Concept: Propulsion

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1. Definition

Propulsion is the science and engineering of systems to move (propel) aircraft, missiles and spacecraft to their destinations. Vehicle propulsion is defined [1] as the action or process of imparting motion to a vehicle by means of a force. Typically the force is generated by changing the momentum of some fluid such as air, by adding energy to the fluid.

2. Introduction

Propelling a vehicle involves generating a force in order to accelerate a vehicle from one state of momentum to another, or to balance other forces to maintain a given state in equilibrium. This is the field of rocket engines, jet engines, internal combustion engines and pulsed detonation engines, but it also deals with ion engines, solar sails, nuclear engines, and even matter-antimatter engines. While the actual engines appear to be immensely complex, the underlying design and operation principles are the basic laws of physics and thermodynamics.

2.1. Thrust and Power

Two basic propulsion concepts are Thrust and Power. Thrust is the force that the propulsion system exerts on the vehicle, measured in Newtons (N), or pounds force (lbf). Power is work done per unit time, measured in watts or foot-pounds per second. Values range from the micro-Newtons of some engines used in spacecraft propulsion, to millions of Newtons for large launch vehicles.

2.2. Working Fluid and Airbreathing Propulsion

The most usual way to generate thrust is to accelerate a fluid, so that its momentum changes. By Newtons second law of motion, the rate of change of momentum of the fluid equals the force exerted by the propulsion system on the fluid. By Newtons third law of motion, the reaction to this force is the thrust acting on the propulsion system, transferred to the vehicle. Propulsion devices which do not involve accelerating a fluid include those that use gravity or electromagnetic fields.

Propulsion systems that operate inside a planetary atmosphere use the gas of the atmosphere as a working fluid. This is called airbreathing propulsion, although the fluid may not be air as we know it on Earth. For instance, engines designed for the atmosphere of Jupiter may ingest hydrogen, and one for the outer planets or their moons may ingest methane or ammonia. A very large space nuclear engine may some day breathe in the occasional molecules in the interstellar gas clouds and accelerate this matter to generate this thrust. Closer to home, a mass driver system for the lunar surface may ingest and accelerate lunar dust. Systems that operate in space where there is no mass to be ingested, must carry all of their own propellant mass, but even these may be able to obtain energy from the sun or from electromagnetic fields.

2.3 Mass Ratio, Velocity Increment and Specific Impulse

Propulsion system metrics include thrust, power, cycle efficiency, propulsion efficiency, specific impulse and thrust-specific fuel consumption. For systems that use a working fluid, the thrust

comes from two basic sources: (1) the reaction to the increase in momentum of the working fluid through the system, and (2) the force due to the excess pressure at the exit plane of the working fluid. The former is called Momentum thrust, and the latter is Pressure thrust. The Equivalent Exhaust Velocity (Ce) is simply the total thrust divided by the mass flow rate of propellant, and gives the exhaust speed achieved if the same total thrust were generated with no pressure thrust component.

The velocity increment, or delta-v is the velocity change needed, to add enough kinetic energy to change the total energy per unit mass of a vehicle, from one energy level to another. Since each orbit or trajectory in space is associated with a specific energy level, the delta-v is used as a measure of the energy difference required to change from one orbit to another.

The mass ratio (MR) of a mission is defined as the ratio of the initial mass to the final mass. Since the difference is the mass of propellant expelled, and any engines, fuel tanks and other components jettisoned, the mass ratio is usually taken as the ratio of the launch mass to the final payload mass in the desired orbit. The mass ratio depends on the delta-v and the equivalent exhaust velocity ce, and is given by the basic Rocket Equation (neglecting gravitational and drag effects)

$$\frac{M_{initial}}{M_{final}} = \exp\left(\frac{\Delta v}{c_e}\right) \tag{1}$$

A useful metric for space propulsion and all large high speed propulsion, is that of specific impulse or Isp, which is simply a way of expressing the equivalent exhaust velocity in a way that avoids confusion of units. Specific impulse is equivalent exhaust velocity divided by a constant that has units of acceleration, the standard value of acceleration due to gravity at Earths surface, or 9.8 meters per second-squared in SI units (the constant is the same regardless of which planet is nearest the vehicle, or where it is relative to the Earth). This gives the specific impulse in units of seconds.

Thus,

$$\frac{M_{initial}}{M_{final}} = \exp\left(\frac{\Delta v}{g_0 Isp}\right) \tag{2}$$

As the delta-v required for the mission increases, the Isp must be large to keep the Mass Ratio manageable. This equation can be used to prove why vehicles that go from Earth to low Earth orbit in a single stage (i.e., without dropping any stages along the way) cannot yet be built unless the Isp is increased beyond the limits of present-day engines or the structure of the tanks used to carry the fuel becomes much stronger and lighter.

At first sight, it appears that higher specific impulse is always better, and this is largely true. However, other considerations dictate the type of propulsion system that is chosen for a given application. One consideration is the engine mass. For example, electric propulsion systems achieve Isp of several thousand seconds, but the system mass per unit thrust is very large, making present-day electrical propulsion systems impractical for high-thrust launch vehicles from Earth. However, engines with thrust on the order of 1N are used to provide thrust for long durations on deep space missions, to achieve very high speeds. More on this after we introduce the idea of propulsive efficiency below.

3. Thermodynamic Cycles

The intensely detailed machinery and the history of propulsion machines can be viewed from the elegant viewpoint of thermodynamic cycles. The science of thermodynamics is, surprisingly, based on three empirical laws, for which no clear proof can be cited, but against which no counter-evidence can be cited either. The zeroth law establishes the notion of temperature, or the degree of hotness. In the context of propulsion systems, temperature is a measure of the amount of energy contained per unit mass of matter. Thermal equilibrium is thus defined by the zeroth law. The first law of thermodynamics establishes a book-keeping relation between work performed by a system, heat (or energy) put into the system, and the energy that remains in the system. This leads to the notion of a Heat Engine, where heat is converted to work. The Carnot cycle defines the most work that can be extracted, given a temperature difference. Different cycles are ways of describing different approaches to extracting as much work as possible from a system.

The ideal heat engine process is as follows: A working fluid (almost always meaning a gas) at state A, with pressure Pa and temperature Ta, is compressed by an input of work, without any irreversible losses to state B, with pressure Pb and temperature Tb. Heat q is then added, at constant volume (if the mass of working fluid is unchanged and the volume is constant, this means that density must be constant), until temperature Tc and pressure Pc is reached. The gas is then allowed to expand, work being extracted from the gas, until pressure comes back down to Pd, which is equal to Pa, and temperature Td, which will be higher than Ta. The thermal efficiency of the system is then the net work extracted, divided by q, the heat put in. This cycle is very close to what is done in an internal combustion engine, where the heat addition occurs when the piston in a cylinder reaches the top or most compressed position, and the time for heat release is so short that the space above the piston can be assumed to not have changed.

Jet engines work on the Brayton cycle, where the heat addition is done at constant pressure, so that in the above cycle description, Pb and Pc are equal. This is more applicable where the fluid is flowing continuously through the engine as in a jet engine or rocket. Neither process is fully reversible one cannot recover the same heat back by converting the fluid back to its original state, and the theoretical maximum efficiency is much below 1. To explain this, one goes to the second law of thermodynamics, which defines the concept of Entropy, or Degree of Disorder. This specifies a minimum level of rise in entropy or irreversible loss that will occur when heat is added.

The thrust of a propulsion system is the force generated along the desired direction. Thrust can come from two sources, for systems that exhaust a gas. The first is the momentum thrust, which comes from the acceleration of the working fluid through the system. It is equal to the difference between the momentum per second of the exhaust and intake flows. Thrust can also be generated from the product of the jet exhaust nozzle cross section area and the difference between the static pressure at the nozzle exit and the outside pressure. This pressure thrust is absent for most aircraft flight where the exhaust is not supersonic, but it is inevitable when operating in the vacuum of space. The total thrust is the sum of momentum thrust and pressure thrust. Dividing the total thrust by the exhaust mass flow rate of propellant gives the equivalent exhaust speed. All else being equal, designers prefer the highest specific impulse, though it must be noted that there is an optimum Isp for each mission. LOX-LH2 rocket engines achieve Isp over 450 seconds, whereas most solid rocket motors cannot achieve 300 seconds. Ion engines exceed 1000 seconds. Airbreathing engines achieve very high values of Isp because most of the working fluid comes free and does not have to be carried on-board.

The higher the specific impulse, the lower the mass ratio needed for a given mission. To lower the mass ratio, space missions are built up in several stages. As each stage exhausts its propellant, the propellant tank and its engines are discarded. When all the propellant is gone, only the payload remains. The relation connecting the mass ratio, the delta v and Isp, along with the effects of gravity and drag, is called the Rocket Equation.

Propulsion systems, especially for military applications, operate at the edge of their stable operation envelope. For instance, if the reaction rate in a solid propellant rocket grows with pressure at a greater than linear rate, the pressure will keep rising until the rocket blows up. A jet engine compressor will stall, and flames may shoot out the front, if the blades go past stalling angle of attack. Diagnosing and solving the problems of instability in these powerful systems has been a constant concern of developers since the first rocket blew up.

3.1. Thermal and Propulsive Efficiency

The thermal efficiency of the Brayton cycle, or the fraction of the heat released, that shows up as work, increases with the overall pressure ratio, i.e., the ratio between the pressure at the end of compression, and the pressure of the outside air. The amount of heat that can be added, and therefore the amount of thrust that can be generated per unit mass flow through the engine, increases with the highest temperature reached at the end of heat addition, which is generally limited by the materials technology and structural strength of the turbine. This is because compression raises the temperature without adding any heat, and therefore the heat addition is limited by the amount of temperature rise that can be achieved without exceeding the limiting temperature. This temperature is called the Turbine Inlet Temperature, and is usually a closely-held secret for state-of-the-art engines.

In a propulsion system, it is not enough to blow fast-moving gases out of a nozzle: the aim is after all to propel the aircraft. The Propulsive Efficiency of the engine measures how much work is done by the thrust generated, on the vehicle, per unit time, and compares it with the amount of energy added to the flow. This metric shows that the best propulsive efficiency is achieved when the exhaust speed is closest to the speed of the aircraft. For airbreathing engines, this result suggests that accelerating a large amount of air through a small speed difference, is more efficient than accelerating a small amount of air through a large speed difference, though both may produce the same thrust. Thus the large turbofan engines of modern airliners are much more efficient than the older but sleeker turbojets that powered airliners until the early 1970s. More on this as we discuss different types of jet engines.

In the case of space missions, this concept implies correctly, that there is an optimum value of specific impulse for a given mission. This is another reason why space launch boosters still use chemical propulsion systems with relatively low specific impulse, rather than high-Isp engines.

Many different kinds of propulsion systems have been developed or proposed. The simplest rocket is a cold gas thruster, where gas stored in tanks at high pressure is exhausted through a nozzle, accelerating (increasing momentum) in the process. All other types of rocket engines add heat or energy in some other form in a combustion (or thrust) chamber before exhausting the gas through a nozzle.

Solid fueled rockets are simple, reliable and can be stored for a long time, but once ignited, their thrust is difficult to control. An ignition source decomposes the propellant at its surface into gases whose reaction releases heat and creates high pressure in the thrust chamber. The surface recession rate is thus a measure of propellant gas generation. The thrust variation with time is built into the rocket grain geometry. The burning area exposed to the hot gases in the combustion chamber changes in a pre-set way with time. Solid rockets are used as boosters for space launch, and for storable missiles which must be launched quickly on demand. Liquid fueled rockets typically use pumps to inject propellants into the combustion chamber, where they vaporize, and chemical reaction releases heat. Typical applications are the main engines of space launchers, and engines used in space, where the highest specific impulse is needed. Hybrid rockets use a solid propellant grain with a liquid propellant injected into the chamber to vary the thrust as desired. Electrical resistojets use heat generated by currents flowing through resistances. Though simple, their specific impulse and thrust to weight ratio are too low for wide use. Ion rocket engines use electric fields or in some cases heat to ionize a gas, and a magnetic field to accelerate the ions through the nozzle. These are preferred for long-duration space missions where only a small level of thrust is needed, but for a long time, with the electrical energy coming from solar photovoltaic panels. Nuclear thermal rockets generate heat from nuclear fission, and may be coupled with ion propulsion. Proposed matter-antimatter propulsion systems use the annihilation of antimatter to release heat, with extremely high specific impulse.

Pulsed detonation engines are being developed for some applications. A detonation is a supersonic shock wave generated by intense heat release. These engines use a cyclic process where the propellants come into contact and detonate several times a second. Nuclear detonation engines were once proposed, where the vehicle would be accelerated by shock waves generated by nuclear explosions in space to reach extremely high velocities. Note that international law prohibits nuclear explosions in space.

4. Advanced concept discussion

4.1. One Dimensional Engine Analysis

Knowing the overall pressure ratio and the turbine inlet temperature, and given picture of the aircraft with the engine installed, one can quite accurately estimate the performance characteristics of the aircraft. This is by the one-dimensional engine analysis that we will see below.

The Ideal Ramjet cycle works as follows. Air coming into an inlet at a flight Mach number, is slowed down, its static pressure increasing as its speed decreases. Fuel is added to this flow and heat is released, reaching a value of stagnation temperature that is the limiting value for the engine. This heat addition is accomplished with no change in stagnation pressure. The hot, high-pressure gas is exhausted through a nozzle until its static pressure reaches that of the outside atmosphere. Through the entire process, the stagnation pressure remains constant. The analysis shows that the exit Mach number of the flow is then equal to the flight Mach number, though the exit static temperature is substantially higher than that of the outside air, so that the exit speed is higher than the flight speed. The thrust is then the difference in the momentum of the exiting flow from that of the incoming flow. In other words, thrust of the ideal ramjet engine is

$$IdealRamjetThrust = m_e U_e - m_a U_a \tag{3}$$

where the m is mass flow rate (kilograms per second), U refers to speed of the flow through the engine, and the subscripts a and e refer to the ambient (or outside, or ahead of the engine) and the exit plane of the engine, respectively.

The rocket engine carries all of its own propellant. Therefore, the second term above is zero, since the speed of the flow relative to the engine when it comes into the engine is zero.

The turbojet has a compressor and turbine added to the ramjet, taking work out of the flow in the turbine and putting it back in the compressor to raise the pressure.

The turbofan runs a fan in addition to the compressor. The flow from the fan does not have heat added to it, so we must make a distinction between this cold or fan flow, and the hot or core flow that goes through the compressor and combustor. The thrust of the turbofan is therefore

$$IdealTurbofanThrust = (m_{eh}U_{eh} - m_{ah}U_a) + ((m_{ec}U_{ec} - m_{ac}U_a) \tag{4}$$

Defining the Bypass Ratio beta as the ratio between the cold and hot airflow rates, and Fuel to Air Ratio f as the ratio between the fuel mass flow rate and the hot air mass flow rate,

$$IdealTurbofanThrust = m_{ah}(((1+f)\,U_{eh} - U_a) + \beta\,(U_{ec} - U_a)) \tag{5}$$

Other engines such as a turboprop or turboshaft engine can be modeled by accounting for beta appropriately. Thus the ideal turbofan analysis can be easily programmed and modified for many variations of the Brayton cycle engine.

5. Component Performance

The ideal ramjet analysis above assumes that there is no loss in stagnation pressure anywhere in the engine. With the ideal turbofan, stagnation pressure and temperature rise in the compressor and fan where work is added to the flow, but again with no increase in entropy. In the turbine, the stagnation pressure and temperature come down as work is taken out, again isentropically. Real engine losses can be modeled as drops in stagnation pressure below the ideal, or, where the stagnation pressure rise is specified, as a rise in stagnation temperature (and therefore extra work needed) to achieve the same stagnation pressure. Thus, the performance of the inlet, the diffuser, combustor and nozzle are defined by their stagnation pressure ratios (ideal being 1) while the compressor and turbine performances are defined by the stagnation temperature change from the ideal to achieve the required work. Below we consider each of these in turn.

5.1. Inlets

Subsonic inlets are designed to minimize the stagnation drop associated with flow separation, while allowing the flow to remain attached over a wide range of static pressures and flow rates. It is important to note here that the mass flow rate of air is not defined by the flight speed, atmospheric air density and area of the inlet. Instead, it is determined by the mass flow demand which is related to the amount of heat being released, and in fact to the conditions at the exit stage of the turbine, downstream. Thus an inlet may find itself operating in suction or external acceleration where the pressure is lower at the entrance plane of the inlet than it is far upstream, or in spillage or external deceleration where the pressure is higher and hence some flow must spill around the inlet.

If the flight speed is supersonic, the supersonic inlet is designed to minimize the stagnation pressure loss due to shocks as the flow is slowed down to sonic conditions at the throat of the inlet, followed by a subsonic diffuser.

5.2. Diffuser

The diffuser is typically a short duct within which the flow is slowed down with minimal loss in stagnation pressure accompanying the rise in static pressure. In a turbojet engine, the diffuser reduces the axial flow Mach number of the incoming flow, and thus allows the compressor to operate at a higher rotational speed given a limiting tip Mach number. Since the diffuser flowfield has an adverse pressure gradient, the major design challenge is to minimize diffuser length and mass without allowing flow separation.

5.3. Compressor

The compressor increases the pressure of the flow in the engine by doing work on it. This permits the heat addition to occur at the highest possible pressure.

5.4. Combustor

The combustor is where heat is released into the flow from chemical reaction with the fuel.

5.5. Turbine

The turbine extracts mechanical work from the heated flow.

5.6. Nozzle

The nozzle allows the remaining excess pressure to drive the flow to high exhaust speeds, thus increasing its kinetic energy.

6. Types of AirBreathing Jet Engines

Some types of airbreathing jet engines are listed below.

6.1. Ramjet and scramjet

Ramjets are used to power vehicles at speeds from about Mach 0.8 to Mach 4. The diffuser slows the flow down to subsonic speeds, increasing the pressure so much that thrust can be generated without a mechanical compressor or turbine. Beyond Mach 4, the stagnation pressure loss in slowing down the flow below Mach 1, is greater than the loss due to adding heat to a supersonic flow. In addition, if such a flow were decelerated to subsonic conditions, the pressure and temperature rise would be too high, either exceeding engine strength, or leaving too little room for heat addition. In this regime, the supersonic combustion ramjet, or scramjet, becomes a better solution. Air Liquefaction: The high pressures encountered in high speed flight make it possible to liquefy some of the captured and compressed air at lower altitudes, using heat transfer to cryogenic fuels such as hydrogen. The oxygen from this liquid can be separated out and stored for use as the vehicle reaches the edge of the atmosphere and beyond. Turboramjet engines using this technology can enable routine travel to and from space, with fully reusable, single-stage vehicles.

6.2. Turbojet

The turbojet is the purest jet engine, with a compressor and turbine added to the components of the ramjet. The turbojet can start from rest, which the pure ramjet cannot. However, since it converts all of its net work into kinetic energy of the jet exhaust, the exhaust speed is high. High propulsive efficiency requires a high flight speed, making the turbojet most suitable near Mach 2 to 3. Since jet noise scales as the 5th or 6th power of jet speed, the turbojet engine could not meet the noise regulations near airports in the 1970s, and was rapidly superseded by the turbofan for airliner applications.

6.3. Turbofan

The turbine of the turbofan engine extracts more work than that required to run the compressor. The remaining work is used to drive a fan, which accelerates a large volume of air, albeit through a small pressure ratio. The air that goes through the fan may exit the engine through a separate fan nozzle, or mix with the core exhaust that goes through the turbine before exiting. The overall exhaust speed being much lower than that of the turbojet, the propulsive efficiency is high in the transonic speed range where airliner flight is most efficient, while ensuring that airport noise levels are far lower than with turbojets. Turbofan engines are now used for most civilian airliner applications and even for fighter and business jet engines.

6.4. Turboprop

In the turboprop engine, a separate power turbine extracts work to run a propeller instead of a fan. The propeller typically has a larger diameter than a fan for an engine of comparable thrust. However the rotating speed of a propeller, constrained by the Mach number at the tip, is only on the order of 3000 to 5000 rpm, as opposed to turbomachine speeds which may be 3 to 10 times higher. Thus a gear box is required.

6.5. Turboshaft

Instead of a propeller, a helicopter rotor or other device may be driven by the power turbine. Automobile turbochargers, turbopumps for rocket propellants, and gas turbine electrical power generators, are all turboshaft engines.

6.6. Propfan

Propfans are turbofans where the fan has no cowling, so that it resembles a propeller and has larger capture area, but the blades are highly swept and wider than propeller blades.

7. Supersets

Statics, dynamics, thermodynamics, chemistry, physics

8. Subsets

Thrust, Power, fuel efficiency, ramjet, turbojet, scramjet, turbofan, turboprop, turboshaft, propfan,turbine, compressor, diffuse, combustion.

9. Other fields

Marine gas turbines, steam cycle power generation, vapor condenser refrigeration.

10. Notes

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