



UNIT 5

JET PROPULSION & ROCKETS



Course Objective:

Applications and the principles of thermodynamics to components and systems.

Course Outcome:

Develop problem solving skills through the application of thermodynamics.



5 JET PROPULSION ENGINES

5.1 Introduction

Jet propulsion, similar to all means of propulsion, is based on Newton's Second and Third laws of motion.

The jet propulsion engine is used for the propulsion of aircraft, missile and submarine (for vehicles operating entirely in a fluid) by the reaction of jet of gases which are discharged rearward (behind) with a high velocity. As applied to vehicles operating entirely in a fluid, a momentum is imparted to a mass of fluid in such a manner that the reaction of the imparted momentum furnishes a propulsive force. The magnitude of this propulsive force is termed as thrust.

For efficient production of large power, fuel is burnt in an atmosphere of compressed air (combustion chamber), the products of combustion expanding first in a gas turbine which drives the air compressor and then in a nozzle from which the thrust is derived. Paraffin is usually adopted as the fuel because of its ease of atomisation and its low freezing point.

Jet propulsion was utilized in the flying Bomb, the initial compression of the air being due to a divergent inlet duct in which a small increase in pressure energy was obtained at the expense of kinetic energy of the air. Because of this very limited compression, the thermal efficiency of the unit was low, although huge power was obtained. In the normal type of jet propulsion unit a considerable improvement in efficiency is obtained by fitting a turbo-compressor which will give a compression ratio of at least 4 : 1.

5.2 Classification

Jet propulsion engines are classified basically as to their method of operation as shown in fig. 5-1. The two main categories of jet propulsion systems are the *atmospheric*

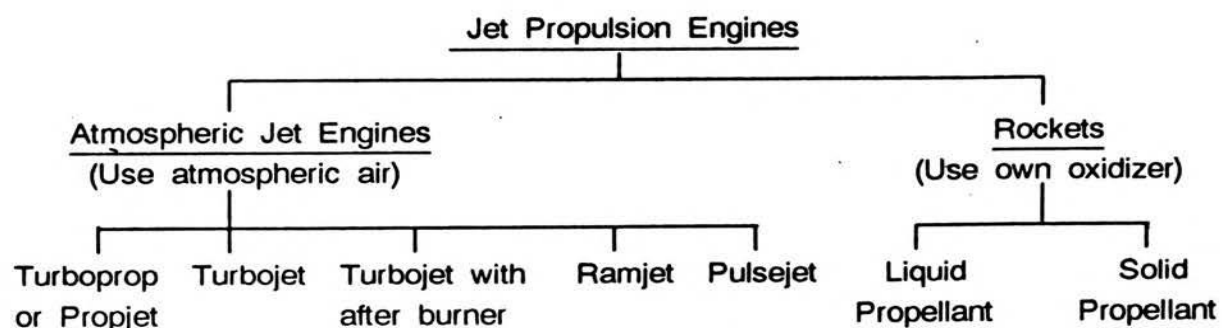


Fig. 5 - 1. Jet propulsion engines.

jet engine and *rocket*. Atmospheric jet engines require oxygen from the atmospheric air for combustion of fuel, i.e. they are dependent on atmospheric air for combustion.

The rocket engine carries its own oxidizer for combustion of fuel and is, therefore,



JET PROPULSION ENGINES

independent of the atmospheric air. Rocket engines are discussed in art. 5-6.

The turboprop, turbojet and turbojet with after burner are modified simple open cycle gas turbine engines. In turboprop thrust is not completely due to jet. Approximately 80 to 90 percent of the thrust in turboprop is produced by acceleration of the air outside the engine by the propeller (as in conventional aeroengines) and about 10 to 20 percent of the thrust is produced by the jet of the exhaust gases. In turbojet engine, the thrust is completely due to jet of exhaust gases. The turbojet with after burner is a turbojet engine with a reheater added to the engine so that the extended tail pipe acts as a combustion chamber.

The ramjet and pulsejet are aero-thermo-dynamic-ducts, i.e. a straight duct type of jet engine without compressor and turbine. The ramjet has the simplest construction of any propulsion engine, consisting essentially of an inlet diffuser, a combustion chamber and an exit nozzle of tail pipe. Since the ramjet has no compressor, it is dependent entirely upon ram compression.

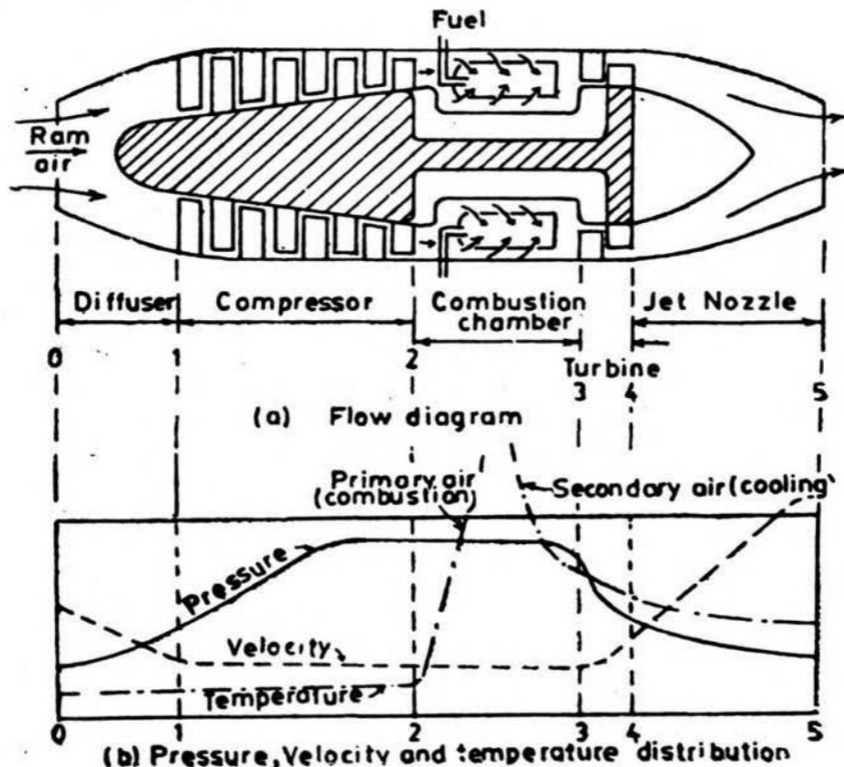


Fig. 5-2 Turbojet engine.

The pulsejet is an intermittent combustion jet engine and it operates on a cycle similar to a reciprocating engine and may be better compared with an ideal Otto cycle rather than the Joule or Bryton cycle. From construction point of view, it is some what similar to a ramjet engine. The difference lies in provision of a mechanical valve arrangement to prevent the hot gases of combustion from going out through the diffuser.

5.3 Turbojet Engine

The turbojet engine (fig. 5-2) is similar to the simple open cycle constant pressure gas turbine plant (fig. 4-2) except that the exhaust gases are first partially expanded in the turbine to produce just sufficient power to drive the compressor. The exhaust gases



Thus, the essential *components* of a turbojet engine are :

- A Rolls-Royce Derwent jet engine employs a centrifugal compressor and turbine of the impulse-reaction type. The unit has 550 kg mass. The speed attained is 960 km/hour.

The hot gases from the combustion chamber then pass through the turbine nozzle ring. The hot gases which partially expand in the turbine are then exhausted through the discharge (propelling nozzle) by which the remaining enthalpy is converted into kinetic energy. Thus, a high velocity propulsion jet is produced.

The diagram is a Temperature-Entropy ($T-s$) plot. The vertical axis is Temperature (T) and the horizontal axis is Entropy (s). The cycle consists of the following processes:

- Diffuser (0-1):** A solid line with an arrow pointing from 0 to 1, showing an increase in both temperature and entropy.
- Compressor (1-2):** A solid line with an arrow pointing from 1 to 2, showing an increase in both temperature and entropy.
- Turbine (3-4):** A solid line with an arrow pointing from 3 to 4, showing a decrease in both temperature and entropy.
- Jet nozzle (4-5):** A solid line with an arrow pointing from 4 to 5, showing a decrease in both temperature and entropy.
- Isentropic expansion (3-5'):** A dashed line with an arrow pointing from 3 to 5', representing a constant entropy process.

Points 1, 2, 3, 4, and 5 are marked on the solid cycle line. Points 0, 1, 2, 3, 4, 5, and 5' are marked on the entropy axis. The area between the solid line (1-2-3-4-5) and the dashed line (1-2-3-5'-1) represents the work output of the turbine minus the work input to the compressor.

JET PROPULSION ENGINES

Some starting device such as compressed air motor or electric motor, must be provided in the turbojet plant. Flight speeds upto 800 km per hour are obtained from this type of unit.

The basic thermodynamic cycle for the turbojet engine is the Joule or Brayton cycle as shown in $T - \Phi$ diagram of fig. 5-3. While drawing this cycle, following simplifying assumptions are made :

- There are no pressure losses in combustion chamber.
- Specific heat of working medium is constant.
- Diffuser has ram efficiency of 100 percent *i.e.*, the entering atmospheric air is diffused isentropically from velocity V_0 to zero (V_0 is the vehicle velocity through the air).
- Hot gases leaving the turbine are expanded isentropically in the exit nozzle *i.e.*, the efficiency of the exit nozzle is 100 percent.

5.3.2 Thrust Power and Propulsive Efficiency : The jet aircraft draws in air and expels it to the rear at a markedly increased velocity. The action of accelerating the mass of fluid in a given direction creates a reaction in the opposite direction in the form of a propulsive force. The magnitude of this propulsive force is defined as thrust. It is dependent upon the rate of change of momentum of the working medium *i.e.* air, as it passes through the engine.

The basis for comparison of jet engines is the thrust. The thrust, T of a turbojet engine can be expressed as,

$$T = m (V_j - V_0) \quad \dots (5.1)$$

where, m = mass flow rate of gases, kg/sec.,

V_j = exit jet velocity, m/sec., and,

V_0 = vehicle velocity, m/sec.

The above equation is based upon the assumption that the mass of fuel is neglected. Since the atmospheric air is assumed to be at rest, the velocity of the air entering relative to the engine, is the velocity of the vehicle, V_0 . The thrust can be increased by increasing the mass flow rate of gas or increasing the velocity of the exhaust jet for given V_0 .

Thrust power is the time rate of development of the useful work achieved by the engine and it is obtained by the product of the thrust and the flight velocity of the vehicle. Thus, thrust power TP is given by

$$TP = T V_0 = m (V_j - V_0) V_0 \frac{\text{N.m}}{\text{sec.}} \quad \dots (5.2)$$

The kinetic energy imparted to the fluid or the energy required to change the momentum of the mass flow of air, is the difference between the rate of kinetic energy of entering air and the rate of kinetic energy of the exist gases and is called propulsive power. The propulsive power PP is given by

$$PP = \frac{m (V_j^2 - V_0^2)}{2} \text{ N.m/sec.} \quad \dots (5.3)$$

Propulsive efficiency is defined as the ratio of thrust power (TP) and propulsive power (PP) and is the measure of the effectiveness with which the kinetic energy imparted to the fluid is transformed or converted into useful work. Thus, propulsive efficiency η_p is given by

$$\eta_p = \frac{TP}{PP} = \frac{m (V_j - V_0) V_0}{1} \times \frac{2}{m (V_j^2 - V_0^2)}$$



$$\therefore \eta_p = \frac{2(V_j - V_o)V_o}{V_j^2 - V_o^2} = \frac{2V_o}{V_j + V_o} = \frac{2}{1 + \left(\frac{V_j}{V_o}\right)} \quad \dots (5.4)$$

From the expression of η_p it may be seen that the propulsion system approaches maximum efficiency as the velocity of the vehicle approaches the velocity of the exhaust gases. But as this occurs, the thrust and the thrust power approach zero. Thus, the ratio of velocities for maximum propulsive efficiency and for maximum power are not the same. Alternatively, the propulsive efficiency can be expressed as

$$\eta_p = \frac{TP}{PP} = \frac{TP}{TP + \text{K.E. losses}} \quad \dots (5.5)$$

Thermal efficiency of a propulsion is an indication of the degree of utilization of energy in fuel (heat supplied) in accelerating the fluid flow and is defined as the increase in the kinetic energy of the fluid (propulsive power) and the heat supplied. Thus,

$$\begin{aligned} \text{Thermal efficiency, } \eta_T &= \frac{\text{Propulsive power}}{\text{Heat supplied}} \\ &= \frac{\text{Propulsive power}}{\text{Fuel flow rate} \times \text{C.V. of fuel}} \quad \dots (5.6) \end{aligned}$$

The overall efficiency is the ratio of the thrust power and the heat supplied. Thus, overall efficiency is the product of propulsive efficiency and thermal efficiency. The propulsive and overall efficiencies of the turbojet engine are comparable to the mechanical efficiency and brake thermal efficiency respectively, of the reciprocating engine.

Problem – 1 : A jet propulsion unit, with turbojet engine, having a forward speed of 1,100 km/hr produces 14 kN of thrust and uses 40 kg of air per second. Find: (a) the relative exist jet velocity, (b) the thrust power, (c) the propulsive power, and (d) the propulsive efficiency.

$$(a) \text{ Forward speed, } V_o = \frac{1,100 \times 1,000}{3,600} = 305.55 \text{ m/sec.}$$

$$\text{Using eqn. (5.1), thrust, } T = m(V_j - V_o)$$

$$\text{i.e., } 14,000 = 40(V_j - 305.55)$$

$$\therefore V_j = \frac{14,000}{40} + 305.55 = 350 + 305.55 = 655.55 \text{ m/sec.}$$

$$\text{Thus relative exist jet velocity, } V_j = 655.55 \text{ m/sec.}$$

$$(b) \text{ Using eqn. (5.2)}$$

$$\text{Thrust power, } TP = T \times V_o$$

$$= 14,000 \times 305.55 = 42,77,700 \text{ N.m/sec. or } = 4,277.7 \text{ kN.m/sec.}$$

$$(c) \text{ Using eqn. (5.3),}$$

$$\text{Propulsive power, } PP = \frac{m(V_j^2 - V_o^2)}{2}$$

$$= \frac{40[(655.55)^2 - (305.55)^2]}{2}$$

$$= 6,727 \times 10^3 \text{ N.m/sec} = 6,727 \text{ KN.m/sec or } 6,727 \text{ kW}$$

$$(d) \text{ Using eqn. (5.4),}$$



is not effective and that there are pulsations created in the combustion chamber which affect the air flow in front of the diffuser.

Since the ram jet engine has no turbine, the temperature of the gases of combustion is not limited to a relatively low figure as in the turbojet engine. Air fuel ratios of around 15:1 are used. This produces exhaust temperatures in the range of 2000°C to 2200°C. Extensive research is being conducted on the development of hydrocarbon fuels that will give 30 percent more energy per unit volume than current aviation gasolines. Investigations are carried out to determine the possibility of using solid fuels in the ram jet and in the after burner of the turbojet engine. If powdered aluminium could be utilized as an aircraft fuel, it would deliver over 2.5 times as much heat per unit volume as aviation gasoline, while some other could deliver almost four times as much heat.

The temperature, pressure and velocity of the air during its passage through a ram jet engine at supersonic flight are shown in fig. 5-4.

The cycle for an ideal ram jet, which has an isentropic entrance diffuser and exit nozzle, is the Joule cycle as shown by the dotted lines in fig. 5-6. The difference between the actual and ideal jet is due principally to losses actually encountered in the flow system. The sources of these losses are :

- ... Wall friction and flow separation in the subsonic diffuser and shock in the supersonic diffuser.
- ... Obstruction of the air stream by the burners which introduces eddy currents and turbulence in the air stream.
- ... Turbulence and eddy currents introduced in the flow during burning.
- ... Wall friction in the exit nozzle.

By far, the most critical component of the ram jet is the diffuser. Due to the peculiarities of streamline flow, a diffuser which is extremely

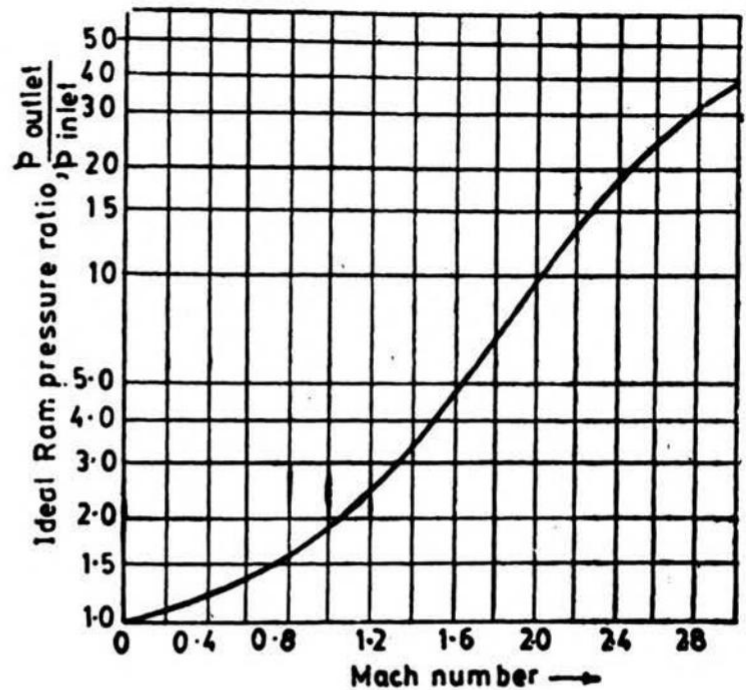


Fig. 5-5. Ram pressure ratio versus Mach number of vehicle for sea level condition.

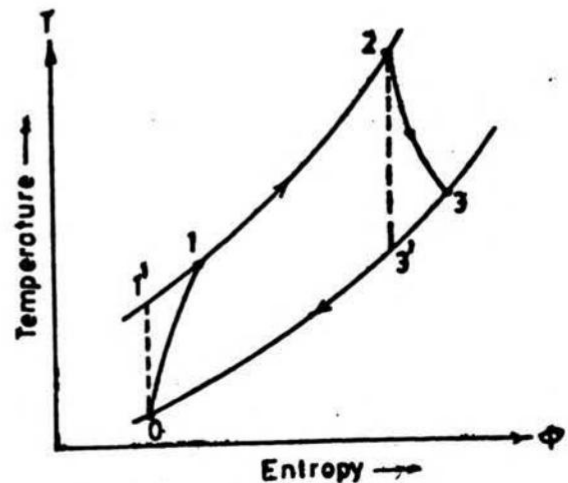


Fig. 5-6. $T - \phi$ diagram of Ram jet engine.



engine weight than any other propulsion engine at supersonic speed with the exception of the rocket engine. The thrust per unit frontal area increases both with the efficiency and the air flow through the engine; therefore much greater thrust per unit area is obtainable at high supersonic speeds. General performance of a ram jet engine in the subsonic range would have a specific fuel consumption between 0.6 to 0.8 kg fuel per N thrust – hr and a specific weight between 0.01 to 0.02 kg per N thrust. The supersonic ram jet engine has a specific fuel consumption between 0.25 to 0.04 and a specific weight between 0.01 to 0.04. Thus, the best performance of the ram jet engine is obtained at flights speeds of 1500 to 3500 km/hr.

5.5 Pulse Jet Engine

The pulse jet engine is somewhat similar to a ram jet engine. The difference is that a mechanical valve arrangement is used to prevent the hot gases of combustion from flowing out through the diffuser in the pulse jet engine.

Paul Schmidt patented principles of the pulse jet engine in 1930. It was developed by Germany during World-War-II, and was used as the power plant for "buzz bomb".

The turbojet and ram jet engines are continuous in operation and are based on the constant pressure heat addition (Bryton) cycle. The pulse jet is an intermittent combustion engine and it operates on a cycle similar to a reciprocating engine and may be better compared with an ideal Otto cycle rather than the Joule or Bryton cycle.

The compression of incoming air is accomplished in a diffuser. The air passes through the spring valves and is mixed with fuel from a fuel spray located behind the valves. A spark plug is used to initiate combustion but once the engine is operating normally, the spark is turned off and residual flame in the combustion chamber is used for ignition. The engine walls also may get hot enough to initiate combustion.

The mechanical valves which were forced open by the entering air, are forced shut when the combustion process raises the pressure within the engine above the pressure in the diffuser. As the combustion products cannot expand forward, they move to the rear at high velocity. The combustion products cannot expand forward, they move to the rear at high velocity. When the combustion products leave, the pressure in the combustion chamber drops and the high pressure air in the diffuser forces the valves open and fresh air enters the engine.

Since the products of combustion leave at a high velocity there is certain scavenging of the engine caused by the decrease in pressure occasioned by the exit gases. There is a stable cycle set up in which alternate waves of high and low pressure travel down the engine. The alternating cycles of combustion, exhaust, induction, combustion, etc. are related to the acoustical velocity at the temperature prevailing in the engine. Since the temperature varies continually, the actual process is complicated, but a workable assumption is that the tube is acting similar to a quarter wave length organ pipe. The series of pressure and rarefaction waves move down it at the speed of sound for an assumed average temperatures.

The frequency of the combustion cycle may be calculated from the following expression:

$$f = \frac{a}{4L} \text{ cycles/sec.} \quad \dots (5.7)$$

where, $a = \sqrt{\gamma RT}$ = sound velocity in the medium at temperature, T , and
 L = length of engine (from valves to exit).



efficient at a given speed may be quite inadequate at another velocity.

Because of the simplicity of the engine, the ram jet develops greater thrust per unit engine weight than any other propulsion engine at supersonic speed with the exception of the rocket engine. The thrust per unit frontal area increases both with the efficiency and the air flow through the engine; therefore much greater thrust per unit area is obtainable at high supersonic speeds. General performance of a ram jet engine in the subsonic range would have a specific fuel consumption between 0.6 to 0.8 kg fuel per N thrust - hr and a specific weight between 0.01 to 0.02 kg per N thrust. The supersonic ram jet engine has a specific fuel consumption between 0.25 to 0.04 and a specific weight between 0.01 to 0.04. Thus, the best performance of the ram jet engine is obtained at flights speeds of 1500 to 3500 km/hr.

5.5 Pulse Jet Engine

The pulse jet engine is somewhat similar to a ram jet engine. The difference is that a mechanical valve arrangement is used to prevent the hot gases of combustion from flowing out through the diffuser in the pulse jet engine.

Paul Schmidt patented principles of the pulse jet engine in 1930. It was developed by Germany during World-War-II, and was used as the power plant for "buzz bomb".

The turbojet and ram jet engines are continuous in operation and are based on the constant pressure heat addition (Bryton) cycle. The pulse jet is an intermittent combustion engine and it operates on a cycle similar to a reciprocating engine and may be better compared with an ideal Otto cycle rather than the Joule or Bryton cycle.

The compression of incoming air is accomplished in a diffuser. The air passes through the spring valves and is mixed with fuel from a fuel spray located behind the valves. A spark plug is used to initiate combustion but once the engine is operating normally, the spark is turned off and residual flame in the combustion chamber is used for ignition, line engine walls also may get hot enough to initiate combustion.

The mechanical valves which were forced open by the entering air, are forced shut when the combustion process raises the pressure within the engine above the pressure in the diffuser. As the combustion products cannot expand forward, they move to the rear at high velocity. The combustion products cannot expand forward, they move to the rear at high velocity. When the combustion products leave, the pressure in the combustion chamber drops and the high pressure air in the diffuser forces the valves open and fresh air enters the engine.

Since the products of combustion leave at a high velocity there is certain scavenging of the engine caused by the decrease in pressure occasioned by the exit gases. There is a stable cycle set up in which alternate waves of high and low pressure travel down the engine. The alternating cycles of combustion, exhaust, induction, combustion, etc. are related to the acoustical velocity at the temperature prevailing in the engine. Since the temperature varies continually, the actual process is complicated, but a workable assumption is that the tube is acting similar to a quarter wave length organ pipe. The series of pressure and rarefaction waves move down it at the speed of sound for an assumed average temperatures.

The frequency of the combustion cycle may be calculated from the following expression:

$$n = \frac{4L}{a} \text{ cycles/sec}$$

where, $a = \sqrt{\gamma R T}$ = sound velocity in the medium at temperature, T , and

L = length of engine (from valves to exit).



A serious limitation placed upon pulse jet engine is the mechanical valve arrangement. Unfortunately, the valves used have resonant frequencies of their own, and under certain conditions, the valve will be forced into resonant vibration and will be operating when they should be shutting. This limitation of valves also limits the engine because the gas goes out of the diffuser when it should go out of the tail pipe.

Despite the apparent noise and the valve limitation, pulse jet engines have several *advantages* when compared to other thermal jet engines.

- . . The pulse jet is very inexpensive when compared to a turbojet.
- . . The pulse jet produces static thrust and produces thrust in excess of drag at much lower speed than a ram jet.
- . . The potential of the pulse jet is quite considerable and its development and research may well bring about a wide range of application.

5.6 Rocket Motors

The jet propulsion action of the rocket has been recognised for long. Since the early beginning, the use of rockets has been in war time as a weapon and in peace time as a signaling or pyrotechnic displays. Although, the rocket was employed only to an insignificant extent in World War-I, marked advances were made by the research that was undertaken at that time. In World War-II, the rocket became a major offensive weapon employed by all warring powers. Rockets and rocket powered weapons have advanced to a point where they are used effectively in military operations.

Rocket type engine differs from the atmospheric jet engine in that the entire mass of the jet is generated from the propellant carried within the engine i.e. the rocket motor carries both the fuel and the oxidizing agent. As a result, this type of engine is independent of the atmospheric air that other thermal jet engines must rely upon. From this point of view rocket motors are most attractive. There are, however, other operational features that make rocket less useful. Here, the fundamentals of rocket motor theory and its applications are discussed.

Rocket engines are classified as to the type of propellant used in them. Accordingly, there are two major groups:

One type belonging to the group that utilizes liquid type propellants and other group that uses solid type propellants.

The basic theory governing the operation of rocket motor is applied, equally to both the liquid and the solid propellant rocket.

Rocket propulsion, at this time, would not be regarded as a competitor of existing means for propelling airplanes, but as a source of power for reaching objectives unattainable by other methods. The rocket motors are under active development programmes for an increasing number of applications. Some of these *applications* are :

- Artillery barrage rockets,
- Anti-tank rockets,
- All types of guided missiles, \
- Aircraft launched rockets,
- Jets assisted take-off for airplanes,
- Engines for long range, high speed guided missiles and pilotless aircrafts, and
- Main and auxiliary propulsion engines on transonic airplanes.

It will be repeated again that the rocket engine differs from the other jet propulsion engines in that the entire mass of the gases in the jet is generated from the propellants



JET PROPULSION ENGINES

carried within the engine. Therefore, it is not dependent on the atmospheric air to furnish the oxygen for combustion. However, since the rocket carries its own oxidiser, the propellant consumption is very high.

The particular advantages of the rocket are :

- .. Its thrust is practically independent of its environments.
- .. It requires no atmospheric oxygen for its operation.
- .. It can function even in a vacuum.
- .. It appear to be the simplest means for converting the thermochemical energy of a propellant combination (fuel plus oxidizer) into kinetic energy associated with a jet flow gases.

Despite its apparent simplicity, the development of a reliable rocket system must be light in weight and the rocket motor must be capable of sustained operation in contact with gases at temperature above 2800°C and at appreciable pressures. The problem of materials is consequently a major one. Furthermore, owing to the enormous energy releases involved, problem of ignition, smooth start up, thrust control, cooling etc. arise.

A major problem of development of rocket is selection of suitable propellant to give maximum energy per premium total weight (propellant plus containing vessels) and convenience factors such as a safety in handling, dependability, corrosive tendencies, cost, availability and storage problems. In general, it can be stated that there is a wide variety of fuels that are satisfactory for rocket purpose, but choice of oxidizers is at present distinctly limited.

5.6.1 Basic Theory : Figure 5-7 shows a schematic diagram of a liquid bi-propellant rocket engine. It consists of an injection system, a combustion chamber, and an exit nozzle. The oxidizer and fuel burnt, in the combustion chamber produces a high pressure. The pressure produced is governed by

- Mass rate of flow of the propellants,
- Chemicals characteristics of the propellants, and
- Cross-section area of the nozzle throat.

The gases are ejected to the atmosphere at supersonic speeds through the nozzle. The enthalpy of high pressure gases is converted into kinetic energy. The reaction to the ejection of the high velocity, produces the thrust on the rocket engine.

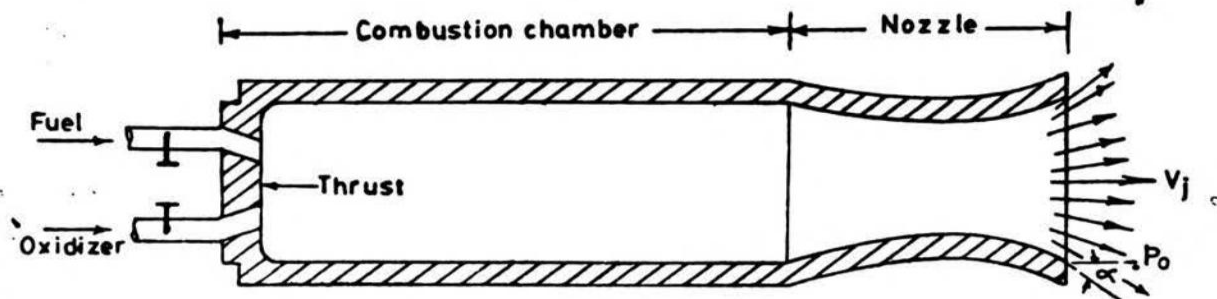


Fig. 5-7. Schematic diagram of a liquid bi-propellant uncooled rocket motor.

The *thrust* developed is a resultant of the pressure forces acting upon the inner and the outer surface of the rocket engine. The resultant internal force acting on the engine is given by

$$\text{Resultant force} = m_p V_j + p_j A_j N$$



where, m_p = Mass rate of propellant consumption, kg/sec,

V_j = Jet velocity relative to nozzle, m/sec,

V_{xj} = Average value of the x-component of the velocity of gases crossing, A_j ,

p_j = Exist static pressure, N/m², and

A_j = Exit area of nozzle, m².

The resultant external forces acting on the rocket engine are $p_o A_o$, where p_o is the atmospheric pressure in N/m². The thrust which is a resultant of the total pressure forces becomes

$$T = m_p V_{xj} + A_j (p_j - p_o) N \quad \dots (5.8)$$

Let V_j = the exit velocity of the rocket gases, assumed constant and

let $V_{xj} = \lambda V_j$. Then, eqn. (5.8) becomes

$$T = \lambda m_p V_j + A_j (p_j - p_o) N \quad \dots (5.9)$$

The coefficient λ is the correction factor for the divergence angle α of the exit conical section of the nozzle. λ is given by

$$\lambda = \frac{1 - \cos 2\alpha}{4(1 - \cos \alpha)} = \frac{1}{2}(1 + \cos \alpha) \quad \dots (5.10)$$

Equation (5.8) shows that thrust of a rocket engine increases as the atmospheric pressure decreases. Therefore, maximum thrust will be obtained when $P_o = 0$, i.e., *rocket engine produces maximum thrust when operating in a vacuum.*

In testing a rocket engine, thrust and propellant consumption for a given time are readily measured. It is convenient then, to express the thrust in terms of the mass rate of flow of propellant and an effective jet velocity, V_{ej}

$$\text{i.e., Thrust, } T = m_p \times V_{ej} \quad \dots (5.11)$$

The *effective jet exit velocity* is a hypothetical velocity and for convenience in test work it is defined from eqns. (5.9) and (5.11) as under :

$$V_{ej} = \lambda V_j + \frac{A_j}{m_p} (p_j - p_o) \text{ m/sec.} \quad \dots (5.12)$$

The effective jet exit velocity has become an important parameter in rocket motor performance.

The *thrust power*, TP developed by a rocket motor is defined as the thrust multiplied by the flight velocity, V_o .

$$TP = T V_o = m_p \cdot V_{ej} \cdot V_o \text{ N.m/sec.} \quad \dots (5.13)$$

The *propulsive efficiency*, η_p is the ratio of the thrust power to propulsive power supplied. The propulsive power is the thrust power plus the kinetic energy lost in the exhaust,

$$\text{i.e., K.E. Loss} = \frac{1}{2} m_p (V_{ej} - V_o)^2 \text{ N.m/sec.}$$

Therefore, the propulsive efficiency may be expressed as

$$\eta_p = \frac{TP}{TP + \text{K.E. Loss}} = \frac{m_p V_{ej} V_o}{m_p V_{ej} V_o + \frac{1}{2} m_p (V_{ej} - V_o)^2}$$



$$\therefore \eta_p = \frac{2(V_o/V_{ej})}{1 + (V_o/V_{ej})^2} \quad \dots (5.14)$$

Specific Impulse, I_{sp} has become an important parameter in rocket motor performance and is defined as the thrust produced per unit mass rate of propellant consumption.

$$I_{sp} = \frac{T}{\dot{m}_p} = \frac{\dot{m}_p \cdot V_{ej}}{\dot{m}_p} = V_{ej} \quad \dots (5.15)$$

Specific impulse, with the units, Newtons of thrust produced per kg of propellant burned per second, gives a direct comparison as to the effectiveness among propellants. It is desirable to use propellants with the greatest possible specific impulse, since, this allows a greater useful load to be carried for a given overall rocket weight.

5.6.2. Types of Rocket Motors : The propellant employed in a rocket motor may be a solid, two liquids (fuel plus oxidizer), or materials containing an adequate supply of available oxygen in their chemical composition (monopropellant). Solid propellants are used for rockets which are to operate for relatively short periods, upto possibly 45 seconds. Their main application is to projectiles, guided missiles, and the assisted take-off aircraft.

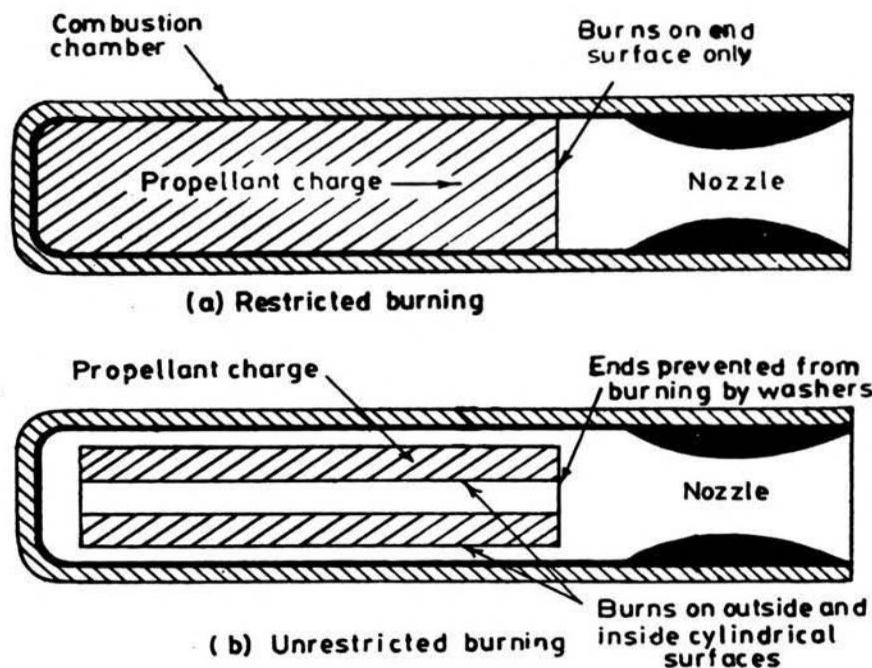


Fig. 5-8 Schematic diagram of a solid propellant rocket. ..

Solid propellant rockets (fig. 5-8) have been of two basic types :

- .. Unrestricted burning types for projectiles and launching rockets; and
- .. Restricted burning types for assisted take-off of aircraft and for propelling missiles.

In the unrestricted burning rocket [fig. 5-8(a)] all surfaces of the propellant grain except the ends are ignited; in restricted burning rockets [fig. 5-8(b)] only one surface of the propellant is permitted to burn. Liquid propellant rockets utilize liquid propellants which are stored in the containers outside the combustion chamber. The basic theory of operation of this type of rocket is same as that for solid propellant rocket. Liquid propellant rockets were developed in order to overcome some of the undesirable features of the

which ar



solid propellant rockets such as short duration of thrust, and no provisions for adequate cooling or control of the burning after combustion starts. Here, the propellant in the liquid

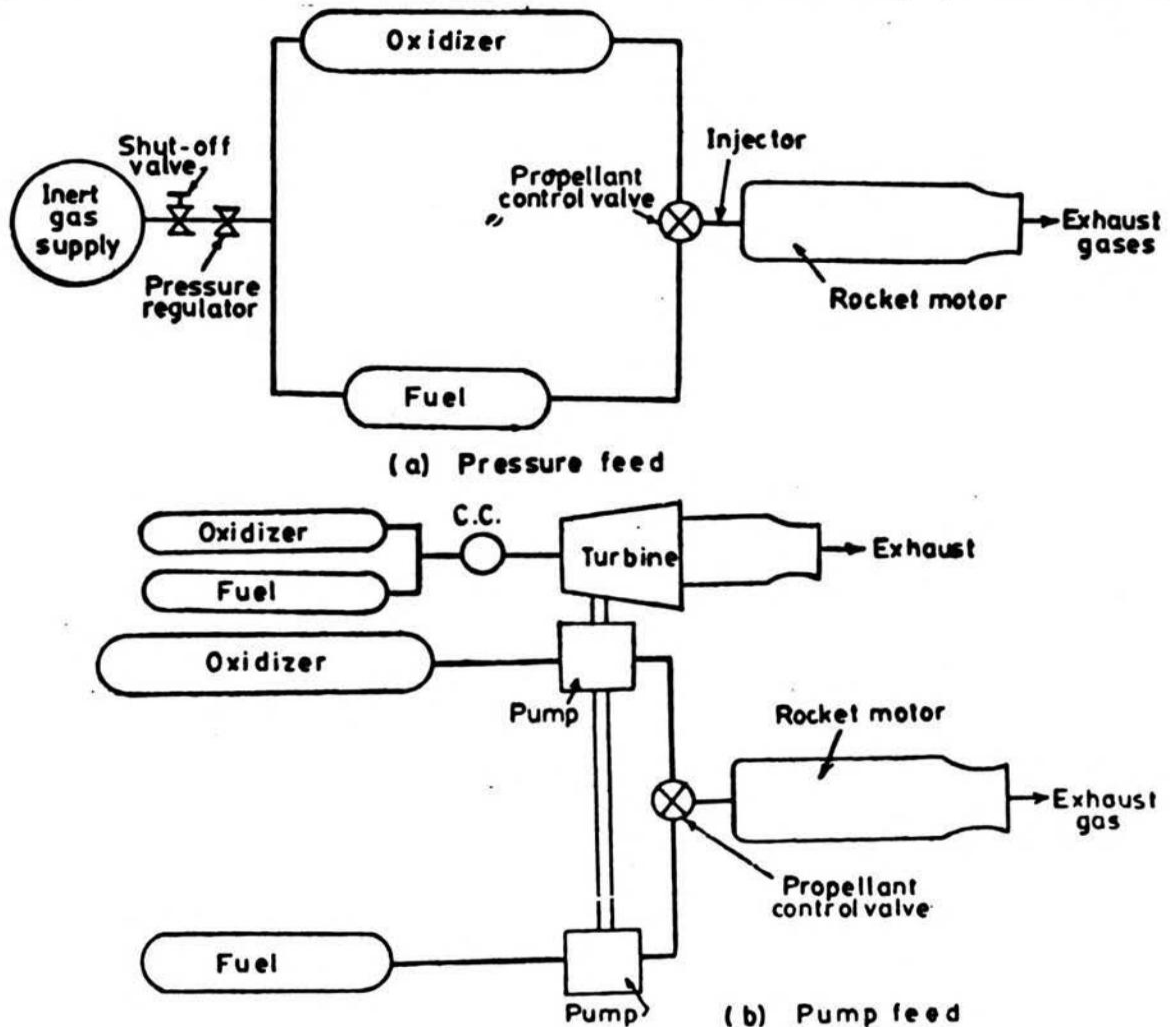


Fig. 5-9. Schematic diagrams of bi-propellant rocket system.

state is injected into a combustion chamber, burned and exhausted at a high velocity through the nozzle. The liquid propellant is also used to cool the rocket motor by circulation of fuels around the walls of the combustion chamber and around the nozzle. Certain liquid fuel, however, such as hydrogen peroxide, burn at such temperatures that no cooling is necessary. Figure 5-9 shows schematic diagrams of pressure feed and pump feed liquid bipropellant rocket systems.

Problem-2 : The effective exit jet velocity of a rocket is 3000 m/sec, the forward flight velocity is 1500 m/sec and the propellant consumption is 70 kg per sec. Calculate : (a) Thrust, (b) Thrust power, (c) Specific impulse, (d) Specific propellant consumption, and (e) Propulsive efficiency of the rocket.

(a) Using eqn. (5.11),

$$\text{Thrust, } T = m_p \times V_{ej} = 70 \times 3,000 = 2,10,000 \text{ N or } 210 \text{ kN}$$

(b) Using eqn. (5.13),

$$\text{Thrust power, } TP = T V_o = 2,10,000 \times 1,500 = 315 \times 10^6 \text{ N.m/s}$$



JET PROPULSION ENGINES

(c) Using eqn. (5.14),

$$\text{Specific impulse, } I_{sp} = \frac{T}{m_p} = \frac{m_p \cdot V_{ej}}{m_p} = V_{ej} = 3,000 \text{ N.s/kg}$$

$$\begin{aligned} \text{(d) Specific propellant consumption} &= \frac{m_p}{T} = \frac{m_p}{m_p V_{ej}} = \frac{1}{V_{ej}} = \frac{1}{3,000} \\ &= 3.3 \times 10^{-4} \text{ kg/N.s} \end{aligned}$$

(e) Using eqn. (5.14),

$$\begin{aligned} \text{Propulsive efficiency, } \eta_p &= \frac{2(V_o/V_{ej})}{1 + (V_o/V_{ej})^2} \\ &= \frac{2(1500/3000)}{1 + (1500/3000)^2} = 0.8 \text{ i.e., } 80\% \end{aligned}$$

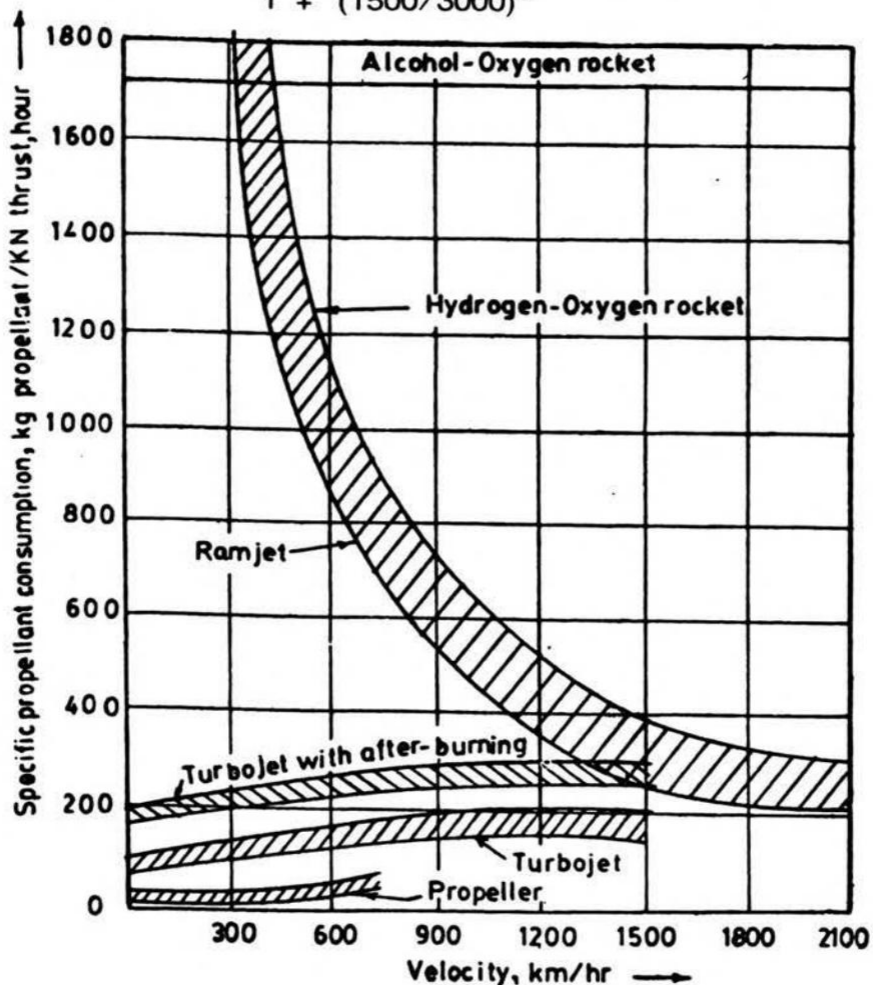


Fig. 5-10. Propellant or fuel consumption versus flight speed for different propulsion systems.

5.7 Comparison of the Various Propulsion Systems

Figure 5-10 shows the specific propellant consumption in kg per kN thrust versus speed for different engines. The curves in this figure indicate that the use of rocket



engines to power air planes, as we know them today, is not feasible because of their high fuel consumption. Also, the use of ram jet engines is not economical at lower than 1500 km/hr vehicle speeds.

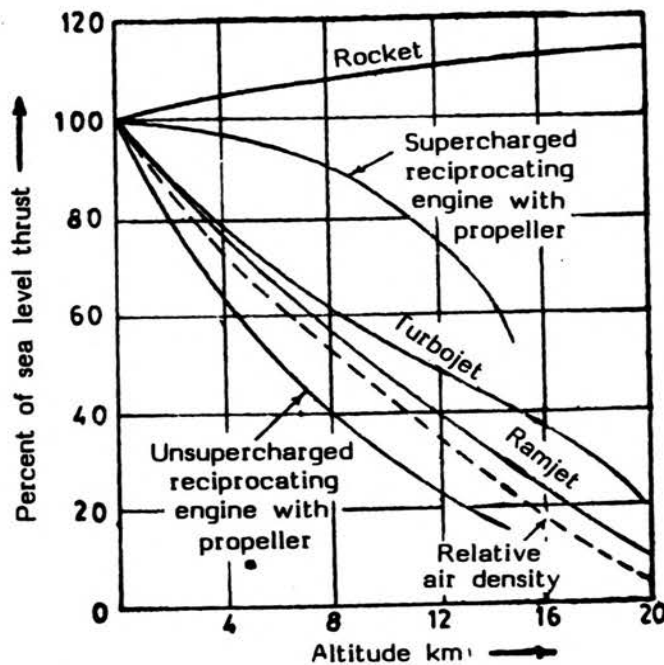


Figure 5-11 shows variation of thrust with altitude for different propulsion systems. It may be noted that the thrust of rocket motor increases with altitude while the thrust of other types of vehicles decreases with altitude.

Fig. 5-11 Variation of thrust with altitude for different propulsion systems.

Figure 5-12 gives relative picture of the probable operating envelope of the various propulsion systems.

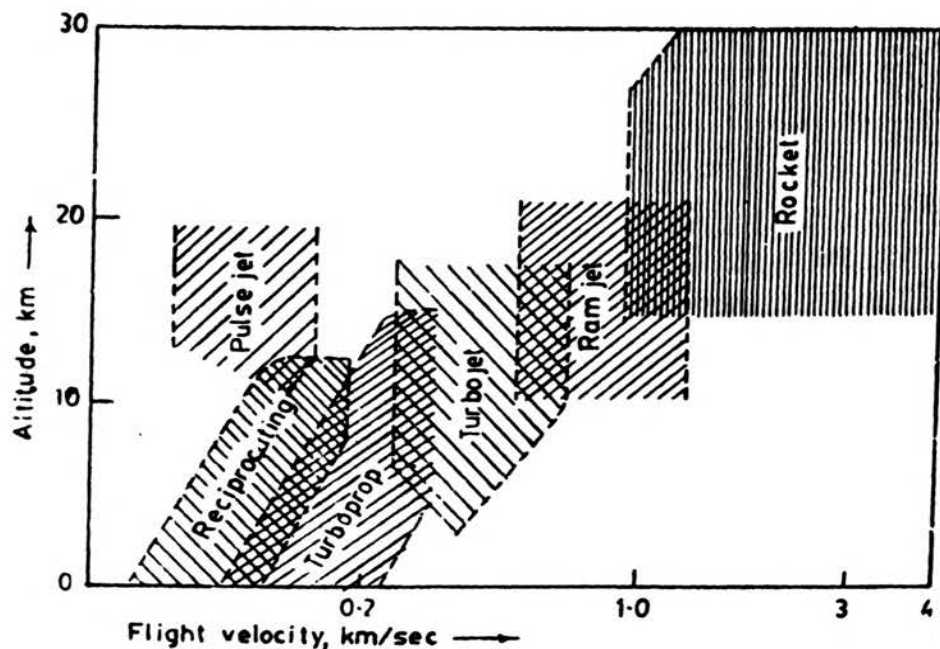


Fig. 5-12 Comparison of probable best performance for various propulsion engines.





INDUSTRIAL APPLICATIONS



INDUSTRIAL APPLICATIONS

- IN AIRCRAFT- Fighter plane, Missiles, Rocket, Airplane.
- Jet propulsion, land and sea transport, racing car.
- The first use of the jet engine was to power military aircraft.
- The General electric company used a “turboprop” jet engine to run an electric generator.
- The jet engine is not only used on aircraft but on boats, where water jets are used to propel the boat forward.
- Normal type of jet engine is used for domestic purpose i.e. Traveling, carrying goods etc.

An aircraft using this type of jet engine could dramatically reduce the time which it takes to travel from one place to another, potentially putting any place on Earth within a 90-minute flight.

Scramjet vehicle has been proposed for a single stage to tether vehicle, where a Mach 12 spinning orbital tether would pick up a payload from a vehicle at around 100 km and carry it to orbit

Rocket applications

1. Satellites in space serve air communication
2. Spacecraft
3. Missiles
4. Jet assisted air planes
5. Pilotless aircraft





TUTORIAL QUESTIONS



Theory Questions:

1. What are the different rocket propulsion systems? Brief the working differences between the propeller-jet, turbojet and turbo-prop.
2. With a neat diagram explain the working of rocket engine
3. Describe briefly about thrust augmentation method used in propulsion.
4. With a neat sketch, explain the working of turbo jet engine.
5. Differentiate between solid propellant and liquid propellant rocket engines.
6. What are the applications of pulse jet engines
7. Give the difference between ramjet and pulse jet engines
8. What are composite and homogeneous solid propellants? How do they work? State their merits and demerits.
9. What is the essential difference between rocket propulsion and turbo-jet propulsion?
10. Write a detailed classification of rockets. Explain liquid propellant rocket with a neat sketch Define and explain the terms:
 - i. Thrust
 - ii. Thrust power,
 - iii. Effective jet exit velocity,
 - iv. Propulsive efficiency related to turbojet engines.
11. What are the various applications of rockets?
12. Explain the advantages and disadvantages of bipropellants used in rocket engines over monopropellants.
2. Derive expressions for the thrust and propulsion efficiency of rockets and compare with those of turbojet

Numerical Problems:

1. A jet propulsion system has to create a thrust of 100 tones to move the system at a velocity of 700 km/hr. If the gas flow rate through the system is restricted to a maximum of 30 kg/s. find the exit gas velocity and propulsive efficiency.



2. In a jet propulsion unit, initial pressure and temperature to the compressor are 1.0 bar and 100C. The speed of the unit is 200m/s. The pressure and temperature of the gases before entering the turbine are 7500 C and 3 bar. Isentropic efficiencies of compressor and turbine are 85% and 80%. The static back pressure of the nozzle is 0.5 bar and efficiency of the nozzle is 90%. Determine (a) Power consumed by compressor per kg of air. (b) Air-fuel ratio if calorific value of fuel is 35,000 kJ/kg. C_p of gases = 1.12 kJ/kg K, $\gamma = 1.32$ for gases.
3. A turbo-jet engine flying at a speed of 960 km/h consumes air at the rate of 54.5 kg/s. calculate i). Exit velocity of the jet when the enthalpy change for the nozzle is 200 KJ/kg and velocity coefficient is 0.97. ii). fuel flow rate in kg/s when air fuel ratio is 75:1 iii). Thrust specific fuel consumption iv). Propulsive power v). Propulsive efficiency.
4. A simple turbine jet unit was tested when stationary and the ambient conditions were 1bar and 150C. The pressure ratio for the compressor was 4:1. A fuel consumption of 0.37kg/s was obtained for an air flow of 23kg/s. Calculate the thrust produced if the exhaust gases from the turbine were expanded to atmospheric pressure in a convergent nozzle. Assume the following data:
 Isentropic efficiency of compressor-80% Isentropic efficiency of turbine-85%
 Efficiency of nozzle-93% Transmission efficiency-98%
 Calorific value of fuel-42000kJ/kg Assuming working fluid to be air throughout.
5. In a turbojet, air is compressed in an axial compressor at inlet conditions of 1 bar and 1000C
 3.5 bar. The final temperature is 1.25 times that for isentropic compression. The temperature of gases at inlet to turbine is 4800C. The exhaust gases from turbine are expanded in a velocity of approach is negligible and expansion may be taken to be isentropic in both turbine and nozzle. Value of gas constant R and index γ are same for air and flue gases.
 Determine
 i) Power required to drive the compressor per kg of air/sec
 ii) Air-fuel ratio if the calorific value of fuel is 42,000 kJ/kg
 iii) Thrust developed / kg of air / sec.





ASSIGNMENT QUESTIONS



ASSIGNMENT QUESTIONS

1. Why is thrust augmentation necessary? What are the methods for thrust augmentation in a turbojet engine?
2. A turbo-jet engine flying at a speed of 960 km/h consumes air at the rate of 54.5 kg/s. calculate i). Exit velocity of the jet when the enthalpy change for the nozzle is 200 KJ/kg and velocity coefficient is 0.97. ii). fuel flow rate in kg/s when air fuel ratio is 75:1 iii). Thrust specific fuel consumption iv). Propulsive power v). Propulsive efficiency.
3. With a neat diagram explain the working of rocket engine
4. What is turbine and classify them?

