CHAPTER 3

Classification of Propulsion Systems

3. 1. INTRODUCTION

Propulsion systems are those that are required to propel the vehicles to which they are attached. By this definition, propulsion systems are many and varied, starting from our muscles using which we propel ourselves in walking, running, swimming, and so on. In engineering, let us first consider the classical reciprocating engines, which can be the steam based external-combustion piston-engines or the petroleum-fuel based internal-combustion piston-engines. The steam engines propel locomotives and ships while the internal combustion piston engines propel automobiles, ships, locomotives, and small low-speed aircraft. The propulsion principle by which the reciprocating engines propel locomotives and automobiles is different from the one in ships and low-speed aircraft. In the former, the wheels, powered by the engine, attempt to push the road or the rails through friction. By the reactive force (Newton's Third Law) the vehicles to which the wheels are attached are pushed in the opposite direction or propelled. In the case of ships and low-speed aircraft, the propellers draw in and push (accelerate) the fluid stream (water in the case of ships and air in the case of aircraft) to a velocity greater than the vehicle-velocity; that is, the momentum rate of the fluid at exit ($\dot{m}_e u_e$) is greater than the momentum rate at entry ($\dot{m}_a u$) to the propellers. Here again, by the reactive force the vehicles are pushed or propelled.

This acceleration of fluid stream is also the means for high-speed propulsion that we find in high-speed aircraft, and rockets and spacecraft. But the high-speed propulsion systems employ nozzles to accelerate the fluid streams and these systems are known as jet propulsion systems. The nozzle accelerates and ejects the fluid stream due to the pressure difference across the nozzle's entry and exit. While propellers accelerate "open" streams, nozzles accelerate the "enclosed" streams and eject them as jets. Be it propellers or nozzles, the thrust is produced essentially due the difference in the momentum rates at the entry and the exit of the propulsion systems. In the case of propeller we have to consider the momentum rates ($\dot{m}u$) at the propeller's entry and exit. But in the case of jet propulsion systems, we have to consider the momentum rates at the entry and the exit of the jet propulsion engine. We consider in detail the derivation of the thrust equation in Chapter 4. Here, neglecting for simplicity the pressure forces, we can write the thrust as equal to the difference in the momentum rates at the exit and the entry.

$$T = \dot{m}_e u_e - \dot{m}_a u \tag{3.1}$$

where $\dot{m}_a$ is the mass flow rate of atmospheric air entering the engine with the flight velocity u and $\dot{m}_e$ is the mass flow rate of combustion gases exiting the nozzle with the velocity u_e.

The jet propulsion systems can be broadly classified into two types:

(1) **air-breathing jet propulsion** systems and

(2) **non-air-breathing jet propulsion** systems or **rocket propulsion** systems.

The subject matter of this book is rocket propulsion systems. However, for the sake of completeness and continuity, let us consider briefly the classification of air-breathing propulsion systems.

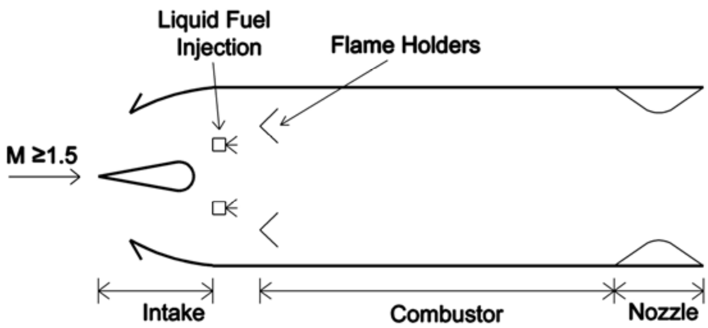

Fig. 3. 1. Schematic sketch of ramjet.

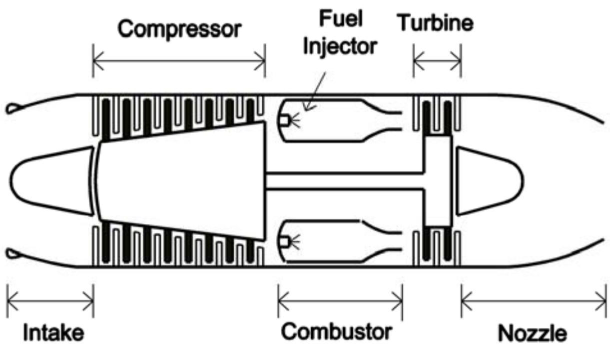

Fig. 3. 2. Basic gas turbine propulsion system, turbojet.

3. 2. CLASSIFICATION OF AIR-BREATHING PROPULSION SYSTEMS

As its name implies, the air-breathing propulsion system breathes (inducts) air from the earth's atmosphere. For the easiness of comparison, let us consider simultaneously the two principal air-breathing propulsion systems. The first one is the **ramjet** and the other is the basic propulsion system using a gas turbine, Figs 3.1 and 3.2. Ramjets propel supersonic missiles. **Gas turbine propulsion** systems propel subsonic and supersonic aircraft. Images of Thor ramjet that powered Bloodhound Missile of United Kingdom are shown in Figs. 3.3 and 3.4. Image of a basic gas turbine propulsion system (turbojet) is shown in Fig. 3.5.

In the ramjet as well as the gas turbine propulsion system, air is inducted at a momentum rate corresponding to the flight velocity. The oxidant required for combustion is the oxygen in air. The inducted air is decelerated (gasdynamically compressed) in the intake (or diffuser). This results in the increase in the static pressure and static temperature of the air-stream with certain losses in total pressure due to surface friction, Figs. 3. 1 and 3. 2. The process is essentially adiabatic. Ramjets mostly power vehicles flying at supersonic speeds. In Fig. 3. 1, therefore, the ramjet intake lip and centre body tip are sketched sharp to negotiate the resulting shock front. The sketch of the turbojet shown in Fig. 3. 2 is intended to fly at subsonic speeds, and hence the intake lip and the center body front are shown rounded. This sketching procedure is followed also for other types of engines.

In the gas turbine propulsion system, the decelerated air is further mechanically compressed by a compressor that results in the increase in the total pressure and total temperature, Fig. 3. 2. The compression process is essentially adiabatic.

In the ramjet as well as gas turbine propulsion system, the liquid fuel, generally kerosene, is injected into the compressed air and burned in the combustion chamber to result in the increase in total temperature and a small loss in the total pressure due to mass addition, friction, and heat addition, Figs. 3. 1 and 3. 2.

Fig. 3. 3. Thor ramjet of Bristol Aero Engines, United Kingdom (http://en.wikipedia.org).

Fig. 3. 4. Bloodhound missile fitted with Thor ramjets, RAF Museum, London (http://en.wikipedia.org).

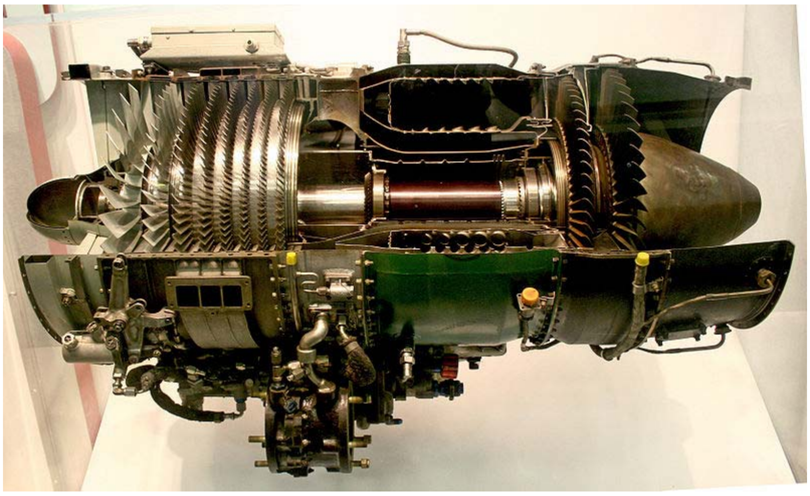

Fig. 3. 5. J85-CE-17A General Electric turbojet engine (http://en.wikipedia.org).

As the gas turbine propulsion system employs a compressor, Fig. 3. 2, the high pressure and high temperature combustion products are mechanically expanded through a turbine that results in the reduction in total pressure and total temperature. The expansion process is essentially adiabatic. The turbine power is used to run the compressor. There is no mechanical compression in ramjet and hence there is no need for the turbine, Fig. 3. 1.

In the ramjet as well as gas turbine propulsion system, the high pressure and high temperature combustion products are gasdynamically expanded in a nozzle to accelerate the stream of the combustion products to a momentum rate that is substantially greater than the inducted value, Figs. 3. 1 and 3. 2. The nozzle expansion results in the decrease in the static pressure and static temperature with certain loss in total pressure due to friction. The nozzle expansion is essentially adiabatic.

As the average Mach number of the fluid through the compressor, combustion chamber, and turbine is low around 0.3 to 0.4, the differences between the total and static values of pressure and temperature are low, around or less than 3% between the total and static temperatures and 12% between the total and static pressures. Note, however, that the differences between the total and static values are substantial in the intake and the nozzle.

We have previously discussed simultaneously two principal air-breathing propulsion systems, ramjet and gas turbine propulsion system. The ramjet has only the gasdynamic compression and expansion, Fig. 3. 1. The gas turbine propulsion system, on the other hand, has gasdynamic and mechanical compression and expansion, Fig. 3. 2. Although we have discussed the differences between the two principal types of airbreathing propulsion systems, it is interesting to note that that the ramjet is a particular case of the gas turbine propulsion system. Without the mechanical compression and expansion — without the compressor and the turbine — the gas turbine propulsion system simplifies into the ramjet. Furthermore, we note that essentially due to the positive difference between the exiting and inducted momentum-rates in the airbreathing propulsion systems, the thrust is produced to propel the vehicle, Eq. (3. 1).

In view of the point that ramjet is only a particular case of gas turbine propulsion system, let us consider the gas turbine propulsion system as a general case of the airbreathing propulsion. The fluid that passes through the propulsion system changes in composition and mass flow rate as per the following.

(1) The low temperature air enters the intake, gets decelerated in the intake, and further compressed in the compressor. The composition of air in this can change due to the increase in pressure and temperature.

(2) Fuel is injected in the combustion chamber and the fuel-air mixture is of composition and mass flow rate different from that of the air through the intake and compressor.

(3) High temperature products of combustion are formed in the combustion chamber and these are of composition different from that of the fuel-air mixture.

(4) High temperature combustion products are expanded through the turbine. Because the pressure and temperature drop across the turbine, the composition of the gas can change from the one at the turbine entry to that at its exit.

(5) Because of the reduction in static temperature and pressure from the nozzle inlet to the exit, the composition of the combustion products at the exit can be different from that at the nozzle inlet.

In spite of the previously discussed realities, for the purpose of idealization, we can assume (1) the composition and the mass flow rate of the fluid stream to be invariant, (2) the processes of compressions and expansions to be isentropic, (3) the fuel addition and the combustion to be at constant pressure, (4) compared to the mass flow rate of air, the fuel mass flow rate to be negligible, (5) the differences between the total and static pressures and between the total and static temperatures to be negligible from the outlet of the intake to the inlet of the nozzle, and (6) the nozzle-exit static pressure to be equal to the atmospheric pressure. Under these idealized conditions the processes can be represented by those in the Brayton or Joule cycle, Fig. 3. 6.

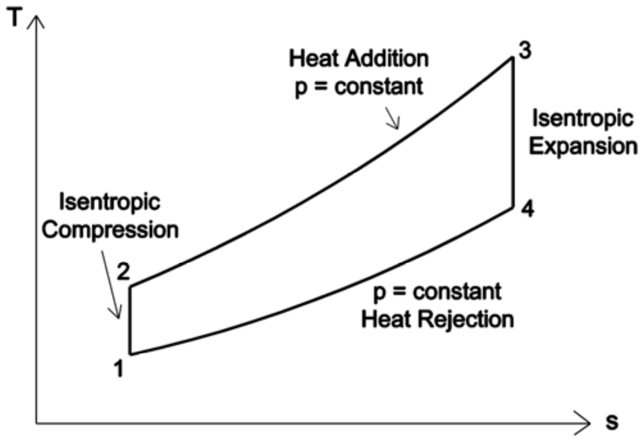

Fig. 3. 6. Brayton or Joule cycle.

With respect to the Brayton cycle (Fig. 3. 6), the process 1 to 2 is the isentropic compression in the intake of a ramjet propulsion-system, or that in the intake and the compressor of a gas turbine propulsion-system. The process 2 to 3 is the fuel addition and combustion at constant pressure. The process 3 to 4 is the isentropic expansion in the nozzle of a ramjet propulsion system or that in the turbine and the nozzle of a gas turbine propulsion-system. The process 4 to 1 is the cooling of the ejected combustion products in the outside atmosphere at constant pressure.

Ramjet

Because there is no moving component within the system, the ramjet is the simplest of all air breathing propulsion systems. The ramjet can be of different types. Based on the fuel type, it is classified as **liquid-fuel ramjet** (Fig. 3.1) and **solid-fuel ramjet**, Fig. 3.7. And, based on the type of combustion, it can be the **subsonic-combustion ramjet** or the supersonic-combustion ramjet or **scramjet**. The previously discussed ramjets (Figs. 3.1 and 3.7) are subsonic combustion ramjets since combustion in these takes place under subsonic condition. Considering now the scramjet, the inducted air at hypersonic speeds in its intake (Mach number greater than around 6) gets decelerated to a supersonic value (Mach number around 2 or less), Fig.

3. 8. Combustion takes place under supersonic condition. Thereafter, the combustion products expand in the nozzle to hypersonic velocities. The scramjet is the simplest system that is most suitable for powered hypersonic-flights within the earth's atmosphere and hence it is actively being developed.

Although the ramjet is the simplest of all the air-breathing propulsion systems, it suffers from a major disadvantage of its inability to produce thrust under static condition and hence its vehicle cannot takeoff from zero speed. The ramjet works on the principle of utilizing the kinetic energy contained in the in-flight-inducted air. Through gasdynamic compression, the kinetic energy of the inducted air is reduced to increase the static pressure of the air. This compressed air after combustion is expanded through the nozzle to produce thrust. When the ramjet is not in flight it cannot induct air on its own and hence it cannot produce a thrust.

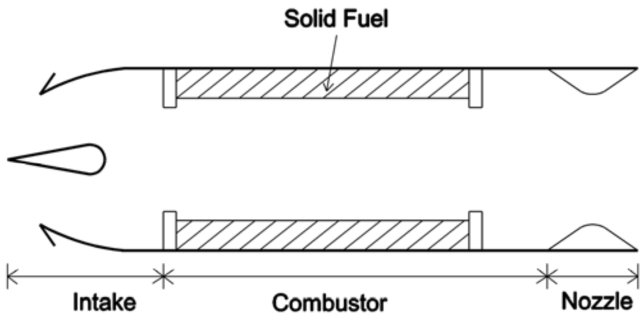

Fig. 3. 7. Schematic sketch of solid fuel ramjet.

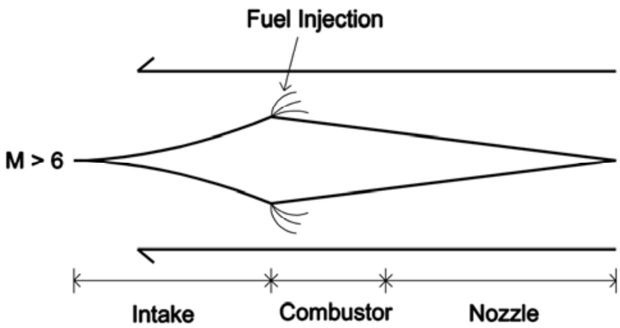

Fig. 3. 8. Schematic sketch of scramjet engine.

The quality of ramjet performance depends on the quantity of the specific kinetic-energy in the inducted air. To have an acceptable performance parameter, say an acceptable thrust per unit mass flow rate of inducted air — this represents the size of an airbreathing propulsion system for a specified thrust — or an acceptable fuel consumption per unit thrust representing the fuel economy, there are lower and upper limits on flight velocities.

Let us consider the subsonic combustion ramjet and first look at the lower velocity limit for flight. There is a minimum flight velocity and correspondingly a minimum kinetic energy that will overcome the internal drag due to various total-pressure losses in the intake, combustion chamber, and nozzle and still have sufficient total pressure for expansion in the nozzle to produce a positive thrust. This condition of producing a positive thrust starts around a flight Mach number of 0.9. For the application of powered flight, this positive internal thrust should be sufficiently higher than the external drag due to the flow over the external surfaces of the vehicle including that of the propulsion system. Therefore, on the point of view of acceptable performance parameters, the minimum flight Mach number for the ramjet is around 1.5.

Let us now look at the upper limit on flight velocity for the subsonic combustion ramjet. The total temperature of the inducted air increases as one increases the flight velocity. We have seen earlier that there is not much of a difference between total and static values from the intake outlet to the nozzle inlet. As we do not have materials to withstand temperatures beyond certain limit, there is an upper limit on the maximum allowable temperature in the combustion chamber. With the increase in the flight velocity, the gap between the total temperature of the inducted air and the maximum allowable temperature reduces. This gap truly represents the quantity of fuel that can be injected into the combustion chamber to produce positive thrust. The reduction in fuel addition means the reduction in thrust. This, beyond certain flight Mach number, leads to a condition of uneconomical fuel-consumption and then unacceptably low thrust per unit mass flow rate of air. For a subsonic combustion ramjet this upper limit appears around a flight Mach number of 5.

Gas Turbine Propulsion System

The gas turbine propulsion system, unlike the ramjet propulsion system, is a complex one. Its major component, the rotating compressor-turbine assembly, is a dynamic one with respect to the engine structure. The design and operation of compressor is complicated because the compressor is not only a dynamic system but also one of adverse pressure gradient — pressure increases along the stream. Furthermore, to withstand temperatures of around 1500K or more of the combustion gases, the turbine blades have to be designed with complex cooling arrangements. These blades are of high temperature resistant materials and have to be fabricated adopting advanced manufacturing techniques.

Although the gas turbine propulsion system is a complex one it has the advantage of its ability to produce thrust when its flight vehicle is stationary — the compressor can still induct air from the quiescent atmosphere. Furthermore, the gas turbine propulsion system offers a wide range of variants that are suitable for different regimes of flight Mach numbers. Maximum flight Mach number that is possible by the gas turbine propulsion system is around 3. Beyond this number, the kinetic energy contained in the inducted air is so high that the mechanical compression and expansion become redundant. And, as indicated earlier, without the compressor and turbine the gas turbine propulsion system simplifies into the ramjet.

The basic gas-turbine propulsion-system we considered earlier, Figs. 3.2 and 3.5, is known as turbojet. This configuration is rarely adopted in current flights. The major variants of gas turbine propulsion system adopted in flights are (1) **turboshaft**, (2) **turboprop**, (3) **turbofan**, and (4) **turbojet with afterburner**.

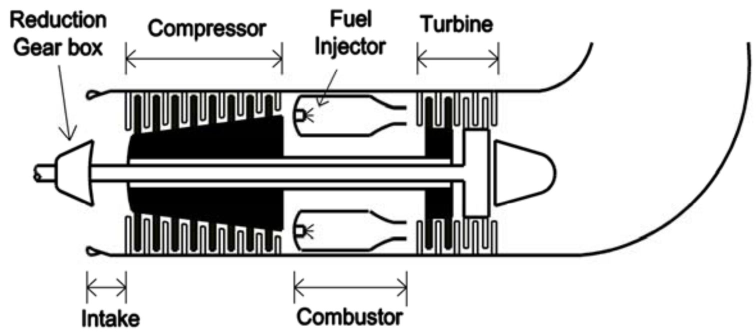

Fig. 3. 9. Schematic sketch of turboshaft engine

Turboshaft Engine In the turboshaft engine used in helicopter propulsion, the turbine produces power in excess of what is required for the compressor and this excess power through a reduction gearbox runs a power shaft. This shaft power can be used to rotate the helicopter blades, the vertically arranged propellers, Fig. 3. 9. The static pressure at the turbine exit is essentially atmospheric and there is very little jet power that can be tapped by way of expanding the turbine exhaust through a nozzle. The maximum forward speed that a typical helicopter can reach is around 300 km/hr and this roughly corresponds to a flight Mach number of 0.25.

Apart from their application in helicopter propulsion, turboshaft gas-turbines are widely used in electric power generation. Here, the power shaft runs an electric generator. The application also exists in the propulsion of ships where the power shaft runs the ship propellers. Also, we find a few applications of this class of propulsion systems in locomotives and racing cars.

Turboprop Engine In the turboprop engine, schematically shown in Fig. 3. 10, the propulsion is partly by the propeller power and partly by the jet power. The turbine power, produced in excess of compressor power, is used to run the propellers through a reduction gearbox. The pressure at turbine exhaust is substantially greater than the atmospheric pressure to enable the expansion through a nozzle to produce a jet thrust. Thus the propulsion of the aircraft is by two thrust-components, one the "cold thrust" from the propeller accelerating the "open" stream and the other the "hot thrust" from the nozzle accelerating the "enclosed" stream. The maximum flight Mach number that is possible for a turboprop-powered aircraft is around 0.6. However, recent developments in the concept of turboprop propulsion have enabled the use of turboprop propulsion to higher flight Mach numbers and altitudes. This concept of turboprop engine with an improved propeller configuration is known as propfan engine and these engines power most of the recent short haul aircraft.

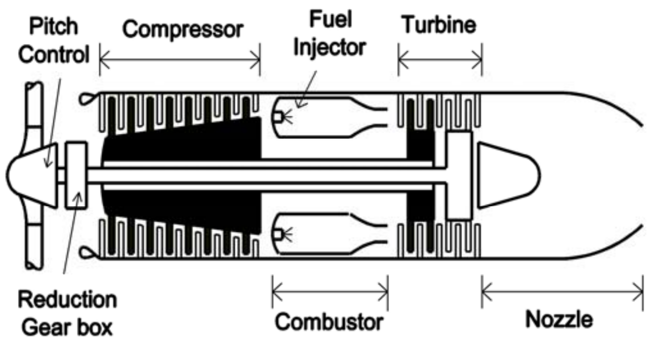

Fig. 3. 10. Schematic sketch of turboprop engine.

Turbofan Engine In the turbofan engine, schematically shown in Fig. 3. 11, the propulsive force is obtained through two jets, "cold" jet and "hot" jet. The turbine power, produced in excess of the basic-compressor power, is used to run an additional compressor of a low pressure-rise. This low-pressure compressor is also known as fan; hence the engine is named as turbofan engine. Air is drawn-in by the fan at a momentum rate corresponding to the flight velocity. After its deceleration in the intake, the fan compresses the inducted air. A part of the fan-compressed air is bypassed into the first nozzle to be expanded to a velocity greater than the flight velocity. Because of this bypass, the turbofan engine is also known as bypass turbojet engine. The balance of the fan-compressed air is further compressed by the basic compressor and fed into the combustion chamber. The combustion products expand through the turbine to supply power to the basic compressor and the fan. The relatively hot turbine exhaust is expanded through the second nozzle. As the turbine exhaust is hotter than the fan-compressed air, the first nozzle is known as cold nozzle and the second one as hot nozzle. Correspondingly the two jets are characterized as cold and hot jets. Thus the propulsion of the aircraft is by two thrust components, one from the cold nozzle and the other from the hot nozzle. Turbofan engines can fly aircraft with maximum fuel economy in the Mach number ranges around 0.9. Such engines have the bypass flow rates about four to five times the flow rates through the basic compressor. Or in other words, the major part of the inducted air gets expanded through the cold nozzle. Almost all the present day transport planes fly in the Mach number ranges around 0.9 and turbofan engines power these.

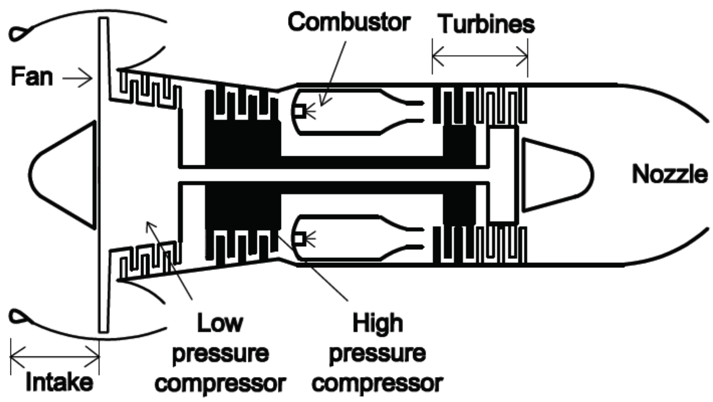

Fig. 3. 11. Schematic sketch of turbofan engine used for transonic flight Mach number, M ≈ 0.9.

For flight in the supersonic regime, the turbofan engine has to have an additional system known as **after-burner** or **reheat.** Due to material limitations, there is an upper limit on the maximum allowable temperature at the turbine entry. Because of this, not all the oxygen contained in the inducted air is used up in the combustion chamber. This means that the adopted fuel air ratio in the combustion chamber is far less than the stoichiometric value. After the turbine expansion, as the temperature has substantially come down, the unused oxygen in the inducted air can be used by injecting and burning additional fuel in the turbine exhaust. This added combustion system is known as after-burner or reheat system. The additional energy added to the turbine exhaust gives increased thrust in the nozzle expansion without much variation in the engine envelope and mass. Such additional thrust is needed for crossing the sonic barrier and flying the aircraft at supersonic speeds. Turbofan engines with after-burners can fly aircraft up to a Mach number of 1.5.

The schematic sketch of a turbofan engine with an after burner is shown in Fig. 3. 12. In this variant, note that the bypass air is ducted all along the engine to get mixed with the turbine exhaust. This engine is known as ducted turbofan-engine or ducted bypass-engine, and in this the bypass flow rate is only a fraction the total inducted air. Such an arrangement is needed for turbofan engines that fly in supersonic regimes.

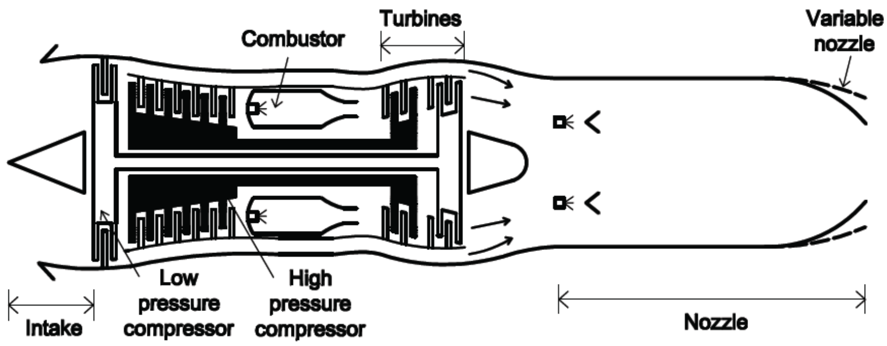

Fig. 3. 12. Schematic sketch of turbofan engine with after burner used for flight supersonic flight Mach number, M ≈ 1.5.

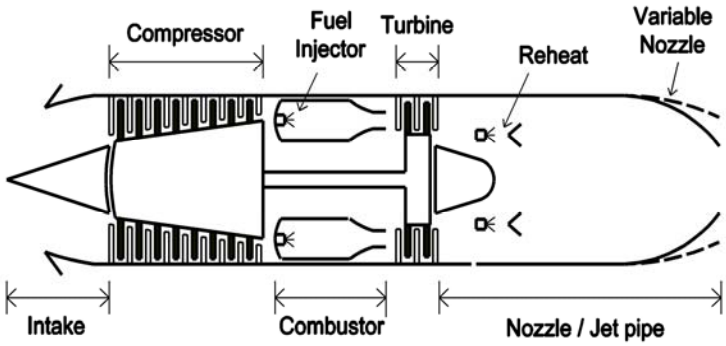

Fig. 3. 13. Schematic sketch of turbojet engine with after burner for supersonic propulsion.

Turbojet Engine As the flight Mach number in the supersonic regime increases, for the suitable turbofan engine the ratio of the bypass flow rate to the flow rate through the basic compressor keeps decreasing. And beyond certain value of Mach number it becomes zero. A turbofan engine with zero bypass flow rate is nothing but a turbojet engine. The schematic sketch of a turbojet engine with an after burner is shown in Fig. 3. 13. The processes that take place in a turbojet engine are previously explained while considering gas turbine propulsion system, Fig. 3. 2. In Fig. 3. 13, additionally we have an after-burner, which is required for supersonic propulsion as explained previously under turbofan engine, Fig. 3. 12.

The nozzle configurations required for optimum performance with and without reheat are different, turbofan and turbojet engines with after-burners will have nozzles of variable configurations as shown in Figs. 3.12 and 3. 13.

With this treatment, we close our discussion on airbreathing propulsion systems. For a more detailed discussion on this topic, see Refs. [1 and 2].

3. 3. CLASSIFICATION OF ROCKET PROPULSION SYSTEMS

The rocket propulsion systems do not draw any air from the atmosphere and the working fluid is generated from or stored within. By this unique quality two characteristics of rocket propulsion systems are evident. First, since the working fluid is to be generated from or stored within, the production of thrust by a rocket propulsion system is not dependent on its surrounding medium. Second, since no part of the working fluid is drawn for free from the surrounding medium, the production of thrust by a rocket propulsion system in earth's atmosphere is more expensive than that by an airbreathing propulsion system. The first characteristic is the most striking one, because be it in water, air, space (vacuum), or atmosphere of another planet where neither fuel nor oxidant is available, a rocket propulsion system can be designed to produce the required thrust.

As the rocket propulsion system does not draw any fluid from its surroundings, the simple thrust-equation, Eq. (3. 1), takes a simpler form. Because there is only the exiting momentum rate, there is no necessity to distinguish between the inducted and the exiting momentum-rates. We, therefore, remove the subscript for the exiting mass flow rate and write the simplified thrust equation for rocket propulsion as,

$$T = \dot{m}u_e \tag{3.2}$$

where $\dot{m}$ is the exiting mass flow rate.

Rocket propulsion can be broadly classified into

(1) **chemical rocket**,
(2) **electric rocket**, and
(3) **nuclear rocket**.

This classification is based on the energy source for the propulsion. In the chemical rocket propulsion, chemicals on combustion release the working fluid as well as the thermal energy. The hot working fluid, namely the combustion products, acquires a high kinetic energy by being expanded through a nozzle — a transformation of thermal energy into kinetic energy. In the electric rocket propulsion, it is the electrical energy that is responsible for the kinetic energy addition to the working fluid. The electrical energy is produced either through solar- or nuclear-energy. The solar energy can be converted into electricity using photovoltaic cells. The heat energy obtained from the radioactive decay or nuclear fission can be directly converted into electricity by the use of either thermoelectric- or thermionic-materials. In the nuclear rocket propulsion, nuclear-fission reactions release thermal energy that is transferred to the working fluid. By expanding the working fluid through a conventional nozzle, the thermal energy is converted into kinetic energy.

Chemical Rocket Propulsion

Chemical rocket propulsion is further classified into

(1) **solid rocket motor**,
(2) **liquid rocket engine**, and
(3) **hybrid rocket engine**.

In the chemical rocket propulsion, a chemical that releases heat on exothermic reaction or combustion is known as propellant. Apart from releasing heat, as previously said, the propellant by way of combustion also produces the working fluid. Depending on the phase of the chemical, it is solid propellant or liquid propellant. It is generally an accepted practice to term the rocket propulsion systems using solid propellants as motors and the ones using liquid propellants as engines. Correspondingly the respective systems are known as solid propellant motors and liquid propellant engines. In an attempt to take benefit of the merits of two different related-systems it is usual in science and technology to resort to hybridization. Rocket technology is not an exception to this. The hybrid rocket propulsion uses one of its two propellants, generally the oxidant, in liquid phase and the other in solid phase.

Solid Rocket Motor The schematic sketch of a solid rocket motor is shown in Fig. 3. 14. There are three major components: (1) igniter, (2) grain, and (3) nozzle. The solid block of propellant, housed by the casing, is known as the grain. The grain contains principally the ingredients of oxidant, termed as oxidizer, and fuel. Usually the central cavity in the grain, as shown in the figure, serves as the combustion chamber. On initiation, the igniter ignites the propellant grain. The grain burns to produce hot combustion products, which are principally in gaseous phase. These expand through the nozzle to exit at high momentum rate. The nozzle is generally a convergent divergent type. There is no incoming momentum rate since the working fluid is generated in-house. The thrust is produced because of the high momentum rate of the exiting combustion products against the zero incoming momentum-rate.

In order to protect the casing walls from hot combustion products a suitable insulator or liner is provided between the propellant grain and the casing. Furthermore, certain areas of the grain may have to be protected from burning for the desired thrust variation with time. This is done by covering such areas with a suitable inhibitor. In the sketch shown in Fig. 3. 14, you see the insulator between the casing wall and the propellant grain and the inhibitor applied at the aft ends of grain. As the convergent divergent nozzle is handling the hot combustion gases, its walls should also protected by proper insulation and adoption of high-temperature resistant materials.

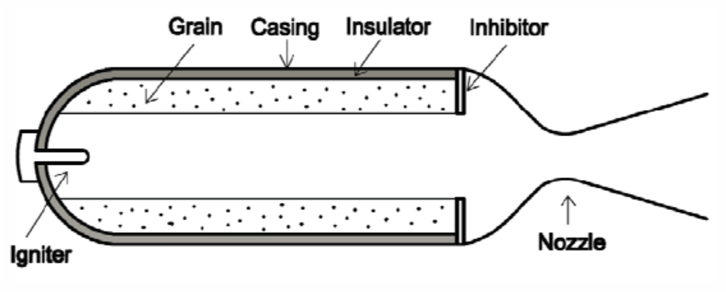

Fig. 3. 14. Schematic sketch of a solid propellant rocket motor.

Solid rocket motor is the simplest of the three chemical propulsion systems because both the fuel and oxidizer are contained in the grain. The major disadvantage of a solid rocket motor is that, once ignited, the thrust is delivered as per the grain configuration and cannot be varied at will. Furthermore the motor cannot be easily stopped and restarted.

Because solid rocket propulsion system is simple and ever ready to fire it finds extensive applications in warfare missiles. The energy content per unit mass of propellant in solid motors is less than that in liquid engines. Nevertheless, because of the system simplicity, invariably huge solid rocket motors are adopted as satellite launch vehicle boosters to overcome the colossal gravitational-force experienced at launch. The classical example is the Solid Rocket Booster (SRB) of the Space Shuttle, Figs. 3.15 and 3.16. Each motor, the primary component of the Space Shuttle's twin solid rocket boosters, generates an average thrust of 11520 kN and is just over 38.5m long and 3.7m in diameter, and weighs about 590 tons.

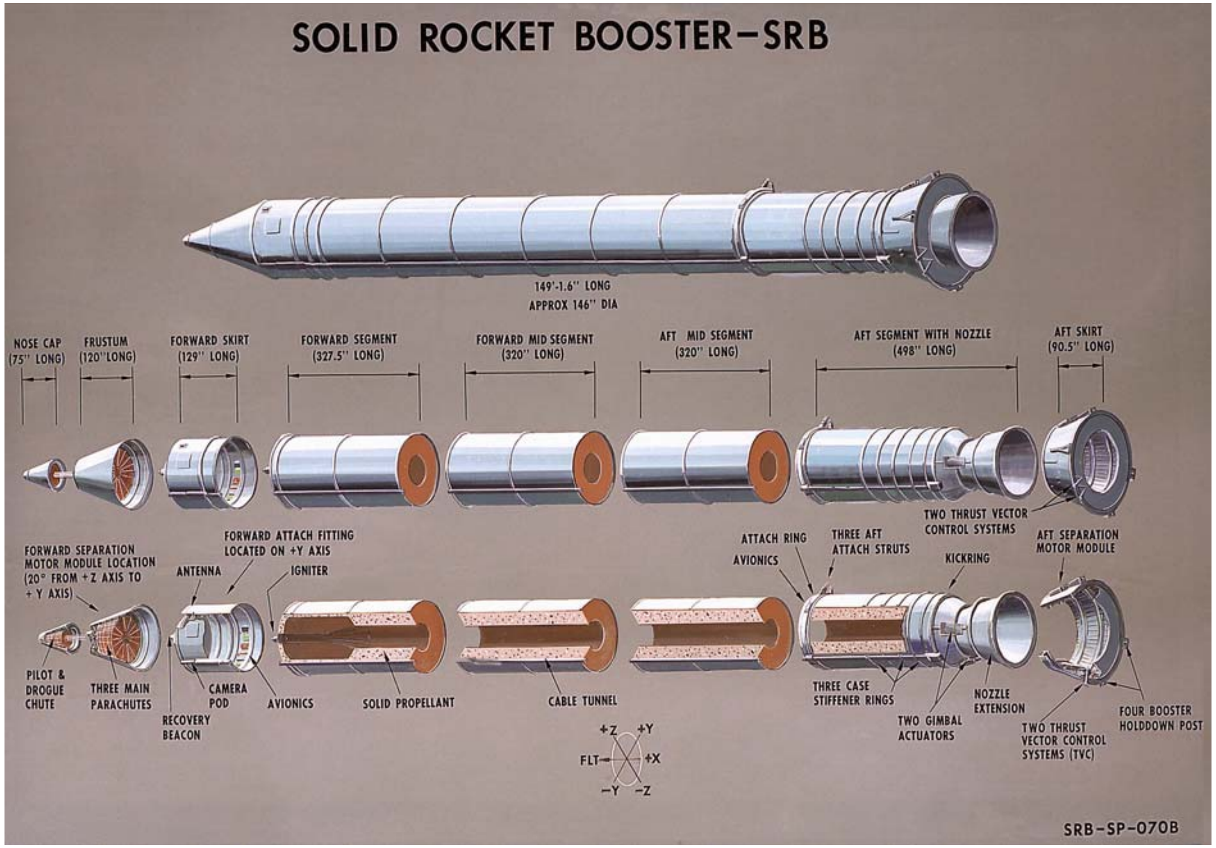

Fig. 3. 15. Views of one of the two solid rocket boosters of the Space Shuttle (NASA/courtesy of nasaimages.org).

Fig. 3. 16. Test firing of the Space Shuttle's solid rocket booster in February 2010 in Promontory, Utah. (www.nasa.gov/centers/marshall).

Liquid Rocket Engine The schematic sketch of a liquid rocket propulsion system is shown in Fig. 3. 17. The system has two major subsystems, the propellant feed system and the engine. For the purpose of cooling, one of the propellants, generally fuel, is circulated around the nozzle and the combustion chamber. The engine comprises of igniter, injector, combustion chamber, and nozzle. The others form the feed system. Based on the type of feed system adopted for the propellant flow, liquid rockets can be classified into pressure-fed liquid rocket and turbo-pump-fed liquid rocket. Note that the one shown in Fig. 3. 17 is a pressure-fed liquid rocket. The inert gas pressurizes the propellants and injects them into the combustion chamber through flow control valves.

The atomized sprays of the injected propellants get mixed and evaporated in the combustion chamber. On ignition, the vapor mixture of propellants burn in the combustion chamber. The combustion-chamber length is designed to allow sufficient residence time to the burning propellants such that the combustion is essentially complete by the time the products of combustion arrive at the nozzle entry.

For large total impulse (thrusting time × thrust), as the pressure-fed system will become very heavy due its high overall feed-system pressure, turbo-pump-fed system is employed. The schematic sketch of a turbo-pump-fed liquid rocket propulsion system is shown in Fig. 3. 18. The image of a turbopump fed liquid rocket engine is shown in Fig. 3. 19. Unlike in pressure-fed systems, in pump-fed systems it is sufficient that the propellant-tank pressures be kept low just to maintain the pressures at the pump-inlets adequately above the vapor pressures of the propellants, the propellant tanks are lighter with thinner walls. The turbo-pumps draw up the propellants from the tanks and pressurize them for injection into the combustion chamber. The turbo-pumps are powered by a turbine that runs by expanding the fuel rich combustion gases from the gas generator. The fuel-rich propellant combination is fed into the gas generator from the main feed lines of propellants. The exhaust from the turbine is frequently expanded through a small nozzle, the thrust of which can be used for control purposes.

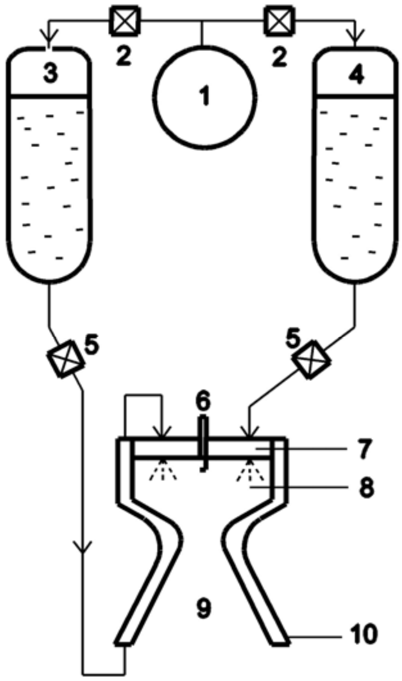

Fig. 3. 17. Schematic sketch of a gas pressurized liquid rocket engine (1: high pressure inert gas, 2: pressurization control valves, 3: fuel tank, 4: oxidizer tank, 5: propellant-flow control valves, 6: igniter, 7: injector plate, 8: combustion chamber, 9: convergent divergent nozzle, and 10: regenerative cooling jacket).

Mostly, liquid rocket engines are required to operate for long durations, several minutes are more. Therefore, a cooling system has to be employed. Usually the fuel is found to have better cooling characteristics. Furthermore, the oxidizer as a coolant may oxidize the metallic surfaces of the coolant passages, resulting in premature engine-failure. In the cooling system, shown in Figs. 3. 17 and 3. 18, the fuel circulates around the nozzle and combustion chamber, cools them, and thus picks up the heat that would have otherwise been lost to the surroundings, if radiatively cooled. The picked up thermal energy in the heated coolant-propellant is fed back into the combustion chamber. Hence the cooling system adopted is known as the regenerative cooling system. Small liquid rocket engines that operate in pulses or for short durations are known as liquid thrusters and they are used for control purposes. Generally radiative cooling is adopted for such thrusters. We will discuss in detail the various types cooling methods adopted for rocket engines elsewhere.

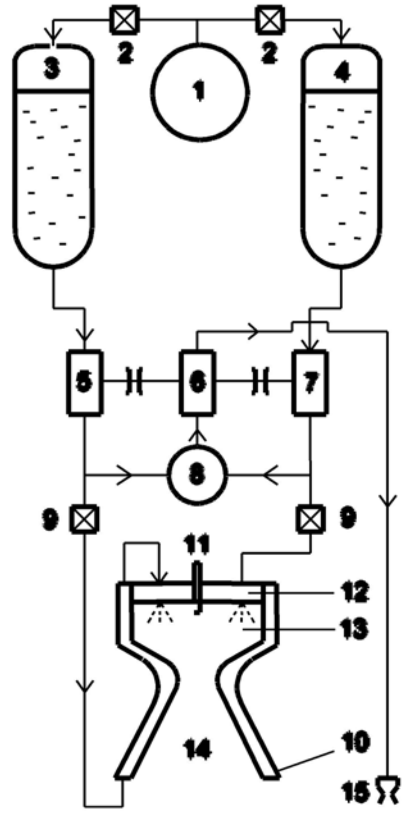

Fig. 3. 18. Schematic sketch of a turbo-pump fed liquid rocket engine (1: low pressure inert gas tank, 2: pressurization control valves, 3: fuel tank, 4: oxidizer tank,5: fuel pump, 6: turbine, 7: oxidizer pump, 8: gas generator, 9: propellant-flow control valves, 10: regenerative cooling jacket, 11: igniter, 12: injector plate, 13: combustion chamber, 14: convergent divergent nozzle, and 15: control thruster).

Liquid rocket engines, with the additional systems needed for propellant supply, propellant injection, and cooling, are not as simple as solid rocket motors. But liquid engines have many advantages over the solid motors. The most striking one is that the thrust of liquid propellant engines can be easily controlled by controlling the propellant flow rates. Furthermore the engines can be stopped and restarted. As the propellants are in liquid phase, one of the propellants, as explained previously, can be effectively used for cooling and hence the liquid engines can be operated for longer duration than that is possible with solid motors. Unlike in solid motors, the propellants in liquid engines are stored away from the combustion chamber and hence the assembly of thrust chamber and nozzle is not that heavy and can be easily gimbaled for thrust vectoring.

In the case of solid motors, the propellant ingredients have to be compatible with each other, as they are required to remain mixed and be stable in the grain for a long time. But in the case of liquid engines the oxidizer and the fuel are stored in separate tanks and only when needed get mixed in the combustion chamber. This "de-linking" gives a wider choice in selecting separately the most suitable oxidizer and fuel. "Wider the choice for its components better is the system." This is a universal rule and hence the performance of liquid rocket engines is ought to be better than that of solid rocket motors. An important figure of merit in this respect is the specific impulse I_{sp} and it is the thrust delivered per unit mass flow rate of propellant. From Eq. (3. 2), .

$$I_{sp} = \frac{T}{\dot{m}} = u_e \tag{3.3}$$

The specific impulse values of liquid engines are always higher than that of solid motors. Under SI units that we follow in this book, the dimension of specific impulse is N-s/kg or simply m/s. Or in other words, the specific impulse is nothing but the effective nozzle exit velocity. While N-s/kg or m/s is the dimension for the specific impulse under SI units, under MKS system of units it is kgf-s/kgm and under FPS system of units it is lbf-s/lbm. The numerical value of specific impulse under the MKS or FPS system of units will be (1/9.8065) times the value that we get under SI units. Commonly the unit mentioned for specific impulse in literatures that adopt MKS or FPS system of units is simply seconds, with the perception that the specific impulse is the thrust force per unit *weight* flow rate of propellant. In Chapter 4, we will discuss in detail about the specific impulse.

Hybrid Rocket Engine The schematic sketch of a hybrid rocket engine is shown in Fig. 3. 20. One of the propellants, usually the oxidizer, is in liquid phase and it has its feed system as in liquid rocket engine. The other propellant, fuel, is in solid phase and is housed by a casing as in solid rocket motor. The injected liquid oxidizer gets atomized and vaporized, and flows through the fuel-grain port. On ignition the combustion takes place between the oxidizer and the fuel vapor blowing from the wall of the grain port. The combustion products expand through the nozzle to exit with a high momentum rate to produce thrust.

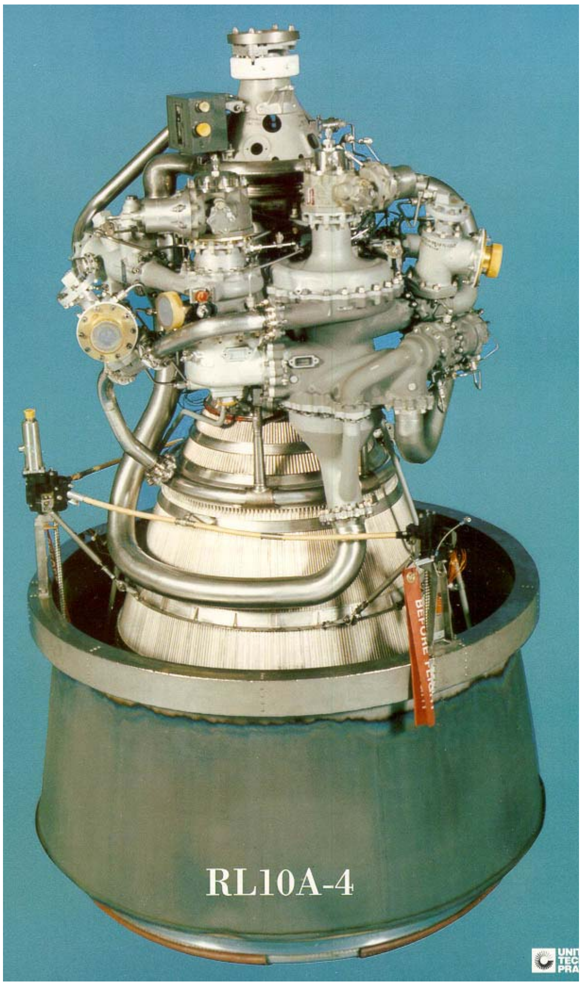

Fig. 3. 19. RL10A-4 liquid oxygen and liquid hydrogen engine used in Centaur upper stage. The engine delivers 93kN with the specific impulse of 4400N-s/kg. (Purdue University: cobweb.ecn.purdue.edu/~propulsi/propulsion).

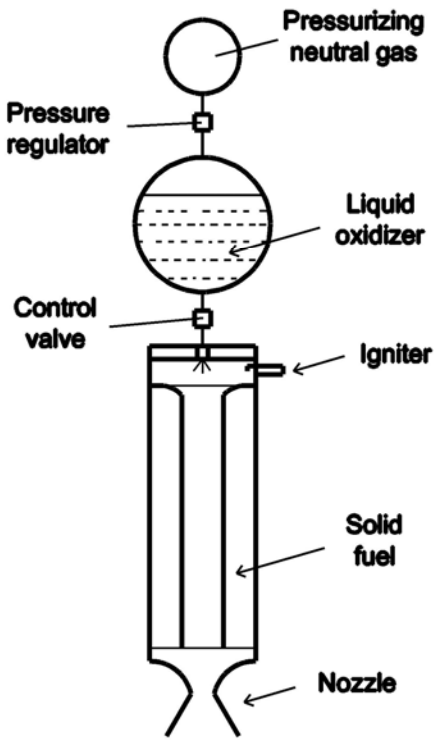

Fig. 3. 20. Schematic sketch of a hybrid rocket propulsion system.

Hybrid rocket engines combine the advantages of both solid rocket motors and liquid rocket engines. They are simpler than liquid rocket engines, though not as simple as solid motors. Hybrid rockets can be stopped and restarted and also have the provision for thrust control by the regulation of the oxidizer flow-rate. Presently developed hybrid rocket engines are of short duration operation essentially due to the limited web thickness possible for the fuel grain. Therefore, these engines do not require active cooling system. Nevertheless, provision always exists to use the liquid propellant in a hybrid engine for active cooling. Developmental studies indicate that the hybrid rocket engines can attain, with lower overall system mass, the specific impulse values comparable to those of liquid engines using earth storable or semi-cryogenic propellant combinations. Compared to the number of flight proven solid rocket motors and liquid rocket engines, the numbers of hybrid rocket engines that are flight proven are meager. However, quite a few research and developmental activities on hybrid rocket engines have been reported in recent years. The motivation for this has been the growing interest towards (1) lower developmental and operational costs without much loss in specific impulse and density specific impulse, (2) safer operational characteristics, and (3) better environmental friendly exhaust.

Electric Rocket Propulsion

Apart from the specific impulse, the thrust efficiency η_T is the second important figure of merit for electric propulsion systems. It is defined as the ratio of the kinetic power of the exiting jet to the input electric power.

$$\eta_T \equiv \left(\frac{\dot{m} u_e^2}{2} \right) \Big/ P_e \qquad (3.4)$$

By using Eq. (3. 3), the thrust efficiency can also be written as,

$$\eta_T = \frac{T u_e}{2 P_e} = \frac{T I_{sp}}{2 P_e} \qquad (3.5)$$

The working fluid in electric propulsion is also termed as propellant, although it, in most cases, does not possess energy source of its own. The required electric energy is produced independently through solar- or nuclear-source, and applied suitably to the propellant.

It is interesting to look at the basic reason behind the electric propulsion system having a very high or very low specific impulse as against chemical propulsion. In solid motors, the propellant ingredients have to be compatible and stable with each other, and remain mixed in a single solid grain that may have to be stored for many years. On ignition, the burning grain produces the working fluid as well as the heat energy. In liquid engines, the "constraints" on the propellant are somewhat relaxed in the sense that the oxidizer and the fuel are separated and stored in different tanks. Only when required, the oxidizer and the fuel are mixed, and the working fluid as well as the heat energy is released on combustion. In electric propulsion however, the propellant serving only as a working fluid and the energy source being independent, the constraints are further relaxed. As the energy-source requirement is de-linked from the propellant, a wide variety of electric propulsion systems are feasible with the specific-impulse as high as ten times to as low as a fraction of the value possible with chemical systems. Also the thrusting times can be as short as a few milliseconds to as long as many months. Some electric propulsion systems have been demonstrated to have a thrusting time of nearly two years, and there are attempts to extend the thrusting time even further.

The thrust-to-mass ratios of electric propulsion systems are very low at five to six orders of magnitude less than the chemical-system values. For example Hall thruster BPT-2000 has a thrust to mass ratio at 2.3×10^{-3} N/kg while liquid oxygen - kerosene engine RD-58M has a thrust to mass ratio at 362 N/kg. As a result of this, for large thrust requirements and high accelerations as required in satellite-launch operations (or in other words for large power requirements), the electric propulsion systems are not at all suitable and the chemical systems are the only alternatives. However, for small thrust levels and low accelerations that are needed or sufficient for in-space operations — spacecraft maneuvers and interplanetary missions — the propellant mass required by a high specific-impulse electric-system is approximately one tenth of that required by a chemical system. Hence, even with its high hardware mass (due to very low thrust-to-mass ratios), an electric system has its overall mass (mass of hardware and propellant) less than that of a chemical system. Furthermore, chemical propulsion systems cannot be used for requirements of very long thrusting-time.

In consideration of the previous discussion, with its relatively unlimited specific energy (specific impulse) but with low thrust capabilities (power) the electric propulsion system is considered to be a **power limited device**. On the other hand, with its relatively limited specific energy (specific impulse) but with unlimited thrust capabilities (power), the chemical propulsion system is considered to be an **energy limited device**.

In a typical spacecraft, the overall mass of a conventional chemical propulsion system is substantial. It varies from about 25 percent in small spacecraft of low earth orbit to about 75 percent in interplanetary missions. Replacing the chemical system with a high specific-impulse electric-system will result in considerable mass savings that may lead to the following advantages. For the given spacecraft mass, more propellant can be stored to enhance the spacecraft lifetime. In addition, for this given condition, with the saving on overall propulsion-system mass, the spacecraft can be equipped with improved- and additional-facilities to give better mission capability and flexibility. Alternatively, for the specified lifetime, less propellant needs to be stored, and this can lead to a lighter spacecraft and hence a smaller launch vehicle with a reduced launch cost. Furthermore, on a different application front such as long duration interplanetary-travel and beyond, the electric propulsion system is the only alternative available at present.

In certain text books in the past, electric rocket propulsion is classified into three, namely, electrothermal, electrostatic, and electromagnetic systems. There is no confusion in listing thrusters under electrothermal propulsion. However, it is invariably seen that propulsion systems listed under electrostatic propulsion do involve or substantially depend on the effects of electromagnetic field, and vice versa. Therefore, without following this past classification, we first list thrusters that can be grouped under electrothermal propulsion and then list other important electric thrusters which operate on the effects of electric and magnetic fields.

Lorentz Force and Hall Effect Before studying different types of electric propulsion systems, we have to first understand the Lorentz force and the resulting Hall effect. Negatively and positively charged particles move under the influence of electric and magnetic fields in electric propulsion systems. Negatively charged particles are mostly electrons and the positively charged particles are electron deficient propellant atoms, namely ions — more correctly cations; an anion is a negatively charged electron-excess atom. Because electrons are extremely lighter than ions, the effect of a force due to electric and magnetic fields is a great deal stronger for electrons than for ions.

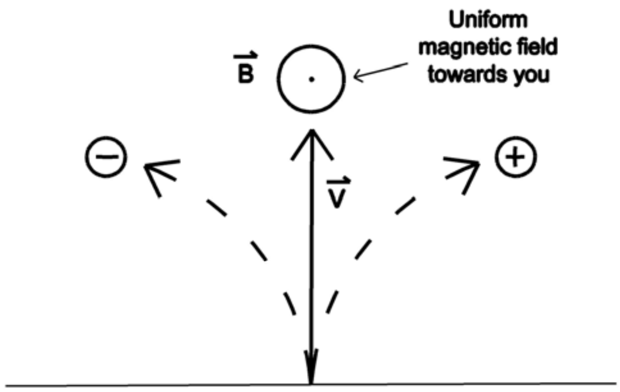

Fig. 3. 21. Lorentz force on the moving charged particle in a uniform magnetic field.

Lorentz force is the force $\vec{F}$, on a point charge q, moving with a velocity $\vec{v}$, due to electric field $\vec{E}$ and magnetic field $\vec{B}$. It is given by the following equation.

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right) \tag{3.6}$$

Let us first consider the influence of magnetic field. Figure 3. 21 depicts the effect of magnetic force on positively and negatively charged particles projected with a velocity $\vec{v}$. A neutral particle projected with a velocity $\vec{v}$ perpendicular to the uniform magnetic field of strength $\vec{B}$ is not affected by the field — shown as an arrow with a solid line in Fig. 3. 21. But, if a positively charged particle of charge q is projected with a velocity $\vec{v}$ perpendicular to the uniform magnetic field of strength $\vec{B}$, then, the particle will experience a magnetic force $q\vec{v} \times \vec{B}$ in the direction normal to both $\vec{v}$ and $\vec{B}$ — shown as an arrow with dotted lines curving to the right as shown in Fig. 3. 21.. If you recall the principles of the vector product operations, the direction of the magnetic force can be easily determined. Alternatively, the direction of the force can be found by the right hand rule that can be stated as follows.

> *For a positively charged particle, with the thumb of right hand pointing along $\vec{v}$ and the index finger along $\vec{B}$, the middle finger kept perpendicular to both $\vec{v}$ and $\vec{B}$ indicates the direction of the magnetic force $q\vec{v} \times \vec{B}$. For a negatively charged particle of charge $-q$, the magnetic force will be in the opposite direction. This is represented in vectorial form as $-q\vec{v} \times \vec{B}$.*

Therefore, the negatively charged particle projected with a velocity will have to curve leftward as shown in Fig. 3. 21.

Now considering both the electric and magnetic fields, the total Lorentz force on the positively charged particle of charge q with velocity $\vec{v}$ will be $q\left(\vec{E} + \vec{v} \times \vec{B}\right)$. On the other hand, the total force will be in the opposite direction for the negatively charged particle. This is represented in vectorial form as $-q\left(\vec{E} + \vec{v} \times \vec{B}\right)$.

The basic physical principle underlying the Hall effect is the Lorentz force. Hall effect is the generation of an electric potential (Hall voltage) perpendicular to both the electric current flowing along a conducting material and the external magnetic field applied at right angles to the current. Polarity of the Hall voltage depends on the moving charge carriers. In most cases, charge carriers are electrons. Figure 3. 22 depicts the Hall effect in a conductor where the charge carriers are predominantly electrons — negatively charged particles. The current I flows from right to left through a thin flat conductor, and the charge carrier electrons move in the opposite direction. The uniform magnetic field is applied perpendicularly downward. The Lorentz force on the charge carrying electrons pushes the electrons toward the edge of the conductor that faces you. This excess negative charge on one side of the conductor results in the Hall voltage and the current that flows across is the Hall current. If the charge carriers are positive as in some semiconductors, the charge carriers move in the same direction as the current I, and the polarity of the Hall voltage will be opposite to that shown in Fig. 3. 22.

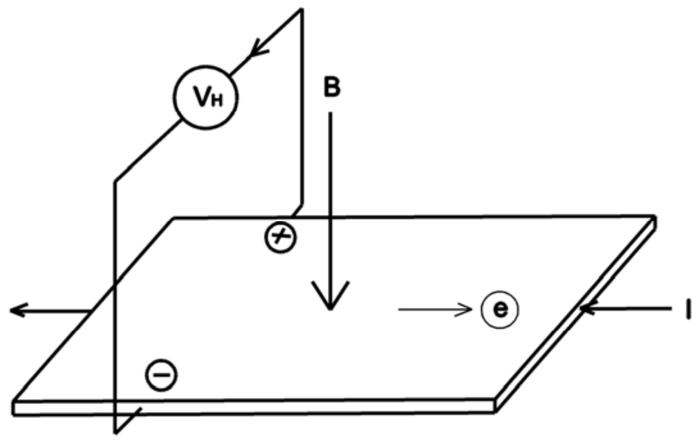

Fig. 3. 22. Hall effect in a conductor, where the charge carriers are predominantly electrons.

Electrothermal Propulsion In electrothermal propulsion, the propellant is electrically heated and expanded through a conventional nozzle. The electrothermal propulsion systems can further be classified as resistojets and arcjets.

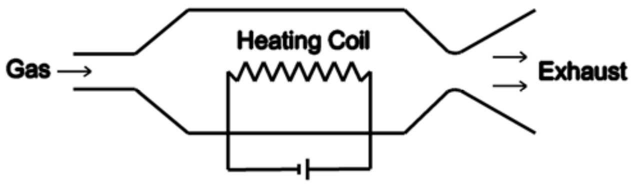

Fig. 3. 23. Schematic sketch of a resistojet

A schematic sketch of a **resistojet** is shown in Fig. 3. 23. The resistojet is the simplest device among all the electric propulsion systems that use fluids as propellants. In a resistojet, an electric current is passed through a high-resistance material to generate the heat that convects into the propellant. Usually catalytically decomposed hydrazine, ammonia, water, or nitrous oxide is adopted as a propellant. The heated propellant-gas expands through the nozzle to produce a thrust.

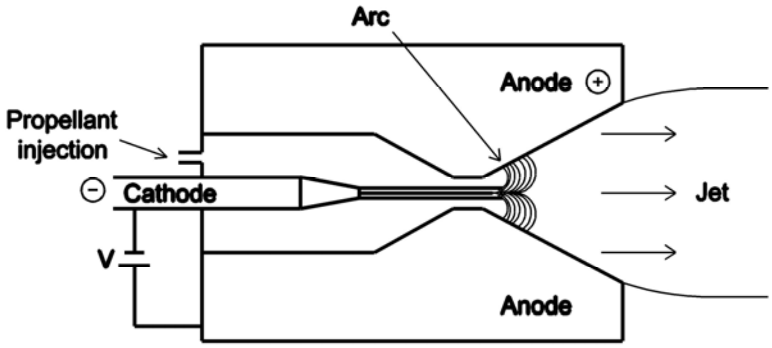

Fig. 3. 24. Schematic sketch of an arcjet.

A schematic sketch of an **arcjet** is given in Fig. 3. 24. In an arcjet, an arc is struck between a cathode and an anode, and the arc heats up the cross-flowing propellant to a very high temperature. The adopted propellant is usually decomposed-hydrazine, ammonia, or hydrogen. The high temperature propellant-gas expands through the nozzle to produce thrust. The image of Esex arc jet engine of Aerojet, USA is shown in Fig. 3. 25. It uses ammonia as its propellant and delivers a thrust of 2N for 15 minutes with maximum 10 restarts at a specific impulse of 7850 N-s/kg.

Fig. 3. 25. Esex Arcjet engine (Aerojet, USA) (www.astronautix.com).

Resistojets are simpler and of higher thrust efficiency than arcjets, and they can use any inert liquid or gas as a propellant. For example even the wastewater or unwanted gas in a space station can be suitably used. However, on the point of view of specific impulse, because the propellants in them can be heated to higher temperatures, arcjets deliver higher specific impulse than resistojets (5000 – 10000 N-s/kg as against around 3500 N-s/kg). This is essentially due to the difference between the heating patterns. In a resistojet the wall of high resistance material convects the heat to the propellant. Due to the limitation on the maximum-allowable material-temperature, around 3000K, the hottest part in a resistojet is the wall that heats up the relatively cooler propellant. But in an arcjet, the hottest zone is the arc region of temperatures in the range of 10000 - 20000K and it is away from the cathode- and anode-surfaces. These surfaces, though relatively cooler, can be of temperatures equal to the maximum allowable values around 3000K. Therefore, the propellants in an arcjet can be heated to higher temperatures to deliver higher specific impulse (you will learn later that specific impulse is proportional to the square root of chamber temperature divided by molar mass of the chamber gas). Furthermore, as the heating in a resistojet is along the walls, not localized as in the case of an arcjet, the propulsion-system length of a resistojet tends to be very high resulting in a larger system mass and an enhanced pressure loss in the heating chamber.

Ion Engine In ion engine or ion thruster, an electrostatic field is principally responsible for the acceleration of ionized propellant gas. In 1959, Herald Kaufman, an engineer at NASA, first built an engine based on this concept and therefore the engine is also known as Kaufman thruster. Although the vapors of cesium and mercury were initially used as propellants, due to the spacecraft-contamination concerns from the use of these liquid metals, the noble gas xenon is presently the most preferred one. Xenon is having a high atomic mass with a low ionization potential. The other noble gases that can be adopted are krypton and argon.

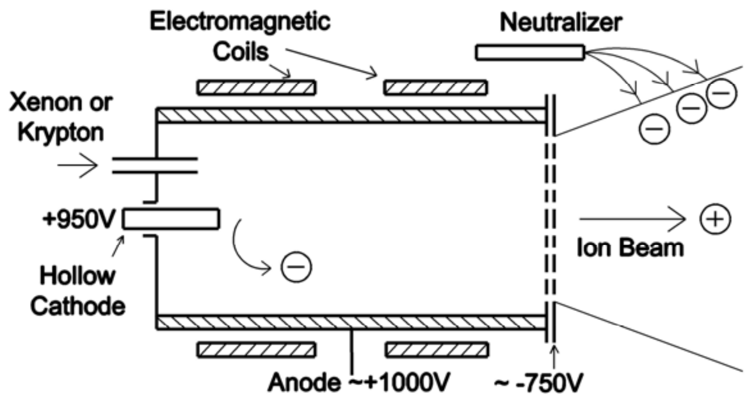

Fig. 3. 26. Schematic sketch of an ion engine.

A schematic sketch of an ion engine is shown in Fig. 3. 26. A neutral propellant-gas enters the ionization chamber. Electrons are emitted by the heated hallow cathode at the center. Attracted by the anode rings arranged at the periphery, the emitted electrons start drifting radially towards them. Also positioned outside the engine chamber are magnetic coils that impose an axial magnetic field to the radially drifting electrons. In the presence of the magnetic field the electrons, due to Lorentz force, take up an elongated spiral-path (approximately similar to the threads on a highly-tapered screw) that improves the probability of successful collision and ionization of propellant atoms. On a successful collision or bombardment, an electron in the outer orbit of the neutral propellant-atom is knocked off. Consequently, the reflected electron after collision, the knocked-off electron, and the electron-deficient propellant atom of positive charge, namely ion, are all obtained. Note that although the magnetic field can influence both the electrons and the ions that are of equal but opposite charges, it is the electrons that are mostly affected because they are much lighter than the ions. A pair of metal grids charged with positive and negative potentials is positioned near the exit and it sets up a strong electric field in the engine chamber. This field pulls and accelerates the propellant ions through the grid-holes to exit the engine as a beam with velocities in the range of 25000 - 40000 m/s, which also corresponds to a specific impulse in the range of 25000 - 40000 N-s/kg.. Finally, the exiting ion beam is neutralized by a stream of electrons that are injected by the neutralizer positioned at the very end of the engine exit. This neutralization is necessary to keep the spacecraft with its engine electrically neutral. Without neutralization, the spacecraft will become negatively charged and the exiting ion beam may be attracted back into the engine. Figure 3. 27 shows the ion engine of DS1 mission being tested in a high vacuum chamber.

Note that plasma is a neutral fluid-mixture of positive-, negative- and neutral-particles and it can be influenced by electric and magnetic fields. When an ion engine is operating at a steady state, a stable dilute-plasma cloud exists in the engine chamber. Through the cloud, streaming in at the cathode end are the emitted electrons and the neutral-propellant gas, and streaming out are the previously emitted electrons and the newly formed knocked-off electrons (both moving toward the anode), and the propellant ions (moving toward the grids). At equilibrium, the numbers of electrons, ions, and neutral atoms in the plasma cloud are essentially constant.

Hall Thruster The Hall effect thruster or simply **Hall thruster** is also known as stationary plasma thruster. As its name implies, the thruster uses the Hall effect to accelerate the ionized propellant-gas.

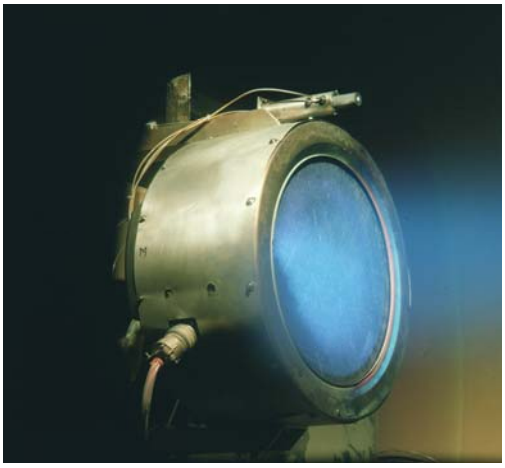

Fig. 3. 27. DS1 mission's xenon ion engine (mass 8 kg, diameter 40cm, and length 40cm) delivers a thrust of 90mN at a specific impulse of 30000 N-s/kg. (http://www.jpl.nasa.gov).

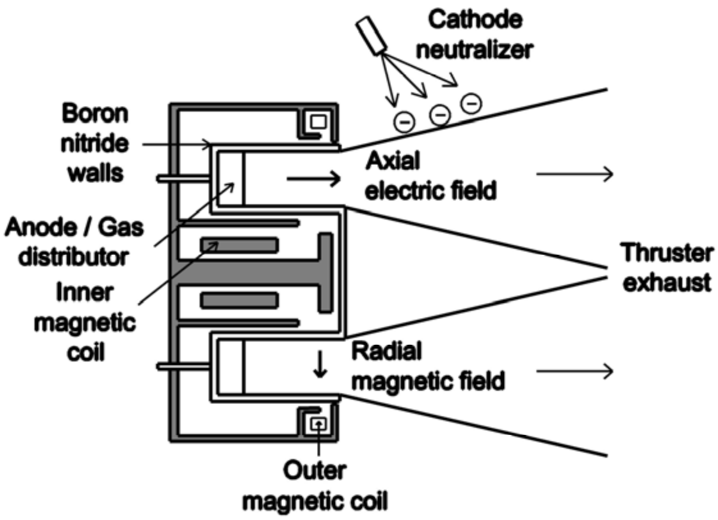

Fig. 3. 28. Schematic sketch of a Hall effect thruster.

A schematic sketch of a Hall thruster is shown in Fig. 3. 28. As in ion engines, in Hall thrusters too xenon is the most preferred propellant gas. Two coaxially positioned dielectric cylinders form an annular passage. At the entry to the annular passage (the anode end) is a perforated anode through which the neutral propellant-gas is injected. Outside the annular passage, at the exit end, is a cathode neutralizer. A potential difference between the anode and the cathode, usually around 300 V, sets up an axial electric field. Magnetic coils are arranged around the axis within the inner cylinder and at the periphery of the outer cylinder. These coils introduce a radial magnetic field B, strong at the exit region and weak at the anode end. Here we see the current I flowing through the coaxial cylindrical conductor experiencing the radial magnetic field B, that is perpendicular to the current I.

The operating principle of Hall thruster is as follows. The cathode neutralizer injects electrons, and a portion of these enters the annular passage from the exit end and attempts to drift towards the anode. But, because of the strong radial magnetic field perpendicular to the annular passage, the electrons attempting to move from the cathode neutralizer to the anode are magnetized and trapped at the exit region to orbit around the axis to give Hall current. At equilibrium, a finite-width annular-ring of azimuthally rotating electrons is formed at the exit region and this ring acts as a virtual cathode grid. Although trapped, due to collisions and instabilities a few of the orbiting electrons do get released from the annular ring to drift towards the anode. In this drift, they may ionize the oncoming propellant atoms. But the major ionization and subsequent acceleration of the propellant ions occur as the propellant enters the annular ring of rotating electrons. Due to the high electron number-density there, the ionization of the propellant atoms is practically complete. Although the radial magnetic field can influence and trap both the electrons and the ions, it is the electrons that are significantly affected because they are much lighter than the ions. The heavy ions, practically unaffected by the magnetic field, are accelerated by the electric field to exit the thruster with velocities in the range of 16000 m/s, which also corresponds to a specific impulse range of 16000 N-s/kg. The other portion of the electrons from the cathode neutralizer joins and neutralizes the exiting ion beam.

Let us compare the plasma discharge in an arcjet with that in a Hall thruster. In an arcjet, it is a non-magnetized plasma discharge essentially perpendicular to the propellant-gas flow. In such a discharge, due to the abundant and fast moving light-electrons towards the anode, the electron-current forms the major part of the discharge and the balance is due to the scarce and slow moving heavy-ions towards the cathode — most heavy ions are swept downstream by the propellant-gas flow. The transfer of arc-heat to the propellant makes it possible to accelerate the propellant gas in the nozzle to produce thrust. In a Hall thruster, it is a perpendicularly magnetized plasma discharge essentially along the propellant-gas flow. In such a discharge the portion of the electrons injected by the cathode neutralizer is trapped in the magnetized annular ring and only a few of the electrons get released at a time to drift towards anode. Consequently, the electron current forms the minor part of the discharge current. However, it does not contribute to the thrust production. On the other hand, the passage of heavy ions is unhindered by the magnetic field and hence the ion current forms the major part. And favorably, this part is responsible for the ion acceleration to produce thrust.

In comparison with an ion engine, a Hall thruster works with a lower system voltage that makes the power processing simpler. Since ion acceleration takes place in a quasi-neutral plasma, Hall thrusters are not limited by space-charge build up as in the case of the ion engine. A major disadvantage in using a Hall thruster is that the exiting beam is quite divergent, that is, the velocity vectors are not quite parallel to the engine axis. This results in a considerable thrust loss. Furthermore, the divergent exiting-beam may hit the other parts of spacecraft and cause operational problems.

In ion engine as well as Hall-effect thruster both electric and magnetic fields are responsible for the propellant acceleration. Traditionally, however, ion engine is categorized under electrostatic propulsion since the magnetic field plays only a minor role. In certain literature, both these engines are grouped under electrostatic propulsion.

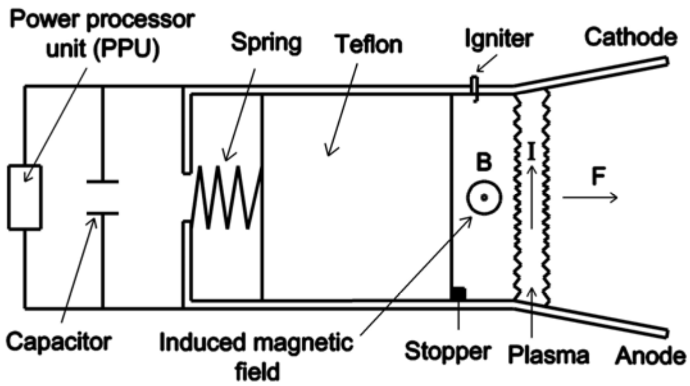

Fig. 3. 29. Schematic sketch of a pulsed plasma thruster.

In **pulsed plasma thrusters**, the current through propellant plasma interacts with the self-induced magnetic field to create a force to accelerate the propellant. A pulsed plasma thruster is schematically shown in Fig. 3. 29. Using a spring, the face of a solid inert-propellant is forced against a stopper at the beginning of the ionization chamber. Usually a chlorofluorocarbon such as Teflon® is used as a propellant. The ionization chamber is generally of rectangular cross section formed by a pair of flat-plate electrodes and a pair of insulator plates. The flat-plate electrodes are generally arranged parallel for a short length and then diverging towards exit. The electrodes are connected to the power supply across a high-voltage (1-2 kV) high-energy capacitor. A spark plug, which acts as the igniter, is positioned close to the propellant face.

The operating principle of the pulsed plasma thruster is as follows. When the high energy capacitor is fully charged, the igniter, by its small discharge, triggers the capacitor to discharge through a high-current arc (of instantaneous value around a few tens of kA) across the face of the propellant. By this high current, a thin slice of propellant is instantly ablated and ionized. Instantly, because of the spring, the new face of the propellant is automatically pushed forward against the stopper. The high current flowing in the loop connecting the plates of anode and cathode introduces a self induced magnetic field. The Lorentz force $\vec{j} \times \vec{B}$ created by the interaction of the electric arc current with a self-induced magnetic field accelerates the ionized plasma. The exiting plasma gives a thrust pulse of about 10μs duration at specific impulse values in the range 10000 – 15000 N-s/kg. The capacitor gets fully charged within a few milliseconds for the next cycle of operation to start.

As the pulsed plasma thruster has its propellant in solid phase, there is no need for the complicated propellant feed system and associated ground-handling scheme as required for liquid- or gaseous-propellant thrusters. WE noted previously that the resistojet is the simplest device among all the electric propulsion systems that use fluids as propellants. With its utmost simplicity in handling its propellant in solid phase, we can say that the pulsed plasma thruster is the simplest of all the electric propulsion systems. Although the pulsed plasma thrusters are among the earliest electric-thrusters used in spacecraft propulsion, their thrust efficiency is quite low around 10%.

A basic version of the **magnetoplasmadynamic thruster** is schematically shown in Fig. 3. 30. A long cylindrical cathode-rod, usually of tungsten, is coaxially positioned inside a short dielectric-cylinder to form an annular passage. Surrounding this cylinder is the anode sleeve with a circular shoulder-ring at the right exit-end. The shoulder ring projects perpendicularly a bit into the annular passage and is positioned a little ahead of the cathode tip.

The operating principle of the magnetoplasmadynamic thruster is as follows. Propellant gas (ammonia, hydrogen, argon, hydrazine, nitrogen, or lithium vapor) is injected into the annular passage through the cover plate at the left end. A high current-arc, struck between the anode shoulder-ring and the cathode, ionizes the propellant gas and sets up a radially inward electric field. The returning high current through the long cathode rod induces an azimuthal magnetic field. The resulting Lorentz force, due to the radially inward electric field and the azimuthal magnetic field, acts on the propellant plasma. Because of the previously explained positioning of the anode shoulder ring with respect to the cathode tip, the resulting Lorentz force has two components: the radially inward component due to the electric field and the axially outward one caused by the magnetic field. The radial component constricts the flow, and is known as the pumping force. And, the axial component accelerates the propellant plasma to produce thrust and is known as the blowing force. The specific impulse that can be achieved by the magnetoplasmadynamic thruster varies from 20000 to 50000 N-s/kg.

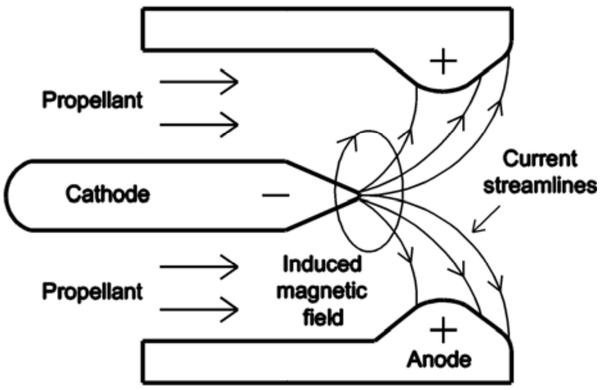

Fig. 3. 30. Schematic sketch of a magneto plamadynamic thruster.

The basic version of the thruster, schematically shown in Fig. 3. 30, is known as self-field magnetoplasmadynamic thruster. Additional magnetic field coils can be arranged around the anode to introduce radial and axial magnetic fields to the accelerating propellant plasma. The thruster with the added magnetic fields is found to deliver higher thrust efficiency and is known as the applied-field magnetoplasmadynamic thruster.

The basic principle of operation of **pulsed inductive thruster** is that a radial magnetic field interacts with an induced azimuthal-current in the propellant plasma to create a force to accelerate the propellant plasma. A schematic sketch of a pulsed inductive thruster is shown in Fig. 3. 31. A thin dielectric circular-plate covers a flat spiral coil. By a sharp “puff” of injection from a conical nozzle, a thin layer of propellant gas (argon or ammonia typically of mass 2mg) spreads at supersonic speed across the plate with azimuthal symmetry. At the same time a bank of capacitors, charged to about 15kV, discharges a high current through the spiral coil lasting only a few microseconds. This discharge generates a time varying radial magnetic field, which in turn induces an azimuthal electric field. This electric field ionizes the propellant-gas layer into a conductive plasma. Now, the time varying radial magnetic-field that is still rising induces in the plasma an azimuthal current that flows in the direction opposite to that through the spiral coil. This azimuthal current, being perpendicular to the radial magnetic field, gives rise to a magnetic pressure between the plasma and the spiral coil accelerating the former to a high velocity in the range of 20000 to 80000 m/s to produce a thrust pulse.

The main advantage of the pulsed inductive thruster is that it is a system without grids and electrodes. The ion engine has electrodes in the form of grids through which the ionized propellant is accelerated. The grids are obstructive to the flow. Furthermore, the charged particles hitting the electrodes cause erosion and limit the life of the propulsion system. Hall thrusters, pulsed plasma thrusters, and magnetoplasmadynamic thrusters have “gridless” electrodes. As a further improvement the pulsed inductive thrusters are “electrodeless” ones thereby completely removing the problem of obstruction as well as erosion of electrodes.

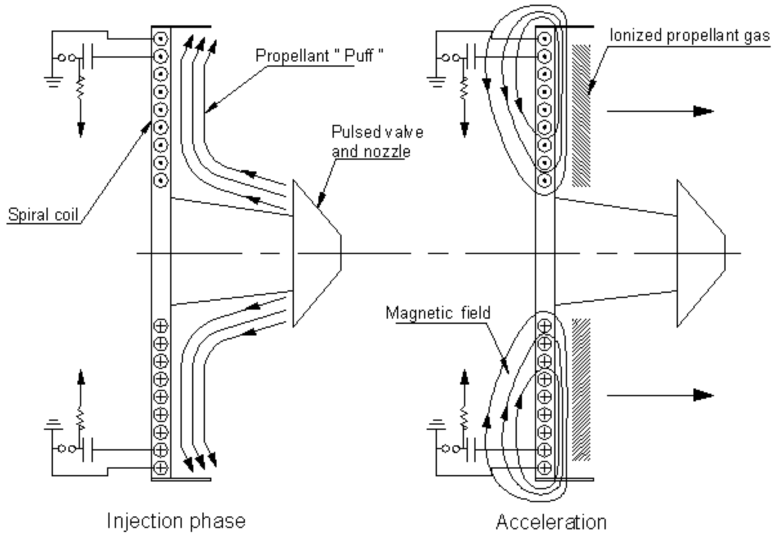

Fig. 3. 31. Schematic sketch of a pulsed inductive thruster.

As a final remark on electric rocket propulsion system, we should make a mention about the grouping under a category and the naming of individual electric thrusters. Under electrostatic propulsion and electromagnetic propulsion, the grouping and naming are more historical and traditional than the exclusive application of electric field or electromagnetic field. Under these two propulsion concepts, one finds in almost all thrusters the interaction of electric and magnetic fields. In certain literatures, Hall thruster is grouped under electrostatic propulsion. In all electric thrusters, barring resitojets, the working fluid at a certain stage becomes plasma.

Most electric thrusters are well developed and are used in more than hundred operational spacecraft. Magnetoplasmadynamic thrusters and pulsed inductive thruster under electromagnetic propulsion system are under development and yet to be fully flight qualified. With the continuous improvement in the reliability of electric rocket propulsion systems, the number of electric thrusters used in spacecraft propulsion is constantly increasing with time.

Nuclear Rocket Propulsion System

In a nuclear rocket engine, the heat from a nuclear-fission reaction is used to heat up, accelerate, and eject a propellant gas, say hydrogen, at high speeds. A schematic sketch of a nuclear rocket engine is shown in Fig. 3. 32. The engine usually has a graphite-based fission reactor containing a mixture of uranium/zirconium carbide in a graphite matrix. The propellant is pumped to circulate around the nozzle and the reactor chamber for the purpose of cooling. The heated propellant gas runs the turbine that powers the pump. Thereafter, the propellant gas enters the heat exchanger tubes that run through the reactor. The nuclear heat is transferred to the propellant gas. The hot propellant gas is accelerated by the conventional nozzle-expansion.

The specific impulse of a nuclear rocket engine can be more than twice that is possible in chemical propulsion systems. A chemical rocket, with its characteristic high thrust-to-mass ratio, can produce practically unlimited jet-power, or in other words unlimited thrust-force. But, it can operate only for a very short duration — at the maximum for a few tens of minutes. This performance of the chemical rocket (practically unlimited power but limited energy) makes it ideally suitable for launching a spacecraft into an orbit against a large gravitational force. But, it does not make it suitable for powering a spacecraft on a deep-space mission. Globally, the most important next step in space exploration is to realize a deep-space mission of a large payload and not too long a mission time (say, a manned spacecraft to Mars with a mission time of a few years). The key to this step lies in finding a propulsion system of reasonably high thrust to mass ratio that can produce fairly a large thrust force continuously for a long duration (many months). Among the near-term technologies, a nuclear rocket engine, which basically has no limitation on its energy, will be the best to meet this requirement.

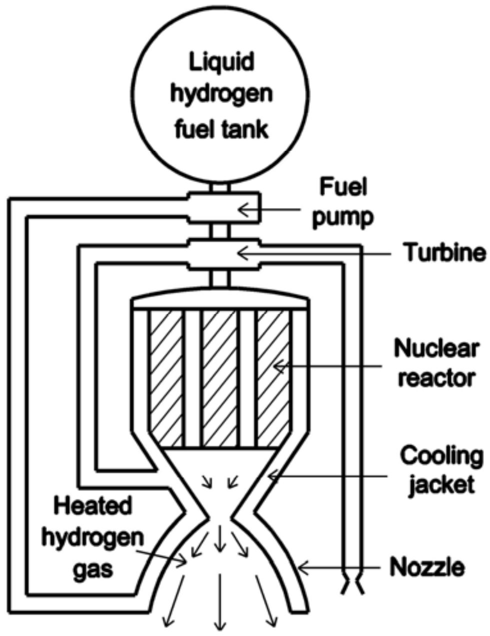

Fig. 3. 32. Schematic sketch of a nuclear rocket.

QUESTIONS

(1) Distinguish the difference between the propulsion of automobiles and locomotives, and that of ships and low-speed aircraft.
(2) What is the difference between the propulsion of low speed aircraft by propellers and that of high speed aircraft and missiles by jet-propulsion engines?
(3) What is common principle by which all mobile systems are propelled?
(4) What are the two types of jet propulsion systems?
(5) Qualitatively plot the total and static pressures and temperatures along the engine axis for a ramjet and a gas-turbine propulsion-

system. Briefly discuss the processes that the working fluid undergoes through the components of the propulsion system.

(6) Consider the case of a gas turbine propulsion system and discuss how the working fluid changes in composition and mass-flow rate as it flows through various components of the propulsion system.

(7) What are the conditions of idealization under which the processes in an airbreathing propulsion system can be considered as those of Joule or Brayton cycle?

(8) In the Joule or Brayton cycle, mark the processes in every component of a gas turbine propulsion system.

(9) What are the various types of ramjet propulsion system? Distinguish the difference in the working principles between subsonic combustion ramjet and the scramjet.

(10) What is the main advantage in using ramjet? What is the major limitation of the ramjet? Also briefly discuss the limitations on the lowest and the highest flight Mach numbers in a subsonic combustion ramjet.

(11) What are the major variants of gas turbine propulsion system?

(12) Explain the working principles of turboshaft gas turbines. What are the applications of turboshaft gas turbines?

(13) Explain the working principles of turboprop propulsion system.

(14) Explain the working principles of turbofan propulsion system.

(15) Where is the necessity of having an after burner in a turbofan or a turbojet propulsion system?

(16) What are the two striking characteristics of a rocket propulsion system and what are their effects?

(17) What are the three types of rocket propulsion systems?

(18) Explain the working principles of a solid propellant rocket motor. What is the major advantage and disadvantage in using this system?

(19) Explain the working principles of a liquid propellant rocket engine. Compare the merits and the demerits of a solid rocket motor with those of a liquid rocket engine.

(20) When does one prefer the turbo-pump-fed liquid rocket over the pressure-fed one?

(21) Explain the working principles of a hybrid rocket engine. Compare its merits and demerits with those of a solid rocket motor and a liquid rocket engine.

(22) “Wider the choice for its components better is the system.” Explain the effect of this rule in the performance improvements in liquid rocket engines over solid rocket motors and in electric propulsion systems over chemical propulsion systems.

(23) For in-space electric propulsion, when does the nuclear energy become the choice for producing electricity over the solar energy?
(24) What are the different types of electric rocket propulsion systems?
(25) Compare the working principles of a resistojet with those of an arc jet and explain how the specific impulse of the latter is higher than that of the former.
(26) Explain the working principles of a Hall thruster.
(27) Explain the difference between the current discharge in an arcjet and that in a Hall thruster.
(28) How the pulsed plasma thruster is the simplest of all electric propulsion thrusters?
(29) Explain the working principles of a magnetoplasmadynamic thruster.
(30) Explain the working principles of a pulsed inductive thruster. What is the main advantage in using the pulsed inductive thruster?
(31) Explain the working principles of a nuclear rocket engine. Where is the necessity for using nuclear rocket engine?

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