1.1 BASIC PRINCIPLE OF PROPULSION

Propulsion is a method by which an object is propelled in a particular direction. The word “propulsion” stems from the Latin word *propellere*, where *pro* means forward or backward and *pellere* means drive or push. In addition, we know that the verb “propel” means to drive or cause to move an object in a specified direction.

Hence, for the study of propulsion we will have to concern ourselves with this propelling force, the motion thereby caused, and the bodies involved. The study of propul-sion is not only concerned with rocket engines but also with vehicles such as aircraft, automobiles, trains, and ships.

We may recall that the principle of Newton’s laws of motion is the basis for the theory of jet propulsion. Jet propulsion can be expounded mainly by the second and third laws of motion.

For example, a spacecraft is flying vertically at uniform speed. The resultant force in the vertical direction must be zero to satisfy Newton’s second law of motion, according to which an unbalanced force acting on the body tends to produce an acceleration in the direction of the force which is proportional to the product of mass and acceleration.

In other words, the spacecraft must produce thrust which must be equal to the drag force caused due to the fluid motion over the body of this spacecraft and the gravitational force. For accelerating the spacecraft, one needs to supply higher thrust than that of drag forces and gravitational force acting on it.

According to Newton's third law of motion, we know that for every acting force, there is an equal and opposite reacting force. The acting force is the force exerted by one body on another, while the reacting force is exerted by the second body on the first. Although these forces have equal magnitude and occur in opposite directions, they never cancel each other because these forces always act on two different objects.

3.1 THRUST EQUATION OF ROCKET ENGINES

An expression for the thrust developed by a rocket engine under static condition can be obtained by applying the momentum equation. For this, let us consider a control volume (CV), as shown in Figure 3.1. The propulsive thrust "F" acts in a direction opposite to V_e. The reaction to the thrust "F" on the CV is opposite to it. The momentum equation for such CV is given by [4]

$$\frac{d}{dt}\int_{cv} \rho V_x \, dV + \int_{cs} V_x \left(\rho V_x \cdot n\right) dA = \sum F_x \tag{3.1}$$

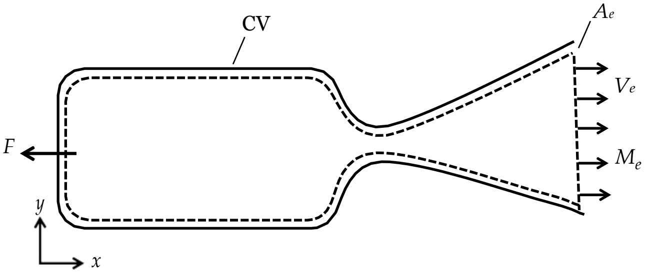


FIGURE 3.1 Control volume of rocket engine.

As the flow is steady in nature, we can neglect the unsteady term in Equation 3.1:

$$\frac{d}{dt}\int_{cv} \rho V_x \, dV = 0$$

Let us now evaluate the momentum flux term and sum of forces acting on CV of Equation 3.1, as given in the following:

$$\int_{cs} V_x \left(\rho V_x \cdot n \right) dA = \int V_x \, dm = \dot{m} V_e \tag{3.2}$$

$$\sum F_x = F + P_a A_e - P_e A_e \tag{3.3}$$

where

F is the thrust
V_x is the velocity component in x-direction
V_e is the velocity component at exit of nozzle
$\dot{m}$ is the mass flow rate of propellant
P_e is the pressure at exit plane of nozzle
P_a is the ambient pressure

By combining Equations 3.3, 3.2 and 3.1 for steady flow, we can have,

$$F = \dot{m} V_e + \left(P_e - P_a \right) A_e \tag{3.4}$$

where the first and second terms represent the momentum contribution and pressure components of thrust, respectively.

1.1 TYPES OF ROCKET ENGINES

The rocket engine can be broadly classified into two categories: (1) chemical rockets and (2) non- chemical rockets.

Based on the physical form of the chemical propellant, chemical rocket engines can be divided into three categories:

(1) solid propellant,

(2) liquid propellant, and

(3) hybrid propellant. But the non- chemical engines based on type of energy are further classified into threecategories:

(1) nuclear rockets,

(2) electrical rockets, and

(3) solar rock- ets. In this book,

Chemical Rocket Engines

In case of chemical rocket engines, chemical energy released during the burning of fuel and oxidizer is used to raise the temperature and pressure of the gas which is expanded in a CD nozzle to produce thrust.

Solid-Propellant Rocket Engines

The solid propel- lant composition, which was initially black powder, underwent a series of changes with time. Currently, solid propellants have found a wider applica- tion in various propulsion and gas-generating systems. It has a wide range of thrust levels ranging from a few N (Newton) to several hundred N.

Besides having a solid form, this propellant can be stored in the combustion chamber ready for use for a longer period of time, on the order of 10–20 years, provided they are hermitically sealed.

Compared to other types of chemical rocket engines, these are economical, reliable, and sim- ple. Hence, these engines find a wider range of both civilian and military applications.

Let us consider a simple SPRE as shown in Figure 1.5a which basically consists of the major components that are a solid propellant, a combustion chamber, an igniter, and a nozzle.

Note that the propellant, which mainly consists of fuel, oxidizers, and various additives, is entirely stored within the combustion chamber in the form of blocks of definite shape called grain and is supported by the walls or by special grids, traps, or retainers (not shown in Figure 1.5a).

Note that this grain contributes to around 80%–95% of the total mass of an SPRE.

The igniter initiates the combustion process on the surface of the propellant when actuated with the help of an electrical switch,. As a result, the propellant grains will start burning and filling the empty com-bustion chamber, hence building up the chamber pressure. Subsequently, the high-temperature and high-pressure gases are expanded in the supersonic nozzle to produce the requisite thrust. Generally, these nozzles are made of high-temperature materials, namely, metals with graphite coating, and are ablative materials that can take a high thermal load with minimal corrosion. Generally, a fixed nozzle is preferred in SPREs as shown in Figure 1.5a. Hence, a solid rocket engine is considered to be a non-air-breathing vehicle without any moving parts. But in recent times, the gimbaled nozzle is being used for controlling the direction of thrust.

As discussed earlier, the main characteristic of a solid propellant rocket engine (SPRE) is its simplicity. In view of its simplicity, the SPRE is particularly well suited for developing very high thrust within a short interval of time, particularly in the booster phase. With recent advancements in propellant chemistry, it can be used for fairly long burning time (sustainers).

Advantages

- It is simple to design and develop.
- It is easier to handle and store unlike liquid propellant.
- Detonation hazards of many modern SPREs are negligible.
- Better reliability than Liquid Propellant Rocket Engine (LPRE) (>99%).
- Much easier to achieve multistaging of several motors.
- The combination pressure in SPREs is generally higher than in LPREs since it is not subject to the limitation of a feed system.
- Development and production cost of SPREs is much smaller than that of LPREs, especially in the high-thrust bracket.

Disadvantages

- It has lower specific impulse compared to LPREs and hybrid propellant rocket engines (HPREs).
- It is difficult to turn off its operation unlike in an LPRE.

- Transport and handling of solid propellants are quite cumbersome.
- It is difficult to use the thrust vector control and thrust modulation.
- The cracks on the propellant can cause an explosion.
- Careful design of the nozzle is required as active cooling cannot be used.
- The erosion of the throat area of the nozzle due to high-temperature solid particles can affect its performance adversely.

1.5.1.2 Liquid Propellant Rocket Engines

It has a wide range of thrust levels ranging from a few N (Newton) to several hundred N. In addition to having a liquid form, this propellant can be stored in a separate tank and can be controlled easily, and hence thrust can be varied easily unlike in an SPRE.

Let us consider a simple LPRE as shown in Figure 1.5b, which basically consists of major components, namely, a propellant feed system, a combustion chamber, an igniter system, and a nozzle. Note that both fuel and oxidizer propellants are stored separately in special tanks at high pressure. Of course the propellant feed system along with the propellant mass contributes significantly to the mass of the engine but it is significantly less compared to the total mass of an SPRE. In fact, sometimes, the mass of the nozzle for deep-space applications is comparable to the propellant mass and its feed system in the case of an LPRE.

The pressurized liquid propellants are converted into spray consisting of arrays of droplets with the help of atomizers as shown in Figure 1.5b. Of course, an igniter is used to initiate the combustion process on the surface of the propellant. As a result, the propellant will start burning and fill up the empty thrust chamber, thereby building up pressure in the chamber similar to that of other chemical rocket engines. Subsequently, these high-temperature and high-pressure gases are expanded in a CD nozzle to produce the requisite thrust. As mentioned earlier, these nozzles are made of high-temperature materials, namely, metals with graphite coating and ablative materials that can take a high thermal load with minimal corrosion. It may be noted that propellant feed lines have several precision valves with whose help the operations of such kinds of rocket engine can be started and shut off at will, and hence repetitive operation is possible for this engine unlike the SPRE. The advantages and disadvantages of an LPRE are enumerated as follows.

Advantages

- An LPRE can be reused.
- It provides greater control over thrust.
- It can have higher values of specific impulse.
- In case of emergency its operation can be terminated very easily.
- It can be used on pulse mode.
- It can be used for long-duration applications.
- It is easy to control this engine as one can vary the propellant flow rate easily.
- The heat loss from the combustion gas can be utilized for heating the incoming propellant.

Disadvantages

- This engine is quite complex compared to the SPRE.
- It is less reliable as there is a possibility of malfunctioning of the turbopump injectors and valves.
- Certain liquid propellants require additional safety precaution.
- It takes much longer to design and develop.
- It becomes heavy, particularly for short-range application.

1.5.1.3 Hybrid Propellant Rocket Engines

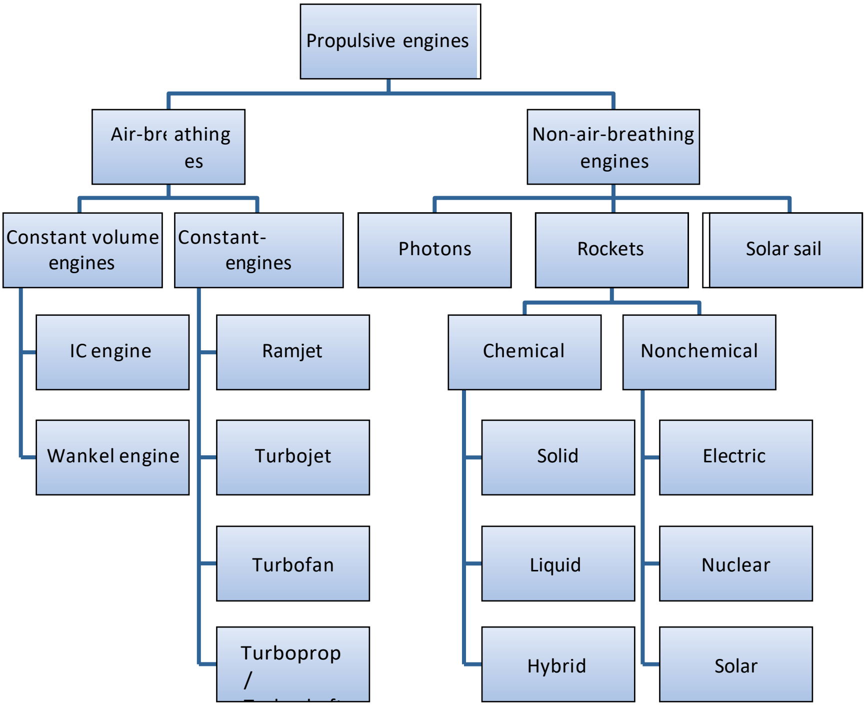
In order to achieve better performance, elements from SPREs and LPREs are combined to devise a new engine known as the HPRE. Note that this engine can use both solid and liquid types of propellants. All permutation and combination of propellants can be used for this kind of engine. But the most widely used propellant combination is a liquid oxidizer along with a solid propellant. Let us consider a simple HPRE as shown in Figure 1.5c, which basically consists of major components, namely, a propellant feed system, a combustion chamber, a solid fuel grain, an igniter system, and a nozzle. Note that only the oxidizer propellant in the present example is stored in a special tank under high pressure. The pressurized propellants are converted into spray consisting of arrays of droplets with the help of atomizers as shown in Figure 1.5c. Some of the propellant evaporates due to the recirculation of hot gases and comes into contact with the gaseous fuel that emanates from the solid fuel grains due to pyrolysis. The combustion products start burning and fill the empty thrust chamber, thereby building up pressure inside the chamber similar to that of other chemical rocket engines. In a similar manner, thrust is produced due to the expansion of these high-temperature and high-pressure gases in a supersonic nozzle. It may be noted that the liquid propellant feed line has a few valves with which the operation of such rocket engines can be controlled at will. Hence, it can find applications in missions that need throttling, restart, and long range. It has similar features to an LPRE, namely, compact, light, economical, and highly reliable. Besides, these engines may have better performance compared to both solid and liquid engines. Hence, these engines may find a wider range of both civilian and military applications, although these are still in research stages. Let us learn the advantages and disadvantages of an HPRE.

Advantages

- An HPRE can be reused.
- It provides greater control over thrust.
- It has relatively lower system cost compared to the LPRE.
- It can have higher values of average specific impulse compared to the SPRE.
- It has higher density of specific impulse than that of the LPRE.
- It has higher volume utilization compared to the LPRE.
- It has start–stop–restart capability.

Disadvantages

- This engine is quite complex compared to the LPRE.
- Its mixture ratio varies to some extent and hence it is quite difficult to achieve steady-state operation.



- It has lower density of specific impulse compared to SPRE.
- There is underutilization of solid fuel due to a larger sliver of residual grain at the end of the operation.
- Certain liquid propellants require additional safety precaution.
- It takes much longer to design and develop.
- It becomes heavy, particularly for short-range application.
- It has an unproven propulsion system for large-scale applications.

- Nonchemical Rocket Engines

.Based on the source of energy, these engines can be broadly divided into three categories: (1) electrical rocket engines, (2) nuclear rocket engines, and (3) solar rocket engines.

SINGLE-STAGE ROCKET ENGINES

Let us consider whether a single chemical rocket engine can provide sufficient velocity increment for various aerospace applications.

As the main objective of the rocket engine is to place the payload, we need to consider the payload mass m_l. In a chemical rocket engine, the major portion of the mass is the propellant mass m_p. The struc-tural mass m_s, which consists of engine structure, supporting structure, tankages, valves, guidance, and control, must be reduced to have higher velocity increment. Then, the total initial mass of the rocket engine m_0 is the sum of all the quantities:

$$m_0 = m_l + m_p + m_s \tag{5.34}$$

When the entire propellant is being burnt during its operation, the burn-out mass m_b as defined earlier is equal to the sum of the structural and payload masses:

$$m_b = m_0 - m_p = m_l + m_s \tag{5.35}$$

Let us now define three mass ratios, namely, payload fraction *LF*, structural fraction *SF*, and propellant fraction *PF*, by dividing Equation 5.34 with the total initial mass m_0:

$$\frac{m_l}{m_0} + \frac{m_s}{m_0} + \frac{m_p}{m_0} = LF + SF + PF = 1 \tag{5.36}$$

As mentioned earlier, the mass ratio MR can be defined as follows:

$$MR = \frac{m_0}{m_b} = \frac{m_0}{m_l + m_s} = \frac{1}{LF + SF} \tag{5.37}$$

Similarly, this mass ratio MR can be expressed in terms of propellant fraction PF as follows:

$$MR = \frac{m_0}{m_b} = \frac{1}{1 - PF} \tag{5.38}$$

Let us define another important parameter known as payload coefficient:

$$\lambda = \frac{m_l}{m_0 - m_l} = \frac{m_l}{m_p + m_s} \tag{5.39}$$

It indicates the mass of the payload that can be carried compared to the propellant and structural masses.. Another important parameter known as structural coefficient ε is defined as the ratio of structural mass to the sum of structural and propellant masses as follows:

$$\varepsilon = \frac{m_s}{m_p + m_s} = \frac{m_b - m_l}{m_o - m_l} \tag{5.40}$$

Note that this expression is true only when the entire propellant is burnt out without any residual unburnt propellant mass.

. When the structural coefficient is small and the rocket engine is quite huge, then the total engine mass including its structural mass will be dictated by the initial propellant mass. Hence, under this condition, the structural coefficient can be considered to remain constant,indicating that it would not be dependent on the vehicle size and, in turn, velocity increment. By using the two mass ratios, namely, payload ratio λ and structural coefficient ε, we can express the mass ratio MR as follows:

$$MR = \frac{m_0}{m_b} = \frac{m_0}{m_o - m_p} = \frac{1+\lambda}{\varepsilon+\lambda} \tag{5.41}$$

For achieving higher attainable velocity increment as per Equation 5.17, with limited I_{sp}, higher MR must be used. In order to have a higher MR, lower m_b is to be used for a given initial engine mass. Thus, a very careful structural design is essential for a given payload. Generally, the payload capacity can be enhanced further for a given m_p and MR, by reducing structural mass (see Equation 5.37). Thus, it is advantageous to reduce the structural fraction SF as much as possible in consistence with the strength requirements of the vehicle. Let us understand further how payload mass can be related to velocity increment by considering Equations 5.17 and 5.37:

$$\Delta V = V_{eq} \ln\left(MR\right) = V_{eq} \ln\left(\frac{1}{LF \quad SF}\right) \tag{5.42}$$

The payload fraction can be expressed in terms of velocity increment and V_{eq} and SF:

$$LF = e^{-\left(\Delta V/V_{eq}\right)} - SF \tag{5.43}$$