is a Quasi-static process.

NOTES

1. A Quasistatic process is also called reversible process.
2. Reversible process can be represented by continuous line.

Thermodynamic Cycle

A series of processes can be put together such that the system returns to initial state. This series of processes is called a thermodynamic cycle.



In the above diagram 1 – 2, 2 – 3, 3 – 4, 4 – 1 represent processes and 1 – 2 – 3 – 4 represents a thermodynamic cycle.

Reversible Process

A process is said to be reversible process if when reversed in direction follows the same path as that of the forward path without leaving any effect on system and surroundings.

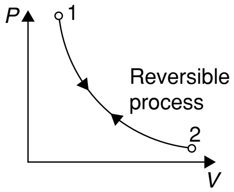


Figure 10 Reversible process

NOTE

No process is truly reversible, but some process are approximated as reversible.

Example:

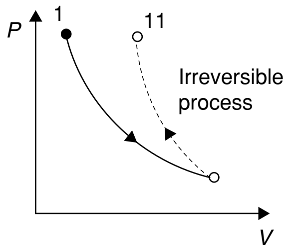
1. Frictionless relative motion.
2. Extension and compression of spring.
3. Frictionless adiabatic expansion or compression.
4. Polytrophic expansion or compression of a fluid.
5. Isothermal expansion or compression.
6. Electrolysis

Irreversible Process

A process which is not reversible is an irreversible process. Friction is the main cause of irreversibility.

Or

A process is irreversible if a system passes through a sequence of non-equilibrium states.



Irreversible process is represented by dashed lines on co-ordinate diagram.

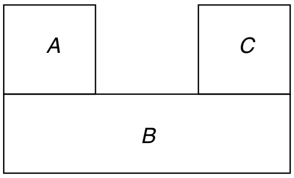
Examples of irreversible process are

1. Fluid flow with friction
2. Combustion of air and fuel
3. Diffusion of gases.
4. Throttling
5. Free expansion
6. Heat transfer
7. Plastic deformation
8. Electricity flow through a resistance
9. Adiabatic mixing

Zeroth Law of Thermodynamics

This is given by Fowler in 1931. This law gives the concept of temperature.

When a body A is in thermal equilibrium with body B and body B is in thermal equilibrium with body C separately, then A and C are in thermal equilibrium.



$$A \xrightarrow{TE} B$$

$$B \xrightarrow{TE} C$$

Then

$$A \xrightarrow{TE} C$$

It serves the basic law of temperature measurement.

Temperature Scale

- A temperature scale is established by assigning numerical values to certain reproducible states. It is customary to use the two fixed points—ice point and steam point.
- Ice point is the equilibrium temperature of ice with air saturated water at a pressure of 101.325 kPa which is assigned a value of 0°C.
- Steam point is the point where a mixture of liquid water and water vapour (with no air) is in equilibrium.
- The temperature scale with two arbitrary points, ice point or freezing point (0°C) and boiling point or steam (100°C) are taken is called as Celsius scale.

  The temperature scale in the SI units is Kelvin scale. In this scale, ice point (273.15 K) and boiling point (373.15 K) is taken.
- The Kelvin scale is related to Celsius scale by $T(\text{K}) = T(°\text{C}) + 273.15$

NOTE

Method used before 1954 for temperature measurement:

$$\boxed{t = \frac{100}{P_s - P_i}(P - P_i)}$$

where P can be any thermodynamic property such as resistance, pressure, volume, voltage. Suffix i and s stands for ice point and steam point respectively.

Method Used After 1954

It is based on single fixed temperature i.e., triple point of water. The triple point of water is taken as 0.01°C (273.16 K)

$$\boxed{T = 273.16\left(\frac{P}{P_{t_P}}\right)}$$

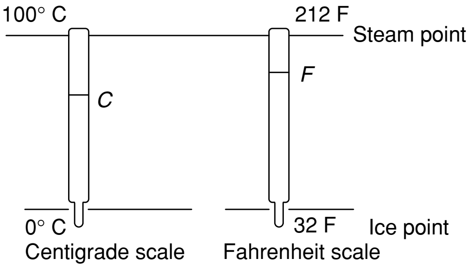
Where

T = Temperature

P = Property corresponding to temperature 'T'

P_{t_p} = Property corresponding to triple point of water.

Relation between temperature scales (°C, K, F)



Let two thermometers one centigrade and the other Fahrenheit be dipped in to water so that the former read 'C' and later reads F

$$\frac{0 - C}{0 - 100} = \frac{32 - F}{32 - 212}$$

$$\frac{C}{100} = \frac{F - 32}{180}$$

$$\frac{C}{5} = \frac{F - 32}{9}$$

Thermometry

The art of measurement of temperature is called thermometry.

Thermometric Principle

The property which changes with temperature is found first and with the help of this property temperature is then found.

Thermometric Property

The property which helps to determine the temperature is known as thermometric property.

Example: Pressure, volume, resistance, voltage, wavelength …etc.

Temperature Measuring Instruments and Their Thermometric Properties

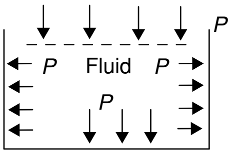
S.No.	Instrument	Thermometric Property
1.	Mercury in glass thermometer	Length
2.	Constant pressure gas thermometer (uses ideal gas equation)	Volume
3.	Constant volume gas thermometer (uses ideal gas equation)	Pressure
4.	Electrical resistance thermometer (uses Wheaston bridge principle)	Resistance
5.	Thermo couple (see beck effect)	Voltage(emf)
6.	Pyrometer (uses plank distribution law)	Wavelength

NOTES

1. All the above instruments are contact type instruments except pyrometers.
2. Pyrometers are non contact type instruments.

Pressure

Force per unit area exerted by fluid normal to the surface is called pressure.



Various Forms of Pressure

Atmospheric Pressure (P_{atm})

Normal pressure measured by barometer in the atmosphere is called atmospheric pressure.

Units of Pressure	Symbol	Numerical Value
Pascal	Pa	1 N/m^2 = 1 kg / m-s^2
Atmosphere	Atm	1 atm = 101325 Pa
Bar	bar	1 bar = 10^5 Pa =100 kPa
Torr or mm of Hg	Torr	1 Torr = 101325/760 = 133.32 Pa
Pounds per square inch	psi	1 psi = 6895 Pa

NOTES

1. Pressure units corresponding too 1 atm

MKS	1.0332 kgf/cm^2 760 mm of Hg
FPS	14.7 lb/in^2
SI	101.325 kN/m^2 10.3 m of H_2O 1.01325 bar

2. 1 micron (1μ) = 10^{-6} m Hg = 10^{-3} mm of Hg
3. 1 torr = 1mm of Hg

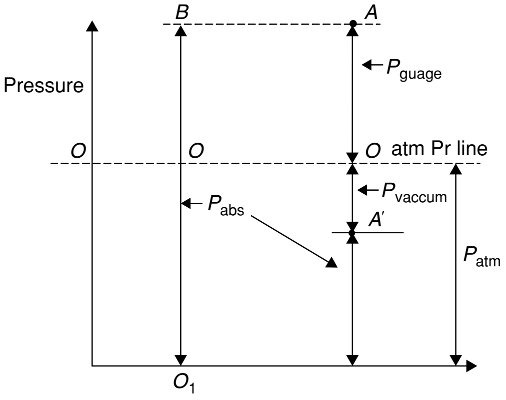


Figure 11 Absolute zero pressure (0K or – 273°C)

Pressure at A = Pressure at B

OA = Gauge P_r

O_1B = absolute pressure

Gauge Pressure (P_{guage})

Pressure measured with respect to atmospheric pressure is called gauge pressure.

- Gauge pressure may be positive or negative.
- If the pressure lies above atmospheric pressure (i.e., at point A shown in figure) is called gauge pressure which is positive.
- If the pressure lies below atmospheric pressure (i.e., at point A' as shown in figure) is called vacuum pressure which is negative.

Absolute Pressure (P_{abs})

The pressure measure with respect to absolute zero pressure is called absolute pressure.

$$\boxed{P_{\text{abs}} = P_{\text{atm}} + P_{\text{gauge}}}$$

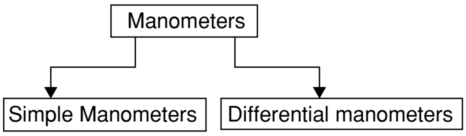
NOTE

* P_{gauge} may be + ve or –ve

* P_{abs} is always + ve

Manometers

It is an instrument used to measure the pressure.



- Simple manometers measures pressure at single point.
- Differential manometers measures the difference in pressure between two points.

Ideal Gas and Real Gas

An ideal gas is an imaginary gas which consists randomly moving particles having negligible space and which do not interact with each other.

The collision between the particles themselves and with the wall of the pipe (in which gas is flowing) is assumed to be perfectly elastic. Therefore there are no intermolecular forces between the particles and no loss of kinetic energy during the flow. These types of gases do not exist in the nature. All gases which are present in the nature are all real gas because there are no assumptions made.

The gas which follows the equation $PV = mRT$ is termed as an ideal gas. This equation came from experimental observation of gases at lower pressure.

$PV = mRT$

Where, P = Absolute pressure (in kPa)

V = Total volume (m^3)

m = Mass of the gas (kg)

R = Characteristic gas constant (kJ/kg-K)

T = Absolute temperature (K)

or $PV = nR_oT$

Where, n = number of moles (kilomoles or kmol)

R_o = Universal gas constant (kJ/kmol-K)

R_o = 8.314 kJ/kmol-K or 8.314 J/mol-K

$$R = \frac{R_o}{M} \quad \{M = \text{Molecular weight of gas}\}$$

For example: Nitrogen (N_2)

$$R = \frac{8.314}{28} = 0.297\frac{\text{kJ}}{\text{kmol-K}}$$

ENERGY TRANSFER

A closed system and its surroundings can interact in two ways.

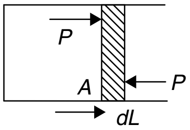
1. By work transfer and
2. By heat transfer

These are called as energy interactions and these bring about changes in the properties of the system.

Work Transfer

- In mechanics, work is defined as the product of force (F) and the distance (dL) moved in the direction of force.

$$\boxed{dW = F \cdot dL}$$



- Consider a piston-cylinder mechanism which is shown above. A pressure 'P' of the gas inside the cylinder is acting on a cross-sectional area 'A'. Then the force acting on the piston is PA. This force is balanced by an external opposing force. If the piston is allowed to move a distance 'dL' under these conditions such that opposing force is balanced by the gas pressure, then infinitesimal work done by the gas is given by

$$\begin{aligned} dW &= FdL \\ &= PA\,dL \\ &= pdV \end{aligned}$$

If there are two states 1 and 2, then the total work done is given by

$$\boxed{W = \int_1^2 PdV} \text{ for non–flow process}$$

NOTES

1. In the pressure–volume (P–V) diagram, the area under the curve represents the work.
2. $\boxed{W = -\int_1^2 Vdp}$ for flow process

   For a flow process, the area left of the P–V curve is the work done.

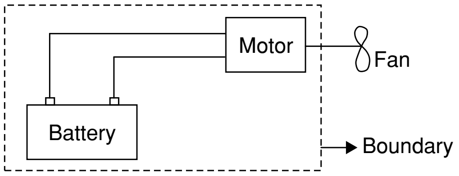
   - The differential of work is not exact. Therefore work is not a property of the system.
   - Work is a path function.

Thermodynamic Definition of Work

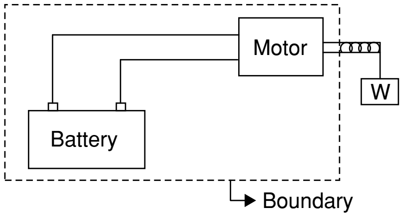
Work transfer is considered to be a boundary phenomenon i.e., an interaction between the system and surrounding should take place.

Definition: 'Work is said to be done by a system if the sole effect on things external to the system can be reduced to the raising of a weight'. The weight may not actually be raised, but the net effect external to the system would be the raising of a weight.

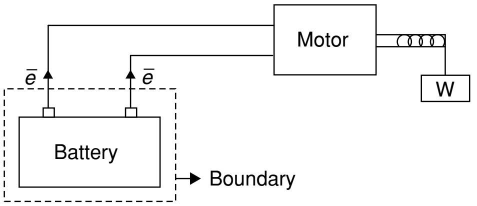
To understand the definition, let us take example of an arrangement of battery and motor as shown in the figure. From battery, motor is attached and a fan is driven by the motor and motor is driven by the battery.



Here work is transferring because system is in position to raise the weight. When this fan is replaced by rope and weight, the work transferred is known as mechanical work or shaft work.

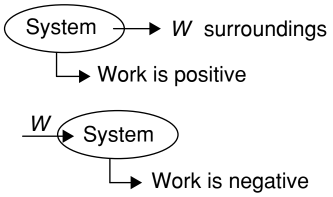


When boundary is considered such that the system is only battery then it is known as electrical work transfer.



NOTE

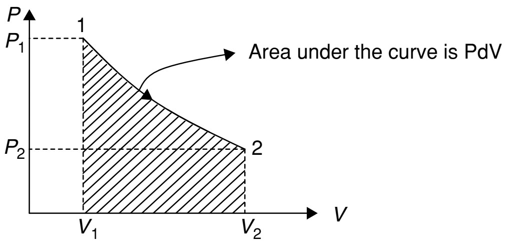
When work is done by a system, it is arbitrarily taken as positive and when work is done on a system, it is taken as negative.



Quasi-static Process

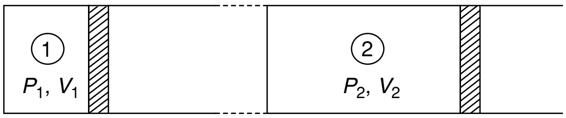
When all the points (or state) in a process are in equilibrium condition i.e., at each and every point (or state), the properties of the system can be measurable then the process is known as Quasi-static process. To attain equilibrium condition at each state, the process should be carried out in very slow manner. Infinite slow process is termed as Quasi-static process. 'Quasi' means 'almost' and 'static' means 'rest'.

A Quasi-static process is also known as reversible process.



Since all the states are in equilibrium condition, the plot of the curve between state 1 to state 2 is possible and the area under the curve between 1 – 2 in P–V plot gives reversible work transfer or quasi-static work transfer.

$$W = \int PdV \text{ [only for reversible process]}$$



Free Expansion

Consider a vessel which is divided into two compartments one compartment contains a gas at a known pressure while the other compartment is evacuated. If the partition is removed, the gas expands and occupies the entire container. In this case, the expansion of gas is not restrained by an opposing force since the other side is vacuum and the work done by the gas is equal to zero. Such an expansion which is not restrained is known as free expansion. Here, the work done is not equal to $\int PdV$.

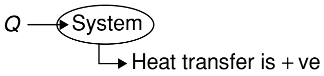
NOTES

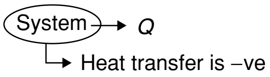
1. Work done in a free expansion process is zero. Also it is an irreversible process.
   - $W = \int PdV$ for reversible process only
   - $W \neq \int PdV$ for irreversible process or free expansion
   - $dw = -\sigma AdL$ for extension of an elastic rod, where σ – stress, A – c/s area, dL – deformation
   - $dw = -TdL$ where T – tension for stretching of wire
   - $dw = EIdt$ for a reversible cell where E – emf, I – current, dt – time
2. Work is done by a system to overcome some resistance. In case free expansion vacuum does not offer any resistance. Therefore the work done in free expansion is zero.

Heat Transfer

The energy transfer across the boundary by virtue of a temperature difference is called heat transfer.

- Heat is not an exact differential it is not a property of the system. It is a path function.
- Heat is a boundary phenomenon.
- Consider a geyser which is used to heat water.
- If we take water alone as a system, the interaction is heat interaction as the temperature of the water rises. If we take geyser and water as a system, there is only work interaction because geyser receives electrical energy from outside. And heat interaction is not there as the temperature difference occurs only inside the system.
- If heat is added into the system, it is taken as positive heat transfer and if heat is removed from the system, it is taken as negative heat transfer.





Summary:

- Work can be converted 100% into heat. But the converse is not possible.
- Also heat and work are path functions and thus inexact differentials
- Heat and work are transient phenomenon
- Heat and work are boundary phenomenon

Specific Heats

Specific heat can be defined and the energy required to raise the temperature of a unit mass of a substance by one degree. In general this energy depends on how the process is executed.

In thermodynamics, we are interested in two kinds of specific heats.

1. Specific heat at constant volume and
2. Specific heat at constant pressure

Specific heat at constant volume 'C_v' is defined as the energy required to raise the temperature of unit mass of a substance by one degree as the volume is maintained constant.

Specific heat at constant pressure 'C_p' is defined as the energy required to raise the temperature of unit mass of a substance by one degree as the pressure is maintained constant.

The specific heat at constant pressure is greater than that at constant volume.

$$\text{i.e., } \boxed{C_p > C_v}$$

Because at constant pressure, the system is allowed to expand and the energy for this expansion work must also be supplied to the system.

$$\boxed{\begin{aligned} C_v &= \left(\frac{\partial u}{\partial t}\right)_v \\ C_p &= \left(\frac{\partial h}{\partial t}\right)_p \end{aligned}}$$

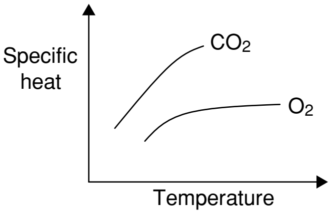
Where 'u' represents internal energy and 'h' represents enthalpy.

Molar Specific Heat

The molar specific heat of a gas is the quantity of heat required to raise the temperature of one mole of the gas through 1°C. Thus molar specific heat = specific heat × molecular weight of the gas

Since there are two specific heats for gases respectively there are two molar specific heats.

Variation of Specific Heats with Temperature



The specific heat of a gas varies with temperature. The above figure shows the variation of CO_2 and O_2 with temperature. The reason for the variation of specific heats with temperature is that the energy associated with each vibration mode becomes greater, especially at high temperatures. The vibration modes available in the atomic structure of CO_2 is more compared to diatomic molecules like O_2, hence the specific heat variation is more in CO_2.

BASIC PROCESSES

Non-Flow Process

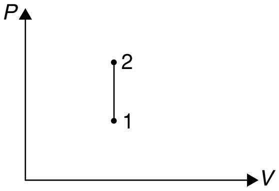
Constant Volume Process (Isochoric Process)

$$V = C \text{ (Constant)}$$

$$dV = 0$$

$$\text{Work done, } W = \int P\,dV = 0$$

$$W_{1-2} = 0$$



Constant Pressure Process (Isobaric Process)

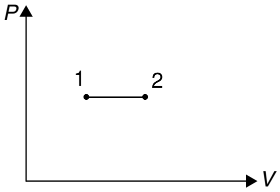
$$P = C \text{ (Constant)}$$

$$dP = 0$$

$$\text{Work done } W_{1-2} = P(V_2 - V_1)$$

NOTE

In P–V diagram the area under the curve represents the work done.



Constant Temperature Process (Isothermal Process)

$$T = C \text{ (Constant)}$$

$$dT = 0$$

$$P_1V_1 = P_2V_2$$

$$\text{i.e., } PV = C \quad \Rightarrow \quad P = \frac{C}{V}$$

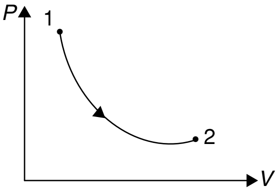
$$W_{1-2} = \int_1^2 PdV = \int_1^2 \frac{C}{V}dV$$

$$W_{1-2} = C\ln\frac{V_2}{V_1}$$

$$\boxed{\begin{aligned} W_{1-2} &= P_1V_1\ln\frac{V_2}{V_1} = P_1V_1\ln\frac{P_1}{P_2} \\ &= P_2V_2\ln\frac{V_2}{V_1} = P_2V_2\ln\frac{P_1}{P_2} \\ &= mRT_1\ln\frac{V_2}{V_1} \\ &= mRT_2\ln\frac{V_2}{V_1} \end{aligned}}$$

NOTE

Any process which is very much slow is called as an isothermal process.



Adiabatic Process

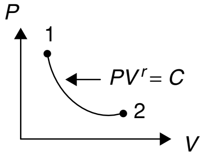
Adiabatic process is a process where heat transfer is zero. i.e., $Q = 0$. Also, any process which is very fast is called adiabatic process.

$$\boxed{\begin{aligned} &PV^r = C \\ &TV^{r-1} = C \\ &TP^{\frac{1-r}{r}} = C \end{aligned}} \text{ for an adiabatic process where } r = \frac{C_p}{C_v}$$

$$PV^r = C \quad \Rightarrow \quad P = \frac{C}{V^r}$$

$$c\int_1^2 PdV = \int_1^2 \frac{C}{V^r}dV$$

$$\boxed{\begin{aligned} W_{1-2} &= \frac{P_1V_1 - P_2V_2}{r-1} \\ &= mR\frac{(T_1 - T_2)}{r-1} \\ &= mC_V(T_1 - T_2) \end{aligned}}$$



$$\text{Where } C_v = \frac{R}{r-1}$$

Polytropic Process

For a polytropic process,

$$\boxed{\begin{aligned} &PV^n = C \\ &TV^{n-1} = C \\ &TP^{\frac{I-n}{n}} = C \end{aligned}} \text{ where } n = \frac{C_p}{C_v}$$

$$\text{Work done} \quad \boxed{W_{1-2} = \frac{P_1V_1 - P_2V_2}{n-1}}$$

NOTE

In the expression of $PV^n = C$,

If $n = 0 \Rightarrow P = C \Rightarrow$ isobaric process

$n = 1 \Rightarrow PV = C \Rightarrow$ isothermal process

$n = 1.4 \Rightarrow PV^{1.4} = C \Rightarrow$ adiabatic process

$n = \mu \Rightarrow V = C \Rightarrow$ isochoric process

Representation of Thermodynamic Process on P–V Diagram

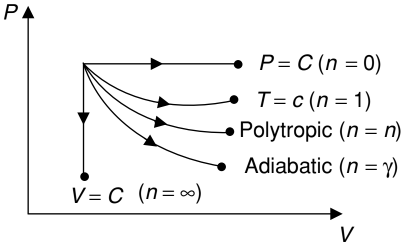


Figure 12 Expansion process

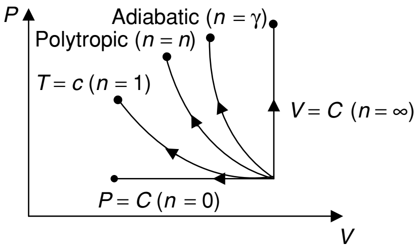
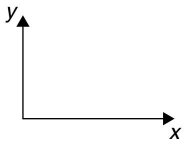


Figure 13 Compression process

Slope of Isothermal Curve in P–V Diagram

$$T = C$$
$$PV = mRT$$
$$PV = C$$



Slope $= \dfrac{dy}{dx}$

Differentiating the equation

$$PdV + VdP = 0$$
$$PdV = -VdP$$
$$\frac{dP}{dV} = \frac{-P}{V}$$

Slope of isothermal curve on P–V diagram $= \dfrac{-P}{V}$

Slope of Adiabatic Curves on P–V Diagram

$$PV^{\gamma} = C$$
$$P(\gamma \cdot V^{\gamma-1}\, dv) + V\gamma\, dP = 0$$
$$\gamma \cdot \frac{PV^{\gamma}}{V} dV = -V^{\gamma} dP$$
$$\frac{dP}{dV} = \frac{-\gamma P}{V}$$

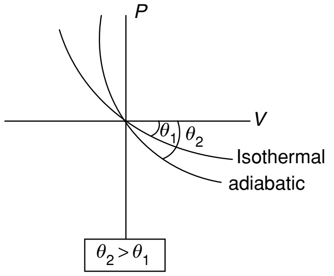
Slope of adiabatic curve $= \gamma\left(\dfrac{-P}{V}\right)$

* Adiabatic slope = $\gamma \times$ Isothermal slope

$$* \ \frac{\text{Adiabatic slope}}{\text{Isothermal slope}} = \gamma$$

* Adiabatic slope > Isothermal slope

$\because (\gamma > 1)$



NOTES

1. In $PV^n = C$ equation, n value indirectly represents the slope of the specific process.
   - For Isochroric process, slope = ∞
   - For Isobaric process, slope = 0
   - For Isothermal process, slope = 1
   - For Adiabatic process, slope = 1.4
2. The slope of the curve always increases in clockwise direction in PV diagram.

Ideal Gas Equations for Various Processes

1. Constant volume process:

   $V = C$, $PV = mRT$

   $$\frac{P_2}{P_1} = \frac{T_2}{T_1}, \ \frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}, \ V_1 = V_2$$

2. Constant pressure process:

   $P = C$, $PV = mRT$

   $$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}; \ \frac{V_1}{T_1} = \frac{V_2}{T_2}$$

3. Adiabatic process ($pv^{\gamma} = c$)

   $PV^{\gamma} = C$ $\qquad$ $P_1V_1^{\gamma} = P_2\, V_2^{\gamma}$

   $PV = mRT$ $\qquad$ $T_1V_1^{\gamma-1} = T_2V_2^{\gamma-1}$

   $$P = \frac{mRT}{V}, \ \frac{V_1}{V_2} = \left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}}$$
   $$\frac{V_1}{V_2} = \left[\frac{T_2}{T_1}\right]^{\frac{1}{\gamma-1}}$$
   $$\frac{T_2}{T_1} = \left[\frac{V_2}{V_1}\right]^{\delta-1}$$
   $$\frac{T_2}{T_1} = \left[\frac{P_2}{P_1}\right]^{\delta-1}$$

4. Polytrophic process $PV^n = C$

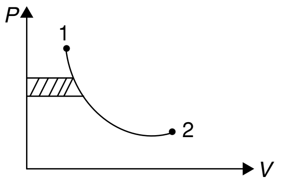
   $$P_1V_1^{\,n} = P_2V_2^{\,n}$$
   $$T_1V_1^{n-1} = T_2V_2^{n-1} \ \Rightarrow \ \frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{n-1}$$
   $$\left(\frac{T_2}{T_1}\right) = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}$$

Flow Process

For a flow process, $\boxed{W_{1-2} = \int_1^2 -VdP}$

NOTES

1. Area left of the P–V curve represents the work done for a flow process.



- For isochoric process, $\boxed{W_{1-2} = V(P_1 - P_2)}$
- For isobaric process, $\boxed{W_{1-2} = \int VdP = 0}$
- For isothermal process,

$$\boxed{\begin{aligned} W_{1-2} &= P_1V_1 \ln\frac{V_2}{V_1} \\ &= P_2V_2 \ln\frac{V_2}{V_1} \\ &= P_1V_1 \ln\frac{P_1}{P_2} \\ &= P_2V_2 \ln\frac{P_1}{P_2} \end{aligned}}$$

2. For an isothermal process, the flow work and non-flow work are same.

- For adiabatic process $\boxed{W_{1-2} = r\dfrac{(P_1V_1 - P_2V_2)}{r-1}}$
- For polytropic process, $\boxed{W_{1-2} = n\dfrac{(P_1V_1 - P_2V_2)}{n-1}}$

Universal Gas Equation

Characteristic gas equation is given by

$$PV = mRT$$

Where

P = Pressure in Pascal

V = Volume in m^3

m = Mass of gas in kg

R = Characteristic Gas constant in J/kgk

T = Temperature in Kelvin

Also $P = \dfrac{m}{V}RT = \rho RT$ where ρ = density

Also, $P\dfrac{V}{m} = RT$

$Pn = RT$ where n = specific volume

Also, $PV = m\dfrac{\bar{R}}{M}T$ where

$\dfrac{\bar{R}}{M}$ = Characteristic gas constant (R)

$\bar{R}$ Universal gas constant

M = Molecular weight

Also $PV = \dfrac{m}{M}\bar{R}T$

$= n\bar{R}T$ where n = no. of moles of gas

$\boxed{PV = n\bar{R}T}$ is known as universal gas equation

Also $PV = \dfrac{N}{A}\bar{R}T = NKT$

Where

N = no of molecules

A = Avagadro number

K is Boltzmann constant

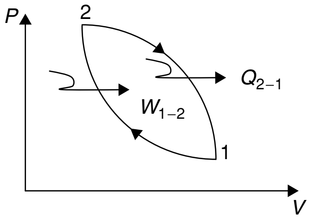
FIRST LAW OF THERMODYNAMICS

The first law of thermodynamics is also known as the 'Conservation of energy principle'. It states that 'energy can neither be created nor be destroyed during a process'. It can only change forms. Therefore every bit of energy should be accounted for during a process.

Example: A rock or stone at some elevation possesses some potential energy and part of this potential energy is converted to kinetic energy as the rock falls. i.e., the decrease in potential energy ($mg\Delta z$) exactly equals the increase in kinetic energy.

First Law for a Closed System Undergoing a Cycle

Let a cycle completed by a system with two energy interactions. i.e., adiabatic work transfer W_{1-2} followed by heat transfer Q_{2-1}



- W_{1-2} is always proportional to heat Q_{2-1}
- The constant of proportionality is called Joule's equivalent or Mechanical equivalent of heat.

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

Where J = Joule's equivalent

$$\oint dW = J\oint dQ$$

In S.I units J = 1 Nm

Mathematically first law of thermodynamics can be stated as $\boxed{\oint \partial Q = \oint \partial W}$ i.e., in a cyclic process the sum of heat interactions is equal to the sum of work interactions in a cyclic process.

$$\therefore\ \oint \partial Q - \oint \partial W = 0$$

i.e., $Q - W$ = a constant

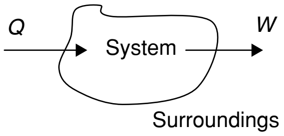
$Q - W$ = internal energy + kinetic energy + potential energy

NOTES

1. Internal energy constitutes the vibration energy, electron energy, spin energy, translational and rotational kinetic energy of the molecules.
   For a non-flow process, $Q - W$ = Internal energy
2. First law of thermodynamics is a quantitative law. It is non-directional.

First Law for a Closed System Undergoing a Change of State

If a system undergoes a change of state during which both heat transfer and work are involved, the net energy transfer will be stored within the system. This stored energy is called internal energy of the system.



$Q - W = \Delta E$

$Q = \Delta E + W$

But $\Delta E = \Delta PE + \Delta KE + \Delta U$

Where

ΔPE = change in potential energy

ΔKE = change in Kinetic energy

ΔU = change in Internal energy

In the absence of ΔKE and ΔPE

$\Delta E = \Delta U$

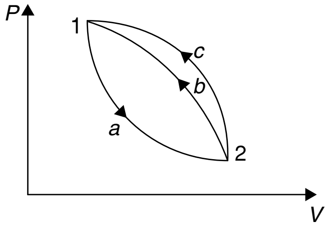
$Q = \Delta E + W$

$Q = \Delta U + W$

$\delta Q = dU + \delta W$

Energy–A Property of the System

Consider system which changes it state from state 1 to state 2 by following the path a and returns from state 2 to state 1 by following the path *b*.



For path *a*

$$Q_a = \Delta E_a + W_a$$

For path *b*

$$Q_b = \Delta E_b + W_b$$

Process *a* and *b* together constitute a cycle

$$\oint \delta w = \oint \delta Q$$

$$W_a + W_b = Q_a + Q_b$$

$$Q_a - W_a = W_b - Q_b$$

$$\therefore \quad \Delta E_a = -\Delta E_b$$

If the system returned from state 2 to state 1 by following the path *C* instead of path *B*, then

$$\therefore \quad \Delta E_a = -\Delta E_c$$

$$\therefore \quad \Delta E_b = \Delta E_c$$

Therefore change in internal energy does not depend on path of the process. It only depends on end conditions of the process. Hence it is a point function and a property of the system.

NOTES

1. Energy E is an extensive property
2. The specific energy, $e = E/m$, is an intensive property.
3. The cyclic integral of any property is zero

$$\oint dE = 0, \quad \oint dv = 0$$

Enthalpy

$$H = U + PV$$

- $H \rightarrow$ Extensive property
- $h = \dfrac{H}{m}$, specific enthalpy is an intensive property
- $h = u + pv$
- **Joule's law:** Internal energy of an ideal gas is purely a function of temperature.

$$U = f(T)$$

$$H = U + PV$$

For an ideal gas $PV = RT$

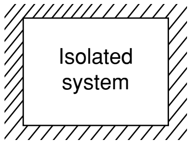
$$H = U + RT$$

$$H = f(T) + RT$$

$$H = f(T)$$

The enthalpy of an ideal gas also depends on the temperature.

Energy of an Isolated System



$\delta Q = 0$

$\delta W = 0$

According to first law

$$\delta Q = dE + \delta W$$

$$dE = 0$$

E = constant

i.e., the energy of an isolated system is always constant.

Heat Transfer in Various Non-Flow Process

Constant Volume Process

$$\delta Q = dU + \delta dW$$

$$\delta Q = dU + PdV$$

$$dV = 0 \; (\because V_1 = V_2)$$

$$\delta Q = dU$$

$$= mc_v \, dT \text{ for an ideal gas}$$

Constant Pressure Process

$$\delta Q = dU + PdV$$

$$P = \text{constant}$$

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

$$\delta Q = dH$$

$$= mc_p \, dT \text{ for an ideal gas}$$

Isothermal Process

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

For an ideal gas $U = f(T)$

$$\because\ T_1 = T_2,\ dT = 0 \rightarrow du = 0$$

$$\delta Q = \delta W$$

Adiabatic Process

The amount of heat transfer in adiabatic process is zero.

Polytropic Process

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

For an ideal gas

$du = mc_v(T_2 - T_1) = mc_v\,dT$

$$\delta Q = mc_v(T_2 - T_1) + \frac{P_1V_1 - P_2V_2}{n-1}$$

$$\delta Q = \frac{mR(T_2 - T_1)}{\gamma - 1} + \frac{P_1V_l - P_2V_2}{n-1}$$

$$\delta Q = \frac{P_2V_2 - P_1V_1}{\gamma - 1} + \frac{P_1V_1 - P_2V_2}{n-1}$$

$$= P_1V_1 - P_2V_2\left[\frac{1}{n-1} - \frac{1}{\gamma - 1}\right]$$

$$\delta Q = \frac{P_1V_1 - P_2V_2}{n-1}\left[\frac{\gamma - n}{\gamma - 1}\right]$$

$$\delta Q = \frac{\gamma - n}{\gamma - 1} \times W_{\text{polytropic process}}$$

Relation between C_P and C_V and R:

$H = U + PV$

$dH = dU + d(PV)$

For an ideal gas

$dH = mC_P\,dT$

$dU = mC_V\,dT$

$PV = mRT$

$\therefore\ mcp\,dT = mc_v\,dT + d(mRT)$

$mC_p\,dT = mc_v\,dT + mRdT$

$C_P = C_V + R$

$C_P - C_V = R$

But $\dfrac{C_P}{C_V} = \gamma,\ C_P = \gamma,\ C_V$

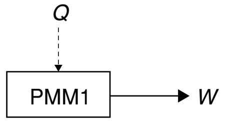
$$C_P - C_V = R$$

$$\delta C_V - C_V = R;$$

$$C_V = \frac{R}{(\gamma - 1)},\ C_P = \left(\frac{\gamma R}{\gamma - 1}\right)$$

Perpetual Motion Machine of the First Kind-PMM1

The first law states that 'Energy can neither be created nor be destroyed, but only get transformed from one form to another'. There can be no machine which would continuously supply mechanical work without some other forms of energy disappearing simultaneously. Such a fictitious machine is called as PMM1.



Difference Between Work and Internal Energy

Work	Internal Energy
1. Work is a path function	1. Internal energy is a point function
2. Work is energy in transition. A body never contains work	2. Internal energy is the energy which body contains
3. work can be converted fully into heat in ideal heat engines	3. Internal energy cannot be fully converted into work even in the most perfect engines
4. Work is not related to the state of the system	4. Internal energy is always related to the state of the substance

NOTE

There exists a property of a system '*u*' such that change in its value is equal to the difference between the heat supplied and the work done during any change in state which is known as internal energy. In an isolated system, the energy of the system remains constant–law of conservation of energy. A perpetual motion machine of first kind is impossible.

Limitations of First Law of Thermodynamics

- It is a law of conservation of energy only. It does not specify the direction of the process.
- All spontaneous processes proceed in one direction only. The first law does not deny the feasibility of a spontaneous process reversing itself.

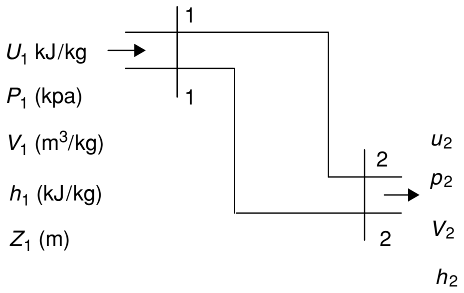
STEADY FLOW ENERGY EQUATION (SFEE)

'Steady Flow' means that the rate of flow of mass and energy across the control surface are constant.

At a particular location of flow, the property of the system will have fixed value and it is not changing with the time is known as steady flow.

Steady flow process can be categorized by the following.

1. Properties do not vary with time.
2. The mass entering and leaving the control volume is same.
3. The total energy entering the control volume is equal to the total energy leaving the control volume.



For steady flow conditions to prevail two conditions are to be satisfied.

1. Mass balance and
2. Energy balance

Mass Balance

$$W_1 = W_2$$

$$\boxed{\begin{gathered}\rho_1 A_1 V_1 = \rho_2 A_2 V_2 \\ \frac{A_1 V_1}{v_1} = \frac{A_2 V_2}{v_2}\end{gathered}}$$

Energy Balance

Internal E + Flow E + Kinetic Energy + Potential E = Constant

$$I.E_1 + F.E_1 + P.E_1 + K.E_1 + \text{Heat}$$
$$= I.E_2 + F.E_2 + P.E_2 + K.E_2 + \text{work}$$

$$u_1 + P_1V_1 + \frac{gZ_1}{1000} + \frac{V_1^2}{2000} + \frac{dQ}{dM}$$
$$= u_2 + P_2V_2 + \frac{gZ_2}{1000} + \frac{V_2^2}{2000} + \frac{dW}{dM}$$

i.e.,
$$\boxed{\begin{gathered} h_1 + \frac{gZ_1}{1000} + \frac{V_1^2}{2000} + \frac{dQ}{dM} \\ = h_2 + \frac{gZ_2}{1000} + \frac{V_2^2}{2000} + \frac{dW}{dM}\end{gathered}}$$

If we multiply both sides with $\frac{dM}{dt}$ we get

$$\boxed{\begin{gathered}\frac{dM}{dt}\left[h_1 + \frac{gz_1}{1000} + \frac{v_1^2}{2000}\right] + \frac{dQ}{dt} \\ = \frac{dM}{dt}\left[h_1 + \frac{gz_2}{1000} + \frac{v_2^2}{2000}\right] + \frac{dW}{dt}\end{gathered}}$$

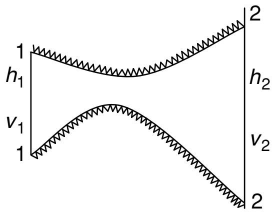
NOTE

SFEE is used for compressible fluids and Bernoulli's equation is used for incompressible fluids.

Applications of SFEE

Nozzle

Nozzle is a device which is used to convert heat energy to kinetic energy.



The nozzle is perfectly insulated.

$$\therefore \qquad \frac{dQ}{dM} = 0$$

Also there is no work output from the nozzle.

$$\therefore \qquad \frac{dW}{dM} = 0$$

∴ SFEE can be written as

$$h_1 + \frac{V_1^2}{2000} = h_2 + \frac{V_2^2}{2000}, \text{ since } gz_1 = gz_2$$

$$V_2 = \sqrt{V_1^2 + 2000(h_1 - h_2)}$$

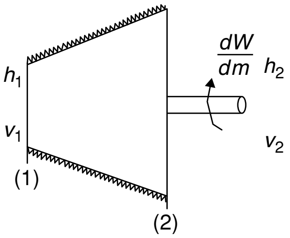
If initial $K.E = 0 \quad \Rightarrow \quad V_1 = 0$, then

$$V_2 = \sqrt{2000\Delta h}$$

$\boxed{V_2 = 44.72\sqrt{\Delta h}}$ where Δh is in kJ/kg.

Turbine

Turbine is a device which used to convert heat energy into work energy.



Turbine is perfectly insulated $\therefore \frac{dQ}{dM} = 0$

∴ SFEE for turbine can be written as

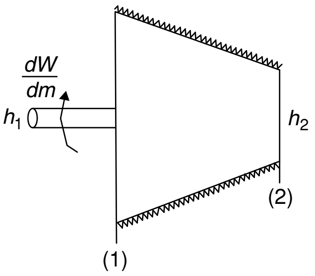
$$h_1 + \frac{V_1^2}{2000} = h_2 + \frac{V_2^2}{2000} + \frac{dW}{dM}$$

where $\frac{dW}{dM}$ is in kJ/kg

$$\boxed{\frac{dW}{dM} = (h_1 - h_2) + \left(\frac{V_1^2 - V_2^2}{2000}\right)}$$

Compressor

Compressor is used to convert a low pressure fluid to high pressure fluid.



Compressor is perfectly insulated

$$\therefore \quad \frac{dQ}{dM} = 0$$

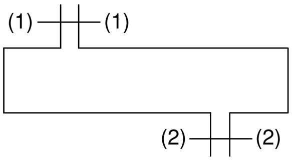
∴ SFEE for compressor can be written as

$$h_1 = h_2 + \frac{dW}{dM}$$

$$\therefore \quad \boxed{\frac{dW}{dM} = (h_1 - h_2) \text{ kJ/kg}}$$

Condensor

Condensor is a device which is used for rejecting heat.



There is no work output from the condenser.

$$\frac{dW}{dm} = 0$$

SFEE for condenser can be written as $h_1 + \frac{dQ}{dM} = h_2$

$$\therefore \quad \boxed{\frac{dQ}{dM} = (h_2 - h_1)} \text{ kJ/kg}$$

Throttle Valve

It is a device used to convert high pressure fluid to low pressure fluid.

It is also perfectly insulated $\therefore \frac{dQ}{dm} = 0$

In a throttle valve, $\frac{dW}{dm} = 0$

∴ SFEE for throttle valve can be written as $\boxed{h_1 = h_2}$

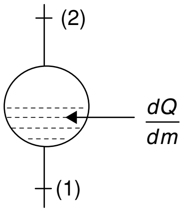
NOTES

In a throttle valve, enthalpy remains constant.

1. For ideal gases, throttling process is an isothermal process.
2. For real gases, temperature may increase or decrease depending on the type of gas
3. For steam, temperature always decreases.

Boiler

It is a device used for raising steam.



SFEE for boiler can be written as

$$h_1 + \frac{V_1^2}{2000} + \frac{dQ}{dM} = h_2 + \frac{V_2^2}{2000}$$

Where $\frac{dW}{dM} = 0$

$$\therefore \quad \boxed{\frac{dQ}{dM} = (h_2 - h_1) + \left(\frac{V_2^2 - V_1^2}{2000}\right)}$$

Also, heat supplied by fuel = heat required to raise the steam

$$\dot{M}_f (\text{kg/s}) CV (\text{kJ/kg}) \eta_c$$

$$= \dot{M}_s (\text{kg/s}) \frac{dQ}{dM} (\text{kJ/kg})$$

Where

CV = calorific value of fuel,

h_c = efficiency of combustion.

Transient Flow Processes

In steady state processes the rate of inflow will be equal to the rate of outflow. Thus there is no accumulation of mass and energy inside the control volume.

In transient flow processes there is accumulation of mass and energy inside the control volume and the rate of inflow and outflow are not identical.

Charging and discharging are transient flow processes.

Let,

M_0 = Mass of the gas in the tank in the initial state before the filling operation

m_f = Mass of the gas in the tank in the final state at the end in the filling operation

u_0 = Initial specific internal energy of the gas in the tank

u_f = Final specific internal energy of the gas in the tank

h = Specific enthalpy of the gas in the supply main from which gas enters the tank

Q = Energy transferred as heat to the tank during filling operation

If we ignore KE and PE changes, then SFEE can be written as

$$\boxed{Q = M_f u_f - M_0 u_0 - (M_f - M_0) h}$$

for charging as well as discharging process.

NOTE

Assuming adiabatic process and $M_0 = 0$

$\boxed{T_f = rT}$ for charging process

Assuming adiabatic process and $m_f = 0$,

$\boxed{T_0 = rT}$ for discharging process

Liquefaction of Gases

Liquefaction of gases is used in several applications like preparation of liquid propellants for rockets, study of material properties at low temperatures etc. Three commonly used liquefied gases are helium, nitrogen and hydrogen. The critical temperatures of these are –268, –147 and –240°C respectively. Above critical temperatures, these exist in gaseous phase only. That is why these exist only in gaseous form at atmospheric temperature. Low temperatures of this magnitude cannot be obtained by ordinary refrigeration techniques. Thus liquefaction is used to lower the temperature below its critical point temperature.

The gas is compressed to high pressure and then cooled at constant pressure in an after cooler. Then the gas is further cooled in a regenerative counter flow heat exchanger and then throttled, then we will get a saturated liquid vapour mixture state. The liquid is collected as the desired product.

Solved Examples

Example 1: The piston cylinder device with air at an initial temperature of 35°C undergoes an expansion process for which pressure and volume are related s given below:

State	1	2	3
p(kPa)	120	50	20
V(m^3)	0.2	0.4	0.8

Calculate the work done (in kJ) by the system from state 1 to 3.

(A) 27.6 (B) 32.5 (C) 21.6 (D) 37.6

Solution:

Since no process is given in the question. Therefore taking polytropic process

$$P_1V_1^n = P_2V_2^n = P_3V_3^n$$

$$n = \frac{\ln\left(\frac{P_1}{P_2}\right)}{\ln\left(\frac{V_2}{V_1}\right)} = \frac{\ln\left(\frac{120}{50}\right)}{\ln\left(\frac{0.4}{0.2}\right)} = 1.263$$

$$n = \frac{\ln\left(\frac{P_2}{P_3}\right)}{\ln\left(\frac{V_3}{V_2}\right)} = \frac{\ln\left(\frac{50}{20}\right)}{\ln\left(\frac{0.6}{0.4}\right)} = 1.322$$

1–2

$$W_1 = \frac{P_1V_1 - P_2V_2}{n-1} = \frac{(120\times 0.2)-(50\times 0.4)}{1.263-1}$$

$$\Rightarrow \quad W_1 = 15.2091 \text{ kJ}$$

2–3

$$W_2 = \frac{P_2V_2 - P_3V_3}{n-1} = \frac{(50\times 0.4)-(20\times 0.8)}{0.322}$$

$$\Rightarrow \quad W_2 = 12.631 \text{ kJ}$$

Total work done = $W_1 + W_2$ = 15.2091 + 12.4223
= 27.631 kJ

Example 2: A mono-atomic ideal gas ($d = 1.66$, molecular weight = 40) is compressed adiabatically from 0.2 MPa, 350 K to 0.4 MPa. The work of compression of the gas (in kJ/kg) is

(A) 36.39 (B) 42.32 (C) 34.97 (D) 31.23

Solution:

$$W = \frac{P_1V_1 - P_2V_2}{(\gamma-1)} = \frac{mR(T_1-T_2)}{\gamma-1}$$

Now $R = \frac{R_o}{M} = \frac{8.314}{40} = 0.20785$ kJ/kg-K

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \quad \Rightarrow \quad T_2 = 350\left(\frac{0.4}{0.2}\right)^{\frac{1.66-1}{1.66}}$$

$$\Rightarrow \quad T_2 = 461.057 \text{ K}$$

$$W = \frac{1\times 0.20785\times(461.057-350)}{0.66} = 34.97455 \text{ kJ/kg}$$

Example 3: A mass of 2 kg air is compressed in a very slow process from 100 kPa to 70 kPa for which PV = constant. The initial density of air is 1.16 kg/m^3. The work done by the piston to compress the air (in kJ) will be

(A) 64.6 (B) 67.9 (C) 52.5 (D) 61.5

Solution:

$$\because \quad P_1V_1 = P_2V_2 \quad \Rightarrow \quad \frac{V_2}{V_1} = \frac{P_1}{P_2}$$

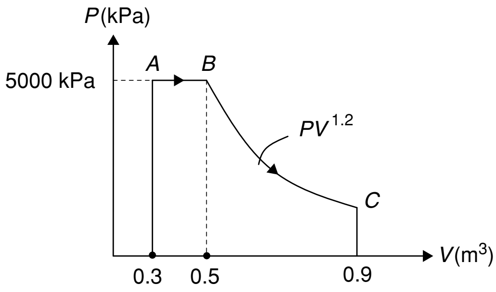
$$W = P_1V_1 \ \ln\frac{V_2}{V_1} = 100\times\frac{2}{1.16}\ln\left(\frac{P_1}{P_2}\right)$$

$$\Rightarrow \quad W = 100\times\frac{2}{1.16}\times\ln\left(\frac{100}{70}\right]$$

$$= 61.4956 \text{ kJ}$$

$$\sim 61.5 \text{ kJ}$$

Example 4: A P–V plot of an expansion process by a gas system is shown as follows. Find the total work by the gas (in MJ)



(A) 2.4 (B) 2.9 (C) 3.1 (D) 3.6

Solution:

Process A–B: $P = C$

$\therefore\ W_{A-B} = P_B(V_B - V_C) = 5000(0.5 - 0.3)$

$\Rightarrow W_{A-B} = 1000$ kJ

Process B – C:

$$P_B V_B^{1.2} = P_c V_c^{1.2}$$

$$\therefore\ P_C = P_B\left(\frac{V_B}{V_C}\right)^{1.2} = 5000 \times \left(\frac{0.5}{0.9}\right)^{1.2}$$

$\Rightarrow P_C = 2469.7$ kPa

$$W_{B-C} = \frac{P_B V_B - P_C V_C}{\gamma - 1} = \frac{[(5000 \times 0.5) - (2469.7 \times 0.9)]}{0.2}$$

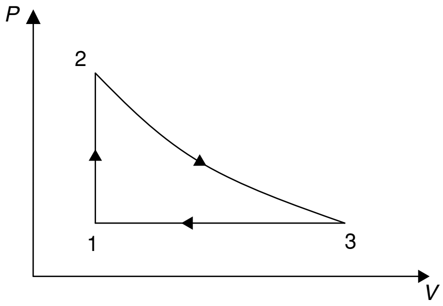
$\Rightarrow\ W_{B-C} = 1386.35$ kJ

Total work done, $W = W_{A-B} + W_{B-C}$
$= 1000 + 1386.35$
$= 2386.35$ kJ
~ 2.4 MJ

Example 5: A fluid system going through a cycle as shown in the figure.

(i) Process 1–2 isochoric heat addition of 300 kJ/kg.
(ii) Process 2–3 adiabatic expansion to its original pressure with loss of 80 kJ/kg in internal energy.
(iii) Process 3–1 isobaric compression to its original volume with heat rejection of 260 kJ/kg.

The amount of work transfer in process 3–1 will be



(A) –40 kJ/kg (B) +40 kJ/kg
(C) 60 kJ/kg (D) –60 kJ/kg

Solution:

Process 1 – 2: $V = C$

$Q_{1-2} = 300$ kJ/kg and $W_{1-2} = 0$

$\Delta U = U_2 - U_1 = Q_{1-2} - W_{1-2}$

$\Rightarrow\ \Delta U = 300 - 0 = 300$ kJ/kg

Process 2–3:

$Q_{2-3} = 0,\ U_3 - U_2 = -80$ kJ/kg

$W_{2-3} = 0 - (-70) = 80$ kJ/kg

Process 3–1:

$Q_{3-1} = -260$ kJ/kg

$U_1 - U_3 = (U_1 - U_2) - (U_3 - U_2)$

$\Rightarrow\ U_1 - U_3 = -300 - (-80) = -220$ kJ/kg

$\therefore\ W_{3-1} = Q_{3-1} - (U_1 - U_3) = -260 - (-220)$
$= -40$ kJ/kg

or $\Sigma Q = \Sigma W$

$\Rightarrow\ 300 + 0 - 260 = 0 + 80 + W_{3-1}$

$\Rightarrow\ W_{3-1} = -40$ kJ/kg

Example 6: A gas contained in a cylinder is compressed, the work required for compression being 4000 kJ. During the process, heat interaction of 1500 kJ causes the surroundings to be heated. The changes in internal energy of the gas during the process is

(A) –5500 kJ (B) –2500 kJ
(C) 2500 kJ (D) +5500 kJ

Solution:

$\delta Q = dW + \Delta U$

or $\Delta U = dQ - dW = -1500 - (-400)$

$\Rightarrow\ \Delta U = 2500$ kJ

Example 7: A fluid is confined in a cylinder by a spring loaded friction less piston so that the pressure in the fluid is a linear function of the volume ($p = a + bV$). The internal energy of the fluid is given by the following equation

$$U = 40 + 3.21\ PV$$

where U is in kJ, p in kPa and V in m³.

If the fluid changes from an initial condition of 200 kPa, 0.04 m³ to a final state of 400 kPa, 0.08 m³, find the magnitude and direction of work transfer (in kJ) and heat transfer (in kJ)

(A) –12 and 65 (B) +12 and +89
(C) 20 and 99 (D) –20 and 77

Solution:

$U_2 - U_1 = 3.21[p_2 V_2 - p_1 V_1]$

$\Rightarrow\ U_2 - U_1 = 3.21\ [-200 \times 0.04 + 400 \times 0.08]$

$\Rightarrow\ U_2 - U_1 = 77.04$ kJ

Now $p = a + bV \quad \Rightarrow \quad 200 = a + b(0.04)$

$400 = a + b(0.08)$

$\Rightarrow\ a = 0;\ b = 5000$

$$\text{Now, } W_{1-2} = \int_{V_1}^{V_2} p\,dV = \int_{v_1}^{v_2} (a + bV)\,dV$$

$$\Rightarrow\ W_{1-2} = \frac{b\left(V_2^2 - V_1^2\right)}{2} = \frac{5000}{2}[(0.08^2 - 0.04^2)]$$

$\Rightarrow\ W_{1-2} = 12$ kJ

$Q_{1-2} = W_{1-2} + \Delta U \quad \Rightarrow \quad Q_{1-2} = +12 + 77.04$

$\Rightarrow\ Q_{1-2} = 89.04$ kJ

Example 8: 2 kg of air has gone through a constant pressure process. It has been experimented that the process is very slow. During the process the temperature changes from 400 K to 800 K. Calculate the work transfer (in kJ) during the process. Assume air as ideal gas.

(A) 274.6 (B) 321.2 (C) 249.7 (D) 229.6

Solution:

$\because$ Reversible $P = C$ process

$\because$ $\delta Q = m\,C_P\,dT$

Now $\delta Q = \delta W + dU \Rightarrow m\,C_P\,dT = \delta W + m\,C_V\,dT$

$\Rightarrow \delta W = m\,dT\,(C_P - C_V) = m\,dT(R)$

$\Rightarrow \delta W = 2 \times (800 - 400) \times 0.287$

$\Rightarrow \delta W = 229.6$ kJ

Example 9: Consider a steady flow of air in an adiabatic passage. Air enters the passage at 100 kPa, 500 K at a velocity of 150 m/s and leaves passage at 510 K. Assuming air to be an ideal gas and neglect potential energy changes and no work transfer occurring, calculate the velocity of air at the exit (in m/s)

(A) 44 (B) 49 (C) 56 (D) 51

Solution:

Given: $P_1 = 100$ kPa, $T_1 = 500$ K, $C_1 = 150$ m/s

$T_2 = 510$ K

$$m\left[h_1 + \frac{C_1^2}{2000}\right] = m\left[h_2 + \frac{C_2^2}{2000}\right]$$

$\because$ $\delta W = 0$, $\Delta P \cdot E = 0$ and $Q = 0$ {adiabatic}

$$C_P T_1 + \frac{C_1^2}{2000} = C_P T_2 + \frac{C_2^2}{2000}$$

$$\Rightarrow 1.005[500 - 510] + \frac{150^2}{2000} = \frac{C_2^2}{2000}$$

$\Rightarrow C_2 = 48.9897$ m/s

$\Rightarrow C_2 \sim 49$ m/s.

Example 10: Air enters and insulated diffuser operating at a steady state with a pressure of 0.7 bar, a temperature of 60°C, and a velocity of 220 m/s. The inlet area is 0.4 m^2. At the exit, the pressure is 1 bar and the area is 0.6 m^2. Assuming no potential energy change and air as an ideal gas, calculate the temperature of air at the exit (in K)

(A) 351.245 (B) 362.34

(C) 373.39 (D) 369.43

Solution:

Given: $P_1 = 70$ kPa, $T_1 = 333$ K

$C_1 = 220$ m/s, $A_1 = 0.4$ m^2

$A_2 = 0.6$ m^2, $P_2 = 1000$ kPa

We know that, $\rho = \dfrac{m}{V} \Rightarrow m = \rho \times V$

$\Rightarrow m = \rho \times A \times L \Rightarrow \dot{m} = \rho \times A \times \dfrac{L}{t}$

$\Rightarrow \dot{m} = \rho AC$

Now $PV = mRT \Rightarrow P = \rho RT$

$$\Rightarrow \rho_1 = \frac{P_1}{RT_1} = \frac{70}{(0.287 \times 333)} = 0.73244 \text{ kg/m}^3$$

$\therefore \dot{m} = \rho_1 A_1 C_1 = 0.73244 \times 0.4 \times 220$

$\Rightarrow \dot{m} = 64.4546$ kg/s

Now $\dot{m} = \rho_1 A_1 C_1 = \rho_2 A_2 C_2 = 64.4546$

$$\rho_2 = \frac{P_2}{RT_2} = \frac{100}{0.287T_2} = \frac{348.432}{T_2}$$

$$\frac{348.432}{T_2} \times 0.6 \times C_2 = 64.4546$$

$\therefore C_2 = 0.3083\,T_2$ (1)

Now $h_1 + \dfrac{C_1^2}{2000} = h_2 + \dfrac{C_2^2}{2000}$

$$\Rightarrow C_P T_1 + \frac{C_1^2}{2000} = C_P T_2 + \frac{C_2^2}{2000}$$

$$(1.005 \times 333) + \frac{220^2}{2000} = 1.005T_2 + \frac{(0.3083T_2)^2}{2000}$$

$\Rightarrow T_2 = 351.245$ K

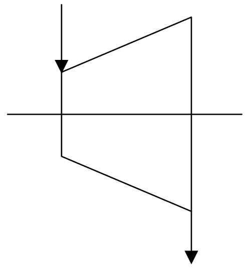
Example 11: The inlet and outlet conditions of steam for an adiabatic steam turbine are as indicated in the notations as usually followed.

$h_1 = 3500$ kJ/kg

$C_1 = 160$ m/s

$Z_1 = 12$ m

$P_1 = 3$ MPa



$h_2 = 2800$ kJ/kg

$C_2 = 100$ m/s

$Z_2 = 8$ m

$P_2 = 70$ kPa

If the mass flow rate of the steam through the turbine is 25 kg/s, then the power output of the turbine (in MW) will be

(A) 15.641 (B) 21.349

(C) 17.695 (D) 12.245

Solution:

$$\dot{m}\left[h_1 + \frac{C_1^2}{2000} + \frac{gz_1}{1000}\right] = \dot{m}\left[h_2 + \frac{C_2^2}{2000} + \frac{gz_2}{1000}\right] + \dot{W}$$

$$25\left[(3500 - 2800) + \frac{(160^2 - 100^2)}{2000} + \frac{(9.81\{12 - 8\})}{1000}\right] = W$$

$\Rightarrow \dot{W} = 17.695$ MW

EXERCISES

Practice Problems I

Direction for questions 1 to 20: Select the correct alternative from the given choices.

1. If the ice point temperature is 100°*x*, steam point temperature 300°*x*, the value of 27°C in °*x* scale is_____.
(A) 154 (B) 144 (C) 134 (D) 124

2. The specific heat at constant pressure C_P is given by $C_p = 45 + \frac{700}{\sqrt{T}} + \frac{6000}{T}$ kJ/kg mole K.

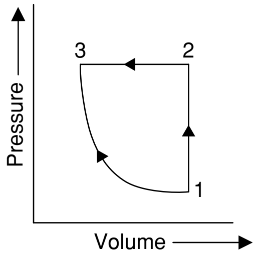
The change in enthalpy when 1 kg of oxygen is heated from 300K to 1000K, in kJ/kg is _____.
(A) 200.55 (B) 350.25
(C) 551.87 (D) 750

3. A system undergoes a cycle *ABCDEF*. The energy transfers during the six processes are tabulated below.

Process	Heat Transfer Q kJ/min	Work Transfer kJ/min	DU kJ/min
AB	220	–	136.3
BC	– 44.3	32.0	–
CD	–	–11.6	–13.4
DE	–	7.0	–28.8
EF	30	–10.0	–
FA	– 8.8	–	–

The rate of work in kW is _____.
(A) 1.5 (B) 2.5 (C) 3 (D) 4.5

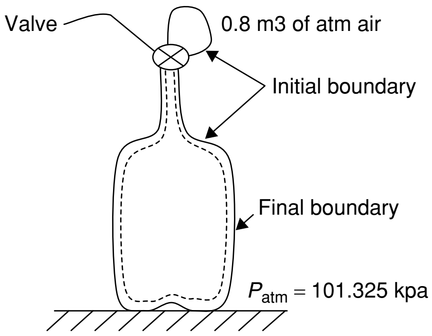
4. The system shown in the figure is taken from state 1 to state 2 by a constant volume process. 310 kJ of heat is supplied to the system. From state 2 the system is taken to state 3 by a constant pressure process. During this process the system rejects 350 kJ of heat and 100 kJ of work is done on it. The system is brought back from state 3 to state 1 by a reversible adiabatic process. The adiabatic work in kJ, if the internal energy at state 1 is 400 kJ, is_____.



(A) 70 (B) 100 (C) 150 (D) 170

5. A piston and cylinder machine containing a fluid system has stirring device in the cylinder. The piston is frictionless, and it is held down against the fluid due to the atmospheric pressure of 101.325 kPa. The stirring device is turned 12,000 revolutions with an average torque against the fluid of 1.5 Nm. Meanwhile the piston of 0.5m diameter moves out 0.9m. The network transfer for the system is _____.
(A) 41.46 (B) –41.46
(C) 25.5 (D) –25.5

6. When the valve of the evacuated bottle shown in the figure is opened, atmospheric air rushes into it. If the atmospheric pressure is 101.325 kPa, and 0.8 m^3 of air (measured at atmospheric conditions) enters into the bottle, the work done by air in kJ is _____.



(A) 25.5 (B) 40
(C) 50.25 (D) 81.06

7. A piston–cylinder device operates 1 kg of fluid at 25 atm pressure. The initial volume is 0.05 m^3. The fluid is allowed to expand reversibly following a process $PV^{1.3}$ = constant, so that the volume becomes double. The fluid is then cooled at constant pressure until the piston comes back to the original position. Keeping the piston unaltered, heat is added reversibly to restore it to the initial pressure. The work done in the cycle in kJ is_____.
(A) 100 (B) 40.25
(C) 27.82 (D) 10.25

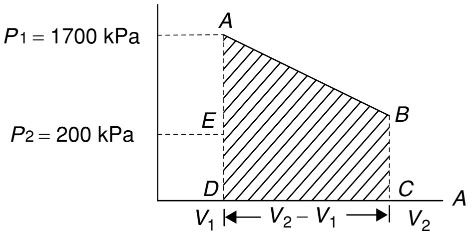
8. An insulated tank initially contains 0.25 kg of a gas with an internal energy of 300 kJ/kg Additional gas with an internal energy of 400 kJ/kg enters the tank until the total mass of gas contained is 1 kg. The final internal energy (in kJ/kg) of the gas in the tank is_____.
(A) 375 (B) 275
(C) 175 (D) 100

9. An insulated box containing 2.5 kg of a gas having C_v= 0.98 kJ/kg K falls from a balloon 5km above the earths surface. The temperature rise of gas when the box hits the ground is_____.
(A) 100 (B) 50.05
(C) 25.05 (D) 5.05

10. A mono-atomic ideal gas (γ = 1.66 molecular weight = 40) is compressed adiabatically from 0.2 MPa, 300 K to 0.4 MPa. The universal gas constant is 8.314 kJ/moleK. The work of compression of the gas (in kJ/kg) is _____.

(A) 59.23 (B) 49.23
(C) 39.23 (D) 29.83

11. An engine cylinder has a piston of area 0.25 m^2 and contains gas at a pressure of 1700 kPa. The gas expands according to a process which is represented by a straight line as shown in figure. The final pressure is 200 kPa. Calculate the work done by the gas if the stroke length is 0.35m.



(A) 83.125 (B) 100
(C) 225.5 (D) 300

Direction for questions 12, 13 and 14: A nozzle is a device for increasing the velocity of a steadily flowing stream. At the inlet to a certain nozzle the enthalpy of the fluid passing is 3022 kJ/kg and the velocity is 61 m/s and at the discharge side the enthalpy of the fluid is 2788 kJ/kg. The nozzle is horizontal and there is negligible heat loss from it.

12. The velocity at nozzle exit in m/s is____.
(A) 400 (B) 686.82
(C) 700 (D) 785.5

13. If the inlet area is 929 cm^2 and the specific volume at inlet is 0.188 per kg. then the rate of flow in kg/s is____.
(A) 5.2 (B) 30.14
(C) 15.5 (D) 35.25

14. For the above problem, If the specific volume at nozzle discharge is 0.6 m^3/kg, the exit area of the nozzle in cm^2 is____.
(A) 63.33 (B) 163.33
(C) 263.33 (D) 363.33

Direction for questions 15, 16 and 17: In an air compressor 12m^3 of air is compressed per minute from 1.0 bar to 6.00 bar. Initial specific volume is 0.32 m^3/kg and the final specific volume is 0.15 m^3/kg. The suction line diameter is 120 mm and the discharge line diameter is 75 mm.

15. The change in flow work between the boundaries in kJ is ____.
(A) 2175 (B) 1525
(C) 1325 (D) 1000

16. The mass flow rate of air in kg/s is ____.
(A) 0.456 (B) 0.625
(C) 0.825 (D) 0.945

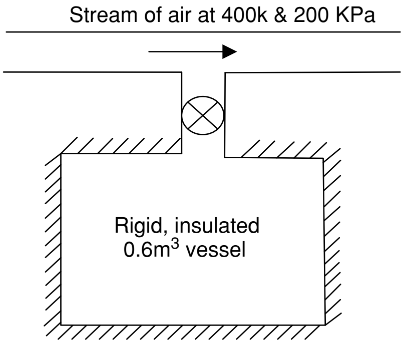
17. The velocity ratio is ____.
(A) 3.04 (B) 2
(C) 1.2 (D) 0.876

Direction for questions 18 and 19: A steam turbine developing 120 kW is supplied steam at 18.5 bar with an internal energy of 2800 kJ/kg and specific volume of 0.21 m^3/kg and velocity of 120 m/s. Exhaust from turbine is at 0.1 bar with an internal energy of 2093 kJ/kg and specific volume equal to 15.5 m^3/kg and velocity 200 m/s. Heat loss from the steam turbine is 37.6 KJ/kg. Neglect potential energy changes.

18. Shaft work output in kJ/kg is ____.
(A) 720 (B) 800
(C) 890.1 (D) 1020

19. Steam flow rate in kg/h is ____.
(A) 285.36 (B) 320.52
(C) 440 (D) 485.33

20. An insulated 0.6 m^3 storage tank that is initially evacuated is connected to a supply line carrying air at 500 K and 200 kPa. The valve is opened and air flows into the tank from the supply line. The valve is closed when the pressure in the tank reaches 200 kPa. The final temperature of air in the tank assuming air as an ideal gas is ____.



(A) 460 (B) 560
(C) 700 (D) 800

Practice Problems 2

Direction for questions 1 to 37: Select the correct alternative from the given choices.

1. In certain scale, ice point temperature is 100 °V, steam point temperature is 3000 °V then the value of 30 °C in o_V scale is ____.
(A) 1400 (B) 1500
(C) 1600 (D) 2000

2. In a closed vessel a gas undergoes reversible expansion from P_1V_1 to final pressure P_2, according to the following laws

(a) Isothermal (b) Adiabatic
(c) Polytrophic ($n > \gamma$) (d) Polytrophic ($n < \gamma$)

Arrange the above four process in the ascending order of their work done

(A) $c < b < d < a$ (B) $a < b < c < d$
(C) $d < c < b < a$ (D) $c < d < b < a$

3. In a closed system gas undergoes reversible adiabatic expansion according to the law $P = 3 + \frac{4}{V^2}$ bar in which volume changes from 0.1 to 0.4 m^3. The work developed during the process is_____.

(A) 1090 kJ (B) 1200 kJ
(C) 2500 kJ (D) 3090 kJ

4. The content of a well-Insulated tank are heated by a resistor of 25 Ω in which 10 A current is flowing. Consider the tank along with its contents as a thermodynamic system. The work done by the system and the heat transfer to the system are positive. The rates of heat (Q), work (W) and change in internal energy (ΔU) during the process kw are_____.

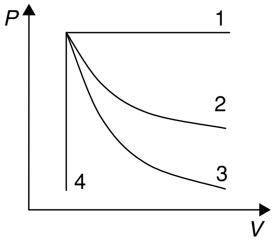
(A) $Q = 0, W = 2.5$: $\Delta U = -2.5$
(B) $Q = 0, W = -2.5,$ $\Delta U = +2.5$
(C) $Q = 2.5, W = 2.5;$ $\Delta U = 0$
(D) $Q = 2.50; W = -2.5;$ $\Delta U = 0$

5. Match List-I with List-II and select the correct answer using the code given below.

List-I

(a) $n = a$ (b) $n = 1.4$
(c) $n = 1.0$ (d) $n = 0$

List-II



Codes:

	a	b	c	d
(A)	4	3	2	1
(B)	1	3	2	4
(C)	4	2	3	1
(D)	1	2	3	4

Direction for questions 6 and 7: A fluid system contained in a piston cylinder machine passes through a complete cycle of 4 processes. The summation of all heat transfer is –340 kJ /cycle. The system complete 200 cycles /min

Process	Q (KJ/min)	W (KJ/min)	dU(KJ/min)
1-2	o	4340	–
2-3	42000	0	–
3-4	– 4200	–	–73200
4-1	–	–	–

6. The change in internal energy during the process 4–1 in kJ/min is_____.

(A) 35540 (B) 25540
(C) 42000 (D) 4340

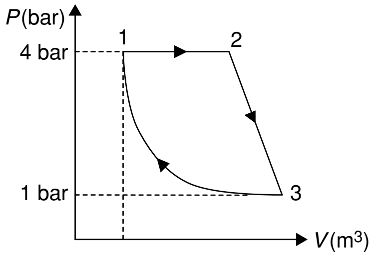
7. The net work done in kW is_____.

(A) 2211.33 kW
(B) 2211.33 kW
(C) 1133.33 kW
(D) Zero

8. Consider steady flow of air (c_p = 1.005 kJ/kg K) in an adiabatic passage. Air enters the passage at 100 kPa, 500 K at a velocity of 150 m/s and exits the passage at 510 K. Assume air to be an ideal gas and neglect gravitational effects. The passage is_____.

(A) Diffuser and the velocity at the exit is approximately 49 m/s
(B) Diffuser and the velocity at the exit is approximately
(C) Nozzle and the velocity at the exit is approximately 179 m/s
(D) Nozzle and the velocity at the exit is approximately 249 m/s

Direction for questions 9 and 10: A system undergoes quasi-static process sequentially as indicated in the figure. 1 – 2 is an isobaric process, 2 – 3 is a polytrophic process with n = 1.4 and 3 – 1 is a process in which PV = constant. The following data made use of $P_1 = P_2 = 4$ bar, $P_3 = 1$ bar and $V_1 = 1\text{m}^3$



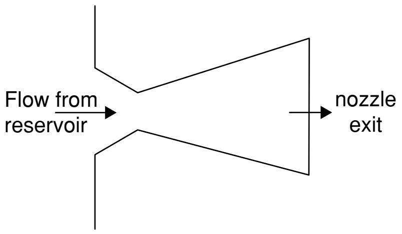
9. Volume of the system at point 2 in m^3 is_____.

(A) 1.741 (B) 2.173
(C) 6.96 (D) 1.486

10. The net heat interaction for the cycle in kJ is_____.

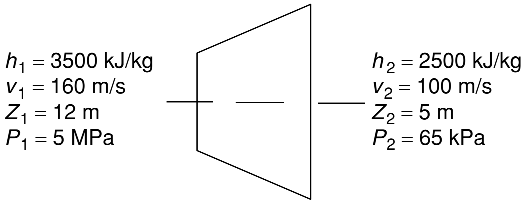
(A) 126 (B) 194
(C) 486 (D) –486

11. The temperature and pressure of air in a large reservoir are 400 K and 3 bar respectively. A converging diverging nozzle of exit are 0.005 m^2 is fitted to the wall of the reservoir as shown in the figure. The static pressure of air at the exit section for isentropic flow through the nozzle is 50 kPa. The characteristic gas constant and the ratio of specific heats of air are 0.287 kg/kg K and 1.4 respectively.



The density of air in kg/m^3 at the nozzle exit is____.
(A) 0.560 (B) 0.600
(C) 0.727 (D) 0.800

12. The inlet and outlet conditions of steam for an adiabatic steam turbine are as indicated in the notations as usually followed.



If mass flow rate of steam through the turbine is 15 kg/s, the power output of the turbine in (MW) is ____.
(A) 12.11 (B) 14.11
(C) 15.11 (D) 20

13. Assume the above turbine to be part of a simple rankine cycle. The density of water at the inlet to the pump is 1000 kg/m^3. Ignoring kinetic and potential energy effects, the specific work in (KJ/kg) supplied to the pump is ____.
(A) 5.5 (B) 4.9
(C) 10 (D) 15.9

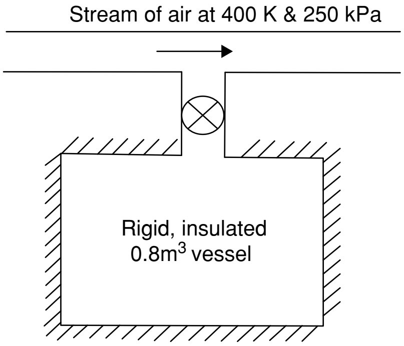
Direction for questions 14 and 15: Air enter an insulated diffuser operating at steady state with a pressure of 0.8 bar, at a temperature of 67 °C, and a velocity of 220 m/s. The inlet area is 0.4m^2. At the exit, the pressure is 1.5 bar and area is 0.6m^2, potential energy changes can be neglected. Assume ideal gas behaviour of air.

14. The mass flow rate of air entering the diffuser in kg/s is ____.
(A) 59.1 (B) 63.15
(C) 70.24 (D) 72.14

15. The temperature of the air at the exit, in degree *K* is____.
(A) 503 (B) 406
(C) 1009 (D) 927

16. A rigid tank is connected through a valve to steam mains, supplying steam at 1 MPa, 400 °C. Heat is transferred from the tank to the surrounding, and the valve is closed when the total amount of cooling is 2500 kJ the energy contained in the tank is the same before and after the process. Neglecting potential and kinetic energy changes the mass of the steam that enters the tank is____.
(A) 2.56 kg (B) 1.25 kg
(C) 0.98 kg (D) 0.76 kg

17. An insulated 0.8 m^3 storage tank that is initially evacuated is connected to a supply line carrying air at 400 K and 250 kPa. The valve is opened and air flows into the tank from the supply line. The valve is closed when the pressure in the tank reaches 250 kPa. The final temperature of air in the tank in K is ____.



(A) 560 (B) 750
(C) 890 (D) 1050

18. General gas equation is
(A) $PV = nRT$
(B) $PV = mRT$
(C) $PV = \frac{1}{3} nRT$
(D) $PV^n = C$

19. Which of the following law is applicable for the behavior of a perfect gas?
(A) Boyle's law
(B) Charles' law
(C) Gay–Lussac law
(D) All of the above

20. According to Kinetic theory of gases, the absolute zero temperature is attained when
(A) Volume of the gas is zero
(B) Pressure of the gas is zero
(C) Kinetic energy of the molecules is zero
(D) Specific heat of gas is zero

21. Which of the following statement holds good for the equation $dQ = dE + dW$.
(A) Any process undergone by a closed stationary system.
(B) Any process, reversible and irreversible and for any system
(C) A closed system when only pdv work is present
(D) Only reversible process

22. Match List-I with List-II and select the correct answer using the codes:

List-I	List-II
a. Work done	1. Point function
b. Thermal equilibrium	2. Path function
c. Internal energy	3. Isolated system
d. No work and heat inter action	4. Equality of temperature

Codes:

	a	b	c	d
(A)	4	2	3	1
(B)	2	4	1	3
(C)	2	3	4	2
(D)	3	1	2	4

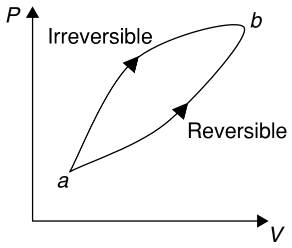
23. In the vander wall's gas equation

$$P + \frac{a}{v^2}(V - b) = RT$$

The constant '*a*' is introduced to compensate for

(A) Reduction in specific volume
(B) Inter molecular forces
(C) Reduction in specific heat
(D) All of the above

24. For the two paths as shown in the figure, one reversible and one irreversible, to change the state of the system from *a* to *b*.



(A) ΔU, Q, W are same
(B) Q, W are same
(C) ΔU, Q are different
(D) ΔU is same

25. Work done is zero for the following process

(A) Constant volume (B) Free expansion
(C) Throttling (D) All of the above

26. The internal energy of a system is function of _____ only

(A) Pressure
(B) Temperature
(C) Volume
(D) Pressure and temperature

27. In a free expansion process

(A) Work done is zero
(B) Heat transfer is zero
(C) Both (A) and (B) above
(D) Work done is zero but heat increases

28. Polytrophic index 'n' is given

(A) $\dfrac{\log\left(\frac{P_2}{P_1}\right)}{\log\left(\frac{V_1}{V_2}\right)}$ (B) $\dfrac{\log\left(\frac{P_1}{P_2}\right)}{\log\left(\frac{V_1}{V_2}\right)}$

(C) $\dfrac{\log\left(\frac{V_1}{V_2}\right)}{\log\left(\frac{P_2}{P_1}\right)}$ (D) $\dfrac{\log\left(\frac{V_2}{V_1}\right)}{\log\left(\frac{P_2}{P_1}\right)}$

29. When an ideal gas flows through a very narrow pipe of uniform cross section, the flow is approximately

(A) Isochoric (B) Isothermal
(C) Isobaric (D) Isenthalapic

30. In polytrophic process, heat rejected is given by

(A) $\dfrac{\gamma - n}{\gamma - 1} \times$ Work done on the system

(B) $\dfrac{\gamma - n}{\gamma} \times$ Work done on the system

(C) $\dfrac{\gamma}{\gamma - 1} \times$ Work done on the system

(D) $\dfrac{\gamma - n}{n} \times$ Work done on the system

31. A sudden fall in the barometer reading is a sign of approaching

(A) Fine weather (B) Rains
(C) Storm (D) Cold wave

32. In case of steady flow system, work can be evaluated using an expression

(A) $W = \int_{\text{initial}}^{\text{Final}} PdV$ (B) $W = \int_{\text{initial}}^{\text{Final}} VdP$

(C) $W = \int_{\text{initial}}^{\text{Final}} -VdP$ (D) $W = \int_{\text{initial}}^{\text{Final}} -PdV$

33. Absolute zero pressure will occur

(A) At sea level
(B) At the centre of the earth
(C) When molecular momentum of the system becomes zero.
(D) Under vacuum conditions

34. Gases have

(A) Three values of specific heat
(B) Two values of specific heat
(C) Only one value of specific heat
(D) None of these

35. The value of C_v for oxygen is 5 cal/mole °K and the ratio of specific heats is 1.4. The difference between C_p and C_v (in cal/mol °K) is

(A) 12.4 (B) 2 (C) 1.4 (D) 1

36. Which law states that the specific heat of a gas remains constant at all temperatures and pressures?
(A) Charles' law (B) Joule's law
(C) Regnault's law (D) Boyle's law

37. Which of the following is not the intensive property?
(A) Pressure (B) Temperature
(C) Density (D) Heat

PREVIOUS YEARS' QUESTIONS

1. A gas contained in a cylinder is compressed, the work required for compression being 5000 kJ. During the process, heat interaction of 200 (kJ) causes the surroundings to the heated. The change in internal energy of the gas during the process is **[2004]**
(A) −7000 kJ (B) −3000kJ
(C) +3000 kJ (D) +7000 kJ

2. Nitrogen at an initial state of 10 bar, 1 m^3 and 300 K is expanded isothermally to a final volume of 2 m^3. The P–V–T relation is $\left(p+\frac{a}{v^2}\right)v = RT$, where $a > 0$. the final pressure **[2005]**
(A) Will be slightly less than 5 bar
(B) Will be slightly more than 5 bar
(C) Will be exactly 5 bar
(D) Cannot be ascertained in the absence of 'a'.

3. A 100 W electric bulb was switched on in a 2.5 m × 3 m × 3 m size thermally insulated room having a temperature of 20°C. The room temperature at the end of 24 hours will be **[2006]**
(A) 321 °C (B) 341 °C
(C) 450 °C (D) 470 °C

4. Match items from groups I, II, III, IV and V. **[2006]**

Group I	Group II	Group III	Group IV	Group V
	When added to the system, is	Differential	Function	Phenomenon
E Heat	*G* positive	*I* Exact	*K* path	*M* Transient
F Work	*H* Negative	*J* Inexact	*L* point	*N* Boundary

(A) $F-G-J-K-M$ (B) $E-G-I-K-M$
$E-G-I-K-N$ $F-H-I-K-N$
(C) $F-H-J-L-N$ (D) $E-G-J-K-N$
$E-H-I-L-M$ $F-H-J-K-M$

Direction for questions 5 and 6: A football was inflated to a gauge pressure of 1 bar when the ambient temperature was 15°C. When the game started next day, the air temperature at the stadium was 5°C. Assume that the volume of the football remains constant at 2500 cm^3.

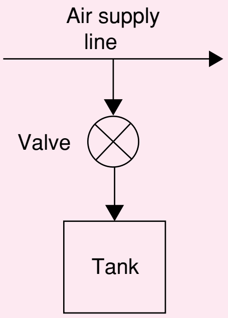
5. The amount of heat lost by the air in the football and the gauge pressure of air in the football at the stadium respectively equal **[2006]**
(A) 30.6 J, 1.94 bar
(B) 21.8 J, 0.93 bar
(C) 61.1 J, 1.94 bar
(D) 43.7 J, 0.93 bar

6. Gauge pressure of air to which the ball must have been originally inflated so that it would equal 1 bar gauge at the stadium is **[2006]**
(A) 2.23 bar (B) 1.94 bar
(C) 1.07 bar (D) 1.00 bar

7. Which of the following relationships is valid only for reversible processes undergone by a closed system of simple compressible substance (neglect changes in kinetic and potential energy)? **[2007]**
(A) $\delta Q = dU + \delta W$ (B) $T\,dS = dU + PdV$
(C) $T\,dS = dU + \delta W$ (D) $\delta Q = \mathrm{d}U + PdV$

8. A balloon containing an ideal gas is initially kept in an evacuated and insulated room. The balloon ruptures and the gas fills up the entire room. Which one of the following statements is TRUE at the end of above process? **[2008]**
(A) The internal energy of the gas decreases from its initial value, but the enthalpy remains constant
(B) The internal energy of the gas increases from its initial value, but the enthalpy remains constant
(C) Both internal energy and enthalpy of the gas remain constant
(D) Both internal energy and enthalpy of the gas increase

9. A rigid, insulated tank is initially evacuated. The tank is connected with a supply line through which air (assumed to be ideal gas with constant specific heats) passes at 1 MPa, 350 °C. A valve connected with the supply line is opened and the tank is charged with air until the final pressure inside the tank reaches 1 MPa. The final temperature inside the tank. **[2008]**



(A) is greater than 350 °C
(B) is less then 350 °C
(C) is equal to 350 °C
(D) May be greater than, less than, or equal to 350 °C, depending on the volume of the tank

10. In a steady state steady flow process taking place in a device with a single inlet and a single outlet, the work done per unit mass flow rate is given by $W = -\int_{\text{inlet}}^{\text{outlet}} VdP$, where V is the specific volume and P is the pressure. The expression for W given above **[2008]**

(A) is valid only if the process is both reversible and adiabatic
(B) is valid only if the process is both reversible and isothermal
(C) is valid for any reversible process
(D) is incorrect; it must be $W = \int_{\text{inlet}}^{\text{outlet}} PdV$

11. A frictionless piston-cylinder device contains a gas initially at 0.8 MPa and 0.015 m^3. It expands quasi-statically at constant temperature to a final volume of 0.030 m^3. The work output (in kJ) during this process will be **[2009]**

(A) 8.32 (B) 12.00
(C) 554.67 (D) 8320.00

12. A compressor undergoes a reversible, steady flow process. The gas at inlet and outlet of the compressor is designated as state 1 and state 2 respectively. Potential and kinetic energy changes are to be ignored. The following notations are used: V = specific volume and P = pressure of the gas.
The specific work required to be supplied to the compressor for this gas compression process is **[2009]**

(A) $\int_1^2 PdV$ (B) $\int_1^2 VdP$
(C) $V_1(P_2 - P_1)$ (D) $-P_2(V_1 - V_2)$

13. A mono-atomic ideal gas (γ= 1.67, molecular weight = 40) is compressed adiabatically from 0.1 MPa, 300 K to 0.2 MPa. The universal gas constant is 8.314 kJkmol^{-1}K^{-1}. The work of compression of the gas (in kJ kg^{-1}) is **[2010]**

(A) 29.7 (B) 19.9
(C) 13.3 (D) 0

14. Heat and work are **[2011]**

(A) Intensive properties
(B) Extensive properties
(C) Point functions
(D) Path functions

15. The contents of a well-insulated tank are heated by a resistor of 23 Ω in which 10 A current is flowing. Consider the tank along with its contents as a thermodynamic system. The work done by the system and the heat transfer to the system are positive. The rates of heat (Q), work (W) and change in internal energy (ΔU) during the process in kW are **[2011]**

(A) $Q = 0$, $W = -2.3$, $\Delta U = +2.3$
(B) $Q = +2.3$, $W = 0$, $\Delta U = +2.3$
(C) $Q = -2.3$, $W = 0$, $\Delta U = -2.3$
(D) $Q = 0$, $W = +2.3$, $\Delta U = -2.3$

Direction for questions 16 and 17: Air enters an adiabatic nozzle at 300 kPa, 500 K with a velocity of 10 m/s. It leaves the nozzle at 100 kPa with a velocity of 180 m/s. The inlet area is 80 cm^2. The specific heat of air C_p is 1008 J/kg.K.

16. The exit temperature of the air is **[2012]**

(A) 516 K (B) 532 K
(C) 484 K (D) 468 K

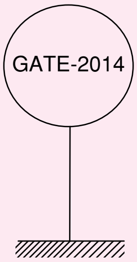
17. The exit area of the nozzle in cm^2 is **[2012]**

(A) 90.1 (B) 56.3
(C) 4.4 (D) 12.9

18. A cylinder contains 5 m^3 of an ideal gas at a pressure of 1 bar. This gas is compressed in a reversible isothermal process till its pressure increases to 5 bar. The work in kJ required for this process is **[2013]**

(A) 804.7 (B) 953.2
(C) 981.7 (D) 1012.2

19. A spherical balloon with a diameter of 10 m, shown in the figure below is used for advertisements. The balloon is filled with helium (R_{He}= 2.08 kJ/kg K) at ambient conditions of 15 °C and 100 kPa. Assuming no disturbances due to wind, the maximum allowable weight (in Newton) of balloon material and rope required to avoid the fall of the balloon (R_{air} = 0.289 kJ/ kg K) is _____ **[2014]**



20. A certain amount of an ideal gas is initially at a pressure p_1 and temperature T_1. First it undergoes a constant pressure process 1-2 such that $T_2 = 3T_1/4$. Then, it undergoes a constant volume process 2–3 such that $T_3 = T_1/2$. The ratio of the final volume to the initial volume of the ideal gas is **[2014]**

(A) 0.25 (B) 0.75 (C) 1.0 (D) 1.5

21. For an ideal gas with constant values of specific heats, for calculation of the specific enthalpy, **[2015]**

(A) it is sufficient to know only the temperature
(B) both temperature and pressure are required to be known

(C) both temperature and volume are required to be known

(D) both temperature and mass are required to be known

22. Temperature of nitrogen in a vessel of volume 2 m^3 is 288 K. A U-tube manometer connected to the vessel shows a reading of 70 cm of mercury (level higher in the end open to atmosphere). The universal gas constant is 8314 J/kmol-K, atmospheric pressure is 1.01325 bar, acceleration due to gravity is 9.81 m/s^2 and density of mercury is 13600 kg/m^3. The mass of nitrogen (in kg) in the vessel is _____. **[2015]**

23. A well insulated rigid container of volume 1 m^3 contains 1.0 kg of an ideal gas [C_p = 1000 J/(kg.K) and C_v = 800 J/(kg.K)] at a pressure of 10^5 Pa. A stirrer is rotated at constant rpm in the container for 1000 rotations and the applied torque is 100 N-m. The final temperature of the gas (in K) is_____. **[2015]**

24. The Vander Waals equation of state is $\int \left[p+\frac{a}{v^2}\right]$ $(v - b) = RT$. Where p is pressure, v is specific volume, T is temperature and R is characteristic gas constant. The SI unit of a is **[2015]**

(A) J/kg-K (B) m^3/kg

(C) $m^5/kg\text{-}s^2$ (D) Pa/kg

25. Work is done on a adiabatic system due to which its velocity changes from 10 m/s to 20 m/s, elevation increases by 20 m and temperature increases by 1 K. The mass of the system is 10 kg, C_v = 100 J/(kg.K) and gravitational acceleration is 10 m/s^2. If there is no change in any other component of the energy of the system, the magnitude of total work done (in kJ) on the system is _______. **[2015]**

26. Steam enters a turbine at 30 bar, 300°C (u = 2750 kJ/kg, h = 2993 kJ/kg) and exits the turbine as saturated liquid at 15 kPa (u = 225 kJ/kg, h = 226 kJ/kg). Heat loss to the surrounding is 50 kJ/kg of steam flowing through the turbine. Neglecting changes in kinetic energy and potential energy, the work output of the turbine (in kJ/kg of steam) is ______. **[2015]**

27. A mixture of ideal gases has the following composition by mass:

N_2	O_2	CO_2
60%	30%	10%

If the universal gas constant is 8314 J/kmol-K, the characteristic gas constant of the mixture (in J/kg-K) is ______. **[2015]**

28. Which of the following statements are TRUE with respect to heat and work? **[2016]**

(i) They are boundary phenomena

(ii) They are exact differentials

(iii) They are path functions

(A) both (i) and (ii) (B) both (i) and (iii)

(C) both (ii) and (iii) (D) only (iii)

29. An ideal gas undergoes a reversible process in which the pressure varies linearly with volume. The conditions at the start (subscript 1) and at the end (subscript 2) of the process with usual notation are: p_1 = 100 kPa, V_1 = 0.2 m^3 and p_2 = 200 kPa, V_2 = 0.1 m^3 and the gas constant, R = 0.275 kJ/kg-K. The magnitude of the work required for the process (in kJ) is _______. **[2016]**

30. The internal energy of an ideal gas is a function of:

(A) Temperature and pressure

(B) Volume and pressure

(C) Entropy and pressure

(D) Temperature only

31 A piston-cylinder device initially contains 0.4 m^3 of air (to be treated as an ideal gas) at 100 kPa and 80°C. The air is now isothermally compressed to 0.1 m^3. The work done during this process is _______ kJ. **[2016]**

(Take the sign convention such that work done on the system is negative)

32. Steam at an initial enthalpy of 100 kJ/kg and inlet velocity of 100 m/s, enters an insulated horizontal nozzle. It leaves the nozzle at 200 m/s. The exit enthalpy (in kJ/kg) is _________. **[2016]**

33. In a 3-stage air compressor, the inlet pressure is p_1, discharge pressure is p_4 and the intermediate pressures are p_2 and p_3 ($p_2 < p_3$). The total pressure ratio of the compressor is 10 and the pressure ratios of the stages are equal. If p_1 = 100 kPa, the value of the pressure p_3 (in kPa) is __________.

ANSWER KEYS

EXERCISES

Practice Problems 1

1. A **2.** C **3.** B **4.** A **5.** B **6.** D **7.** C **8.** A **9.** B **10.** D
11. A **12.** B **13.** B **14.** C **15.** A **16.** B **17.** C **18.** C **19.** D **20.** C

Practice Problems 2

1. C **2.** A **3.** D **4.** B **5.** A **6.** A **7.** B **8.** A **9.** D **10.** A
11. C **12.** C **13.** B **14.** D **15.** B **16.** D **17.** A **18.** B **19.** D **20.** D
21. B **22.** B **23.** B **24.** D **25.** D **26.** B **27.** C **28.** A **29.** D **30.** A
31. C **32.** C **33.** C **34.** B **35.** B **36.** C **37.** D

Previous Years' Questions

1. C **2.** B **3.** D **4.** D **5.** D **6.** C **7.** D **8.** C **9.** A **10.** C
11. A **12.** B **13.** A **14.** D **15.** A **16.** C **17.** D **18.** A **19.** 5300 to 5330
20. B **21.** A **22.** 4.4 to 4.6 **23.** 1283.4 to 1287.4 **24.** C **25.** 4.5 **26.** 2717
27. 274 to 276 **28.** B **29.** 15 **30.** D **31.** –55.6 to –55.4 **32.** 85 **33.** 460–470