TURBO MACHINES

BME IV/I

Chapter Five: Theoretical Jet Engines

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Chapter overview

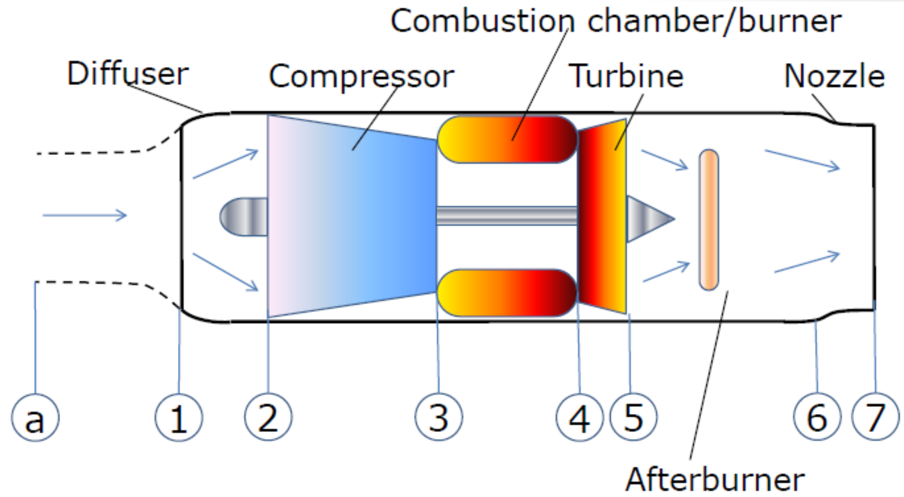
- Introduction to jet engines
- Classification of jet engines
- Turbine powered Jet Engines
- Ram Powered Jet Engines
- Non-continuous Combustion jet engines
- Rocket Engine
- Hybrid jet Engines
- Engines used on Aircrafts Operating in Nepal

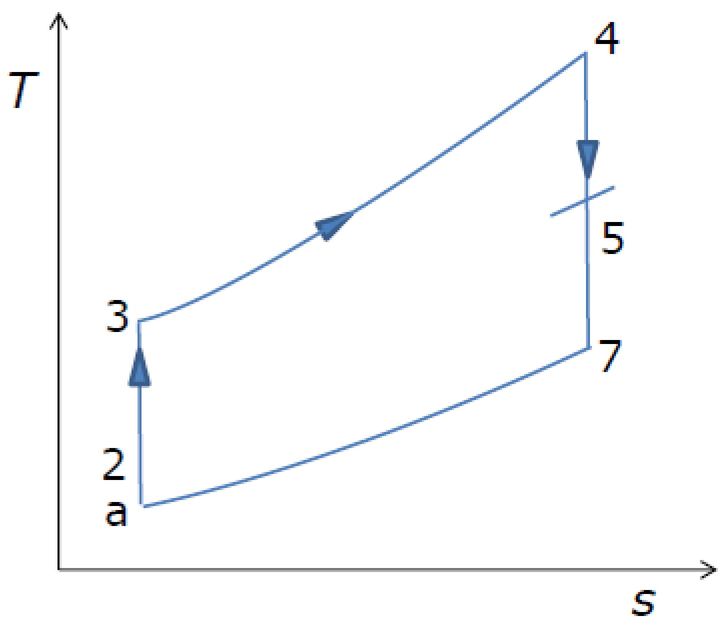
Jet engines

- Jet engines are also called as gas turbines.
- A jet engine having a turbine-driven compressor and developing thrust from the exhaust of hot gases is a turbojet engine.
- Ideal Brayton cycle is a closed cycle, whereas *gas turbines operate in the open cycle mode*.
- All air-breathing jet engines operate on the Brayton cycle (open cycle mode).
- The most basic form of a jet engine is a turbojet engine.
- Some of the parameters of a jet engine cycle are usually design parameters and hence often fixed *a priority*: eg. compressor pressure ratio, turbine inlet temperature etc.

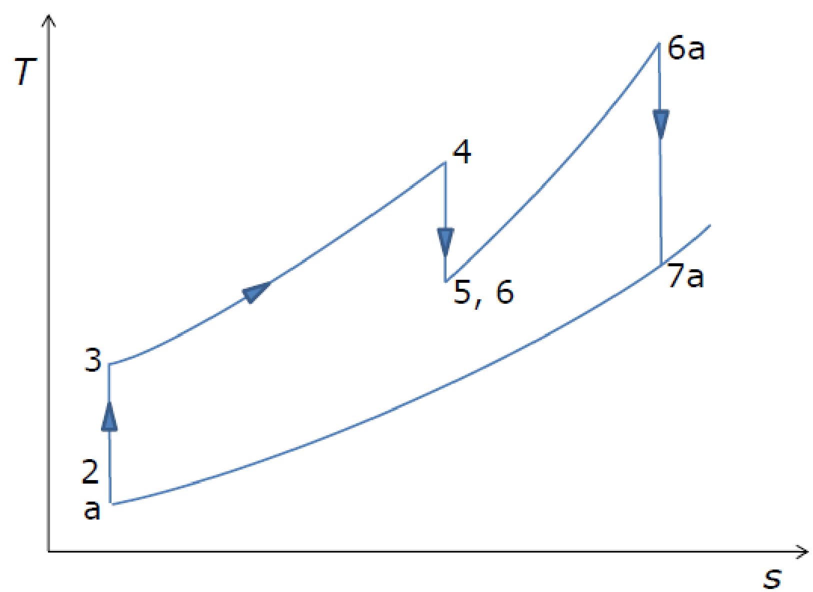
CONTD…

Ideal cycle for jet engines





Ideal turbojet cycle (without afterburning) on a T-s diagram



Ideal turbojet cycle with afterburning on a *T-s* diagram

CONTD…

- **Afterburning:** used when the aircraft needs a substantial increment in thrust. For eg. to accelerate to and cruise/travel at supersonic speeds.
- Since the air-fuel ratio in gas turbine engines are much greater than the stoichiometric values, there is sufficient amount of air available for combustion at the turbine exit.
- There are no rotating components like a turbine in the afterburner, the temperatures can be taken to much higher values than that at turbine entry.

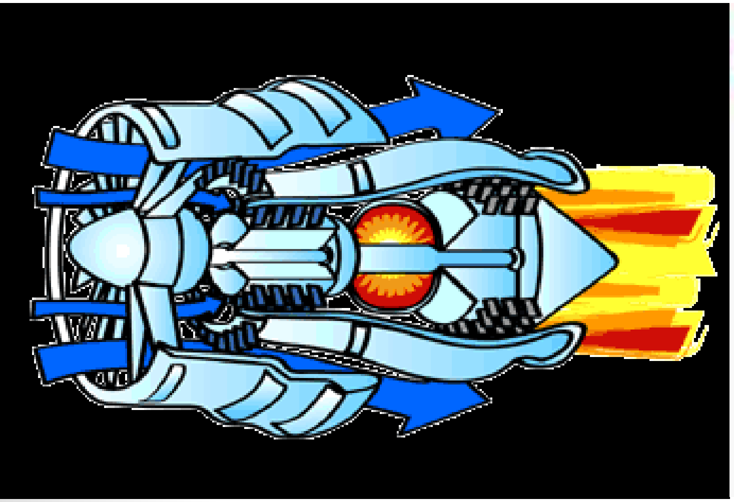
JET ENGINE CLASSIFICATION

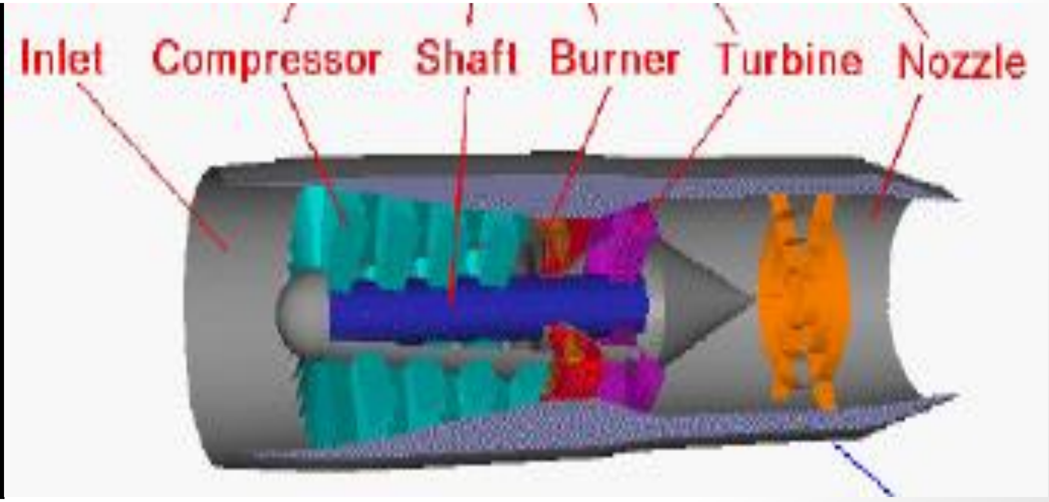
- Continuous combustion/Turbine Powered
  - Turbo Jet
  - Turbo Fan
  - Turbo prop
  - Turbo shaft
- Ram Powered
  - Ideal/Pure Ramjets
  - Scramjets, Air turbo ramjet, Bussard Ramjet
- Non- Continuous Combustion
  - Pulsejets (Deflagration Engine)
  - PDE (Pulsed Detonation Engines)
- Rocket Propulsion
- Hybrid jet Engines
  - Combined Cycles Engines
  - Advanced Propulsion

Turbine powered Jet Engines

Turbo jet engine

- Turbine used to drive the compressor.
- All intake air passes through the combustion chamber and exits through the nozzle.
- All thrust produced by hot, high-speed exhaust gases.





CONTD…

Characteristics of turbojet engine

- Low thrust at low forward speeds.
- Relatively high thrust specific fuel consumption (TSFC) at low Altitudes and airspeeds. This disadvantage decreases as altitude and air speed increase.
- Long takeoff roll required.
- Small frontal area results in reduced ground-clearance problems.
- Lightest specific weight(W/T)
- Ability to take advantage of high ram-pressure ratios.
- **These Characteristics indicate that the turbojet engine would be best for high –Speed, high –Altitude, long distance flight.**

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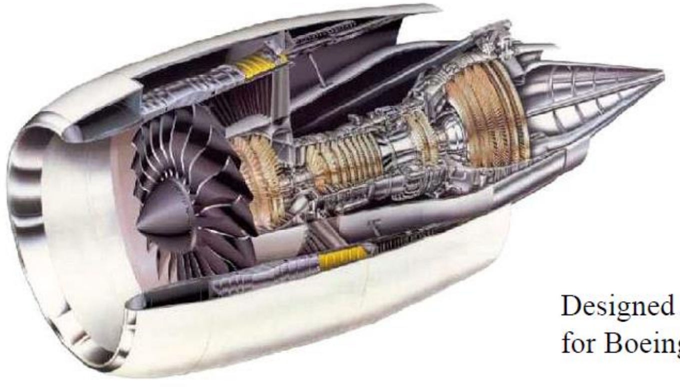

G90 Turbo engine

Turbofan (fan jet) engine

- A fan is placed in the intake cover, in front of compressor.
- Dramatically increases the amount of air pulled in the intake.
- Only a small percentage passed through the engine, the rest of cold air is Bypassed.
- Part of the thrust through the hot exhaust gases and part by the cold bypassed air.
- Produces cooler exhausts and quieter engines.
- High by-pass ratio are most commonly used in larger commercial aircraft.

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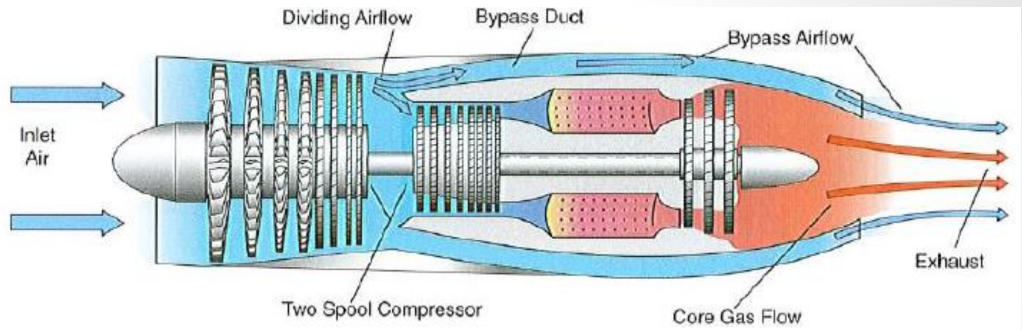
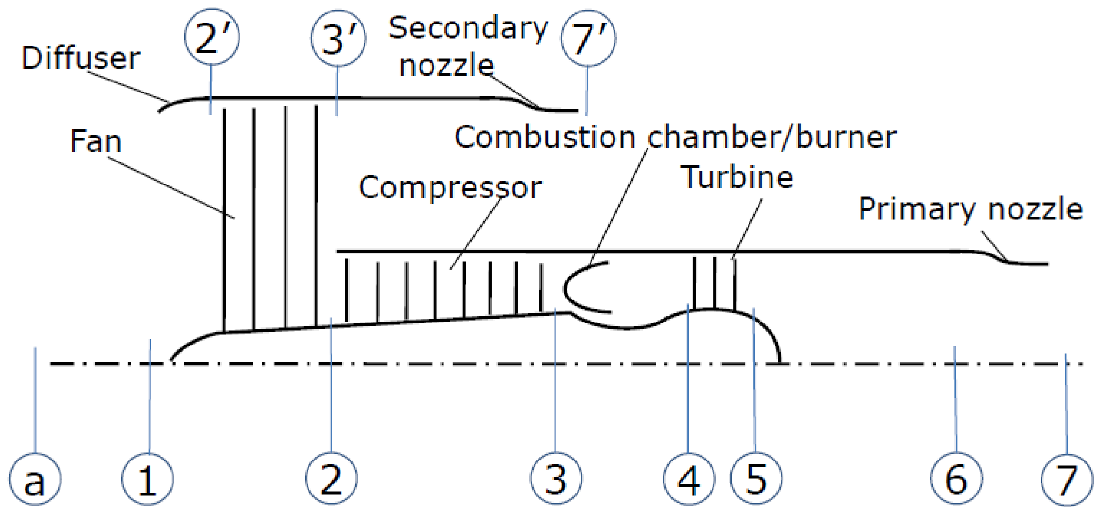


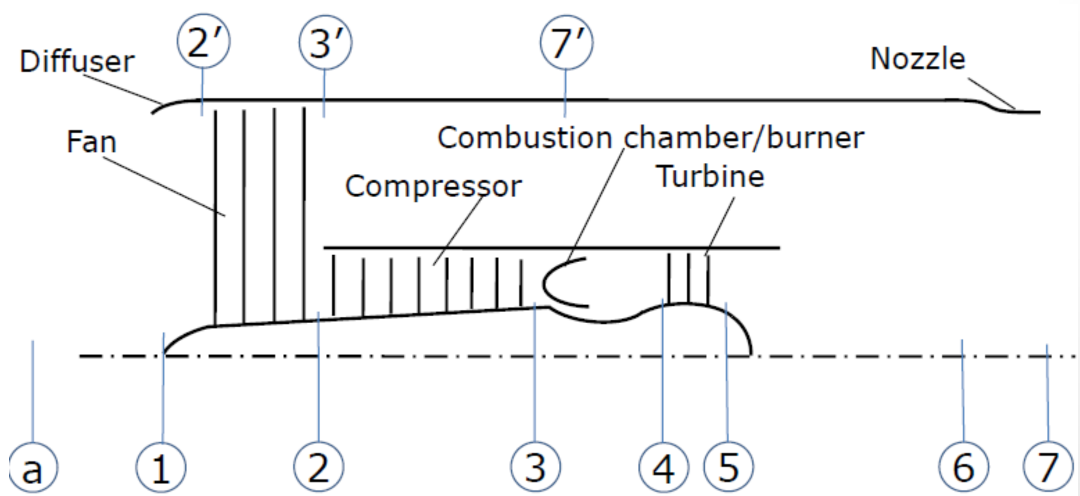
- Propulsion efficiency is a function of the exhaust velocity to flight speed ratio.
- This can be increased by reducing the effective exhaust velocity.
- In a turbofan engine, a fan of a larger diameter than the compressor is used to generate a mass flow higher than the core mass flow.
- This ratio is called the bypass ratio. $(\dot{m}_{cold} / \dot{m}_{hot})$
- Turbofan engines have a higher propulsion efficiency as compared with turbojet engines operating in the same speed range.

CONTD…

- Schematic of an unmixed turbofan engine and station numbering scheme



- Schematic of a mixed turbofan engine and station numbering scheme



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Different processes in an unmixed turbofan cycle are the following:

- a-1: Air from far upstream is brought to the air intake (diffuser) with some acceleration/deceleration
- 1-2’: Air is decelerated as is passes through the diffuser
- 2’-3’: Air is compressed in a fan
- 2-3: Air is compressed in a compressor (axial or centrifugal)
- 3-4: The air is heated using a combustion chamber/burner
- 4-5: The air is expanded in a turbine to obtain power to drive the compressor
- 5-6: The air may or may not be further heated in an afterburner by adding further fuel
- 6-7: The air is accelerated and exhausted through the primary nozzle.
- 3’-7’: The air in the bypass duct is accelerated and expanded through the secondary nozzle.

CONTD…

Characteristics of turbofan engine

- High propulsive efficiency at medium airspeeds.(up to mach one).
- Weight falls between the turbojet and turboprop.
- Ground clearances are less than turboprop, but not as good as turbojet.
- TSFC and specific weight fall between turbojet and turboprop.
- Considerable noise level reduction of 10 to 20 percent over the turbojets.
- Superior to the turbojet in " hot day " performance.
- Two thrust reversers are needed.

These Characteristics show that the turbofan engines are suitable for long range, relatively high speed flight.

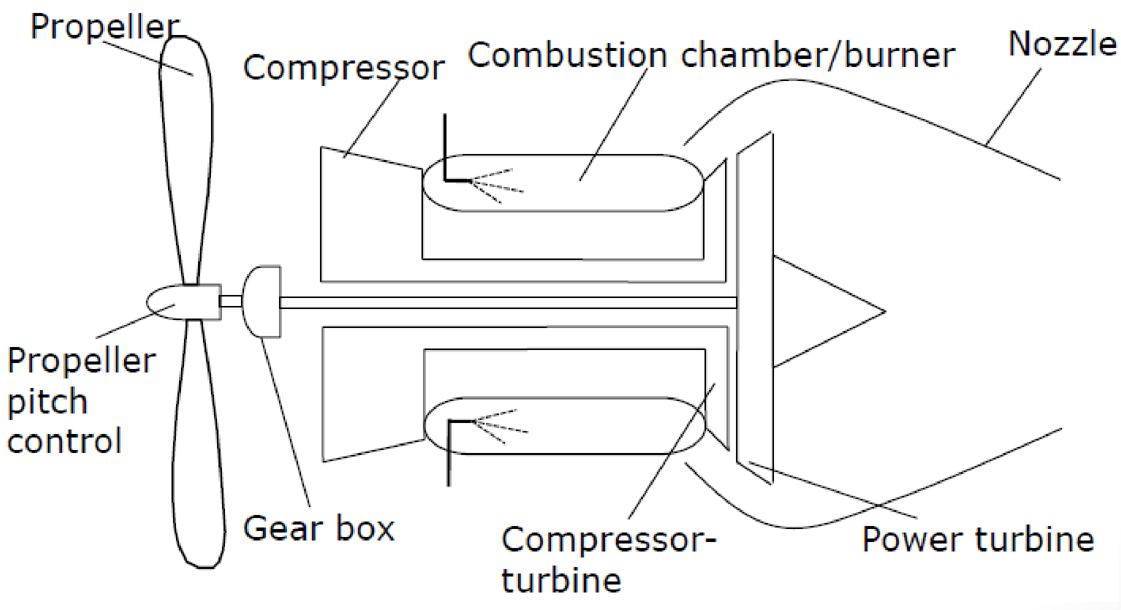
CONTD…

Ideal turboprop engines

- Turboprop engines generate a substantial shaft power in addition to nozzle thrust.
- Jet engine used to turn a large propeller, which produces most (90% or more) of the thrust.
- These have applications at relatively lower speeds.
- These usually have a free-turbine or power turbine to drive the propeller or the main rotor blade.
- Stress limitations require that the large diameter propeller rotate at a much lower rate and hence a speed reducer is required.

CONTD…

- Turboprops may also have a thrust component due to the jet exhaust in addition to the propeller thrust.
- Thrust consists of two components: the propeller thrust and the nozzle thrust.
- The total thrust is equal to the sum of the nozzle thrust and the propeller thrust.



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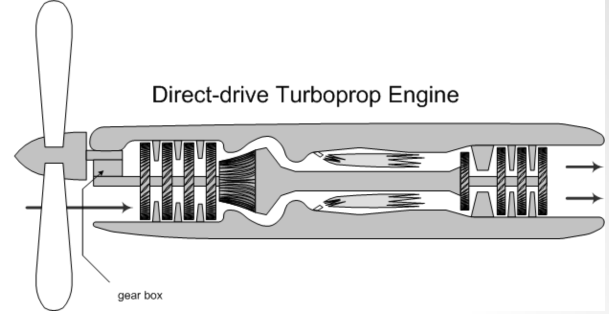
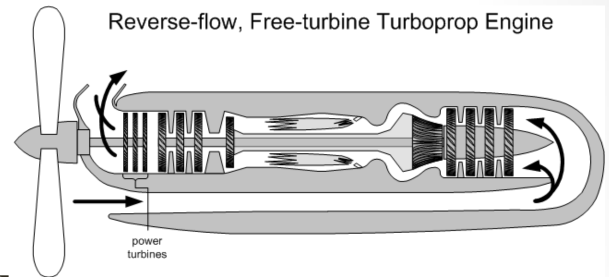




- There are two types of turboprop engine
  - Direct-drive turboprop
  - Free-turbine turboprop
- With the direct-drive system, the propeller is connected to a shaft and turbine and the speed of the propeller is modified through a reduction gear mechanism.
- In the free-turbine system, the propeller is connected to a power turbine which “floats” in the high pressure exhaust gases in the turbine section.
- The free-turbine provides easier maintenance as the power section is not physically connected to the core turbine, but are less powerful by weight and less fuel efficient when compared to direct-drive turboprops.

CONTD…

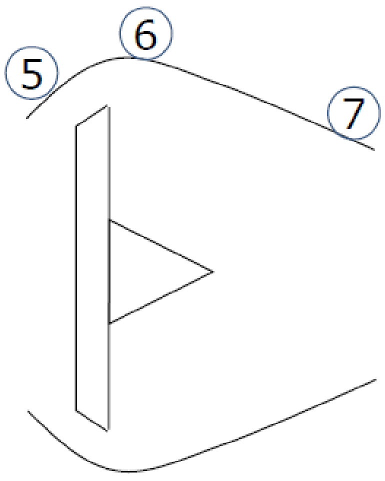
- These aircraft are popular with regional airlines, as they tend to be more economical on shorter journeys.
- Characteristics of turboprop engine:
  - High propulsive efficiency at low airspeeds. (up to 500 mph).
  - Shorter takeoff roll required
  - Lowest TSFC.
  - More complicated and heavier than turbojets.
  - Large frontal area of propeller and engine combination necessitates longer landing gears for low wing airplane.
  - Efficient reverse thrust possible.
  - ***These Characteristics show that the turboprop engines are superior for lifting heavy loads off short and medium runways.***

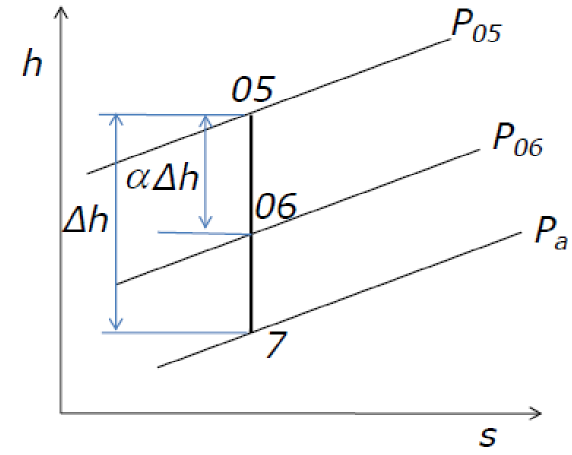
CONTD…

Ideal Turboshaft engines:

- Turboshaft engines, generate only shaft power.
- These engines are used in helicopters. The shaft power is used to drive the main rotor blade.
- Both turboprops and turboshafts have applications at relatively lower speeds.
- These usually have a free-turbine or power turbine to drive the propeller or the main rotor blade (turboshafts).
- Stress limitations require that the large diameter propeller rotate at a much lower rate and hence a speed reducer is required.
- In turboshafts, however, there is no thrust component due to the nozzle.

CONTD…





Enthalpy-entropy diagram for power turbine-exhaust nozzle analysis

VTOL V-22 (Osprey)

Ideal ramjet engines

- Ramjet is the simplest of all the air breathing engines.
- It consists of a diffuser, combustion chamber and a nozzle.
- Ramjets are most efficient when operated at supersonic speeds.
- When air is decelerated from a high Mach number to a low subsonic Mach number, it results in substantial increase in pressure and temperature.
- *So, Ramjets do not need compressors and consequently no turbines as well.*
- In a ramjet, there are no compressors and turbines and hence the analysis is simpler.

CONTD…

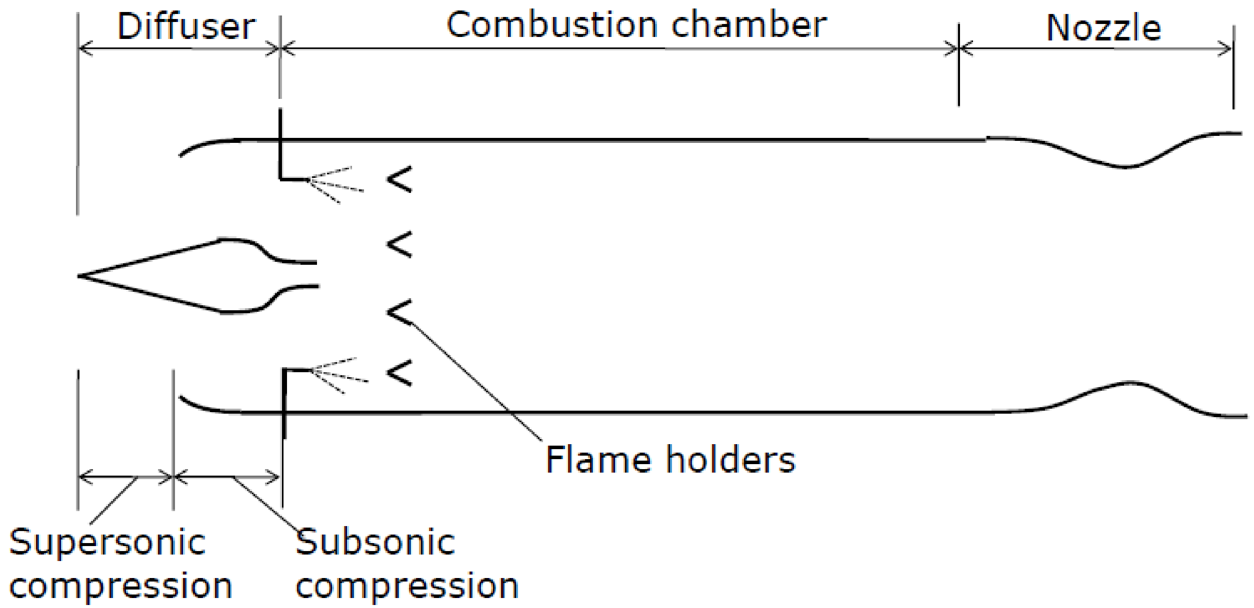
- Also called **Athodyd** (Aerothermodynamic Duct), **Lorin Tube** or **flying stovepipe.**

Assumptions of ideal ramjet engines

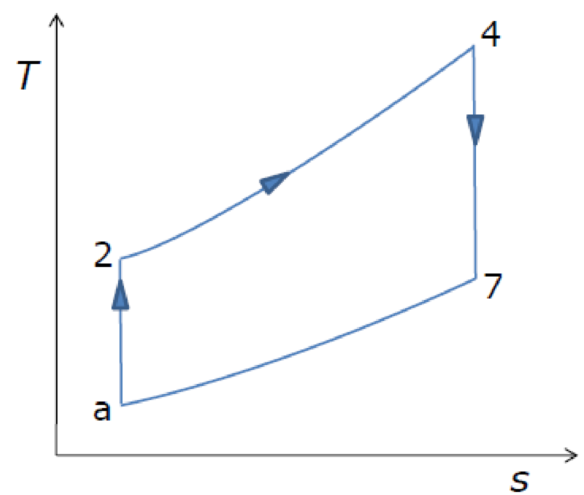
- The dissipation of kinetic energy and thermal energy are absent.
- The pressures in the inlet and in the exhaust sections are equal to the back pressure.
- The stagnation pressure does not vary during heating.
- The working substance is an ideal gas the specific heat of which is constant.

CONTD…

- Schematic of typical ramjet engine



- Ideal ramjet cycle on a T-s diagram



a-2: Isentropic compression in the intake
2-4: Combustion at constant pressure
4-7: Isentropic expansion through the nozzle

CONTD…

- Since ramjets depend upon the ram compression without the use of compressors, *ramjets cannot generate static thrust.*
- Therefore ramjets have to be taken to a sufficiently high speed at which ramjets can start generating thrust of its own.
- Subsonic combustion ramjets have combustor low velocities M2 usually taken between 0.3 and 0.35, and for ideal performance analysis the pressure remains constant (Brayton cycle).
- The low velocity is necessary to keep the flame holders from blowing out, meaning the flames deattach from the flame holders.
- The flow velocity after combustion is larger then before combustion, but still smaller than unity $M2 < M3 << 1$.

CONTD…

- The ratio of the temperature at the inlet and the temperature at the exit is needed to find the thrust.
- Since there is no downstream turbine, a ramjet combustor can safely operate at stoichiometric fuel : air ratios, which implies a combustor exit stagnation temperature of the order of 2,400 K (2,130 °C; 3,860 °F) for kerosene.
- Normally, the combustor must be capable of operating over a wide range of throttle settings, for a range of flight speeds/altitudes.
- A ramjet needs to move forward to develop thrust and is dependent on the ram compression of the incoming air flow.
- Efficient compression of the incoming flow requires high enough velocities.

CONTD…

Advantages

- No moving parts
- Light in weight
- Wide variety of fuels (hydrogen , hydrocarbons etc) can be used.

Disadvantages

- Cannot start of its own, requires a launching device to attain certain velocity. So a ramjet is equipped usually with a turbojet.
- High fuel consumption at low Mach no.
- Complicated Intake and Diffuser design and matching
- Combustion Instability/ requirements of flame holders
- Structural limits are for instance the melting temperature or maximum internal pressure of a material or construction determined by the combustor stagnation temperature Tt3 for a chosen material.

CONTD…

SUPERSONIC COMBUSTION RAMJET (SCRAMJET)

- Ramjet operating in the hypersonic system must operate with supersonic combustion and without normal shock waves to avoid reaching unnecessary high heat transfer and structural loads.
- Scramjet engines operate on the same principles as ramjets, but *do not decelerate the flow to subsonic velocities.*
- Scramjet combustor is supersonic: *the inlet is supersonic and decelerates the flow to a lower Mach number for combustion*, after which it is accelerated to an even higher Mach number through the nozzle.
- By limiting the amount of deceleration, temperatures within the engine are kept at a tolerable level, from both a material and combustive standpoint.
- Even so, current scramjet technology requires the use of *high-energy fuels and active cooling schemes* to maintain sustained operation, often using hydrogen and regenerative cooling techniques.

Non- Continuous Combustion JE

- **Deflagration** is a term describing *subsonic combustion propagating* through heat transfer; hot burning material heats the next layer of cold material and ignites it.
- **Detonation** is a type of combustion involving a *supersonic exothermic front accelerating* through a medium that eventually drives a shock front propagating directly in front of it.

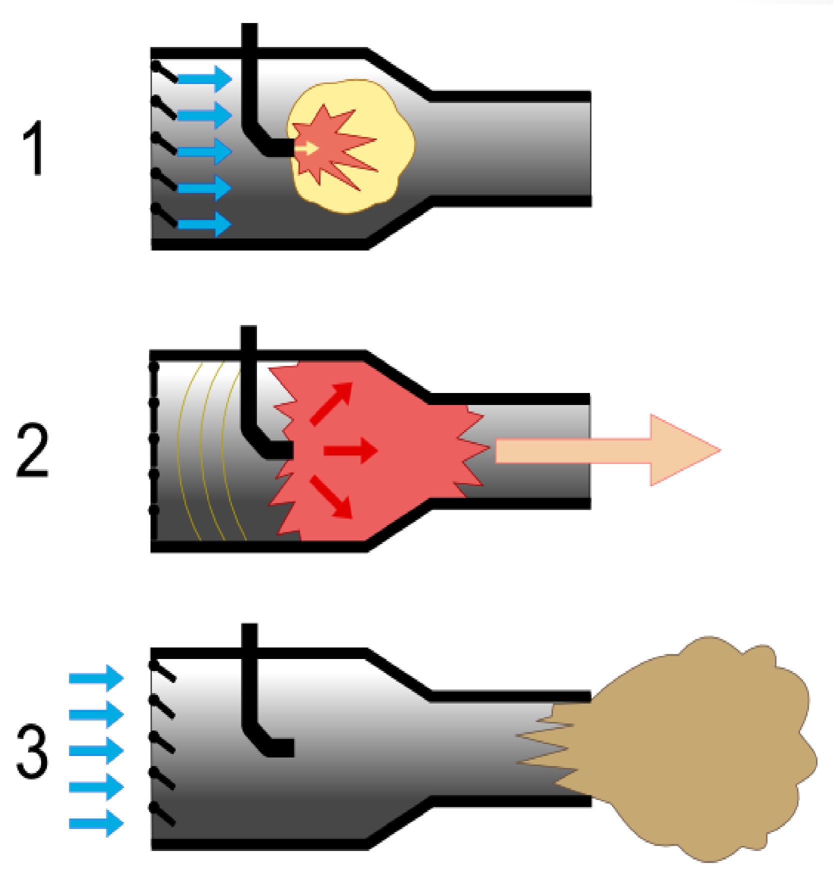
- Deflagrations are subsonic combustion waves: $M_1<1$.
  - Characteristic of combustion in ramjet and turbojet engines.
  - Typical deflagrations propagate at speeds on the order of 1-100 m/s.
  - Across a deflagration, the pressure decreases while the volume increases: $P_2<P_1$ and $v_2>v_1$.

- Detonations are supersonic combustion waves: $M_1>1$.
  - Typical detonation waves propagate at a velocity on the order of 2000 m/s (M_1 on the order of 4-8).
  - Across a detonation, the pressure increases while the volume decreases: $P_2>P_1$ and $v_2<v_1$.
  - For detonations in stoichiometric hydrocarbon fuel-air: P_2/P_1~20.

CONTD…

PULSE JET ENGINE (Deflagration Engine)

- Pulsejets are very simple devices where flow comes in through valves.
- When the combustion is initiated, the flow goes to high temperature and pressure and the flow is evacuated through a nozzle, which could be a convergent or a convergent divergent nozzle.
- As it is evacuated, these valves are forced open and the flow comes in.
- The cycle is repeated.



CONTD…

PULSE JET CYCLE

- The combustion event begins when the combustion chamber pressure is above atmospheric and the temperature of the fuel/air mixture increases, due to mixing with residual products, to the auto ignition temperature.
- A compression wave is generated and combustion increases both temperature and pressure in the combustion chamber, driving the flow toward the exit and inlet at gradually increasing velocity.
- The relatively short combustion event ends and when the compression wave reaches either the pulsejet inlet or the exit, an expansion wave due to overexpansion and travels back into the combustion chamber.

CONTD…

- Flow velocity reaches its positive maximum at the exit at this time. The expansion wave decreases the pressure in the exhaust tube and the combustion chamber to sub atmosphere, resulting in backflow at both the inlet and exit.
- The next charge of air enters into the chamber due to this backflow at the inlet. The mass addition increases the combustion chamber pressure. When the pressure in the combustion chamber approaches the atmosphere pressure, the next cycle begins.
- *Pulsejets operate at around 45 to 50 pulses per second*. They are very fast pulses and the jet engine can operate in a pulsating manner to create almost continuous thrust generation.

CONTD…

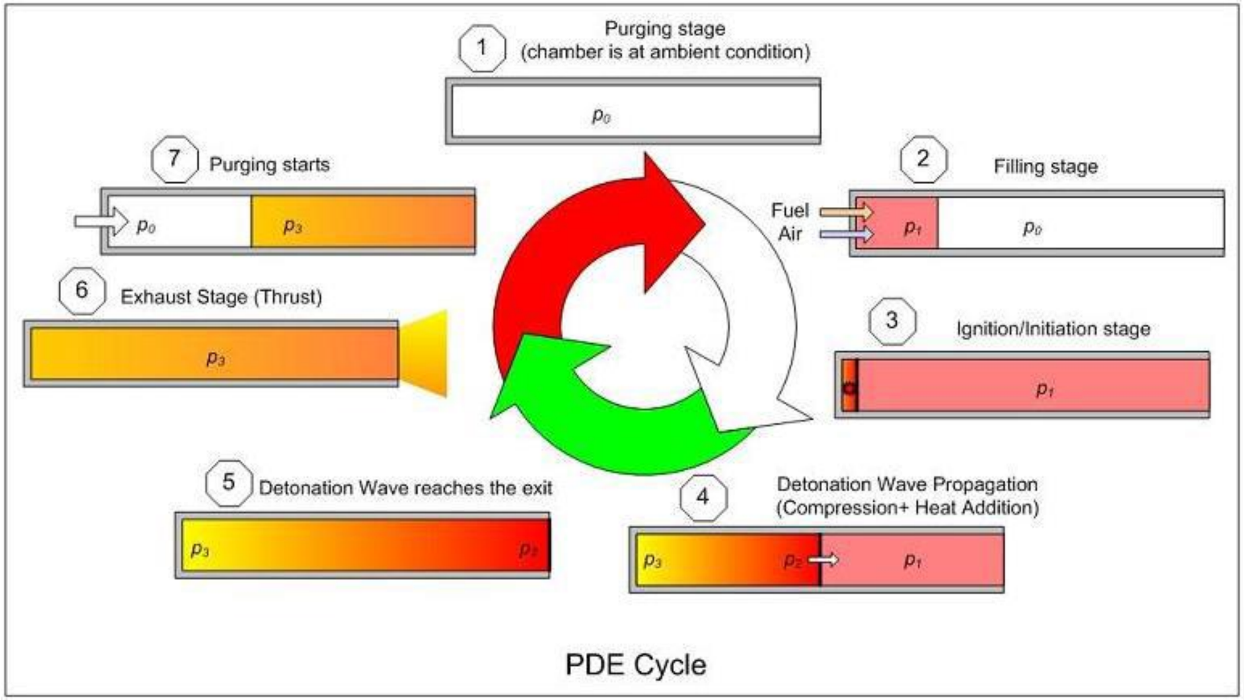
LIMITATIONS

- The fuel injection system, combustion chamber, and the inlet geometry must be carefully designed to create a fast mixing process and the necessary fluid dynamic and acoustic time scales to permit pulsejet operation.
- Another challenge is the heat loss to the walls due to the high surface-area-to volume ratio. Large thermal losses have a direct impact on overall combustor efficiency and they can increase kinetic times and narrow flammability limits through suppression of the reaction temperatures.
- For the oscillating combustion process to be self-sustaining, excessive heat loss, which lowers the temperature of the walls and the residual gas, must be prevented, is generated.

CONTD…

PDE (PULSE DETONATION ENGINE)

- It is a type of propulsion system that uses detonation waves to combust the fuel and oxidizer mixture.
- Supersonic combustion systems
- Constant volume heat addition



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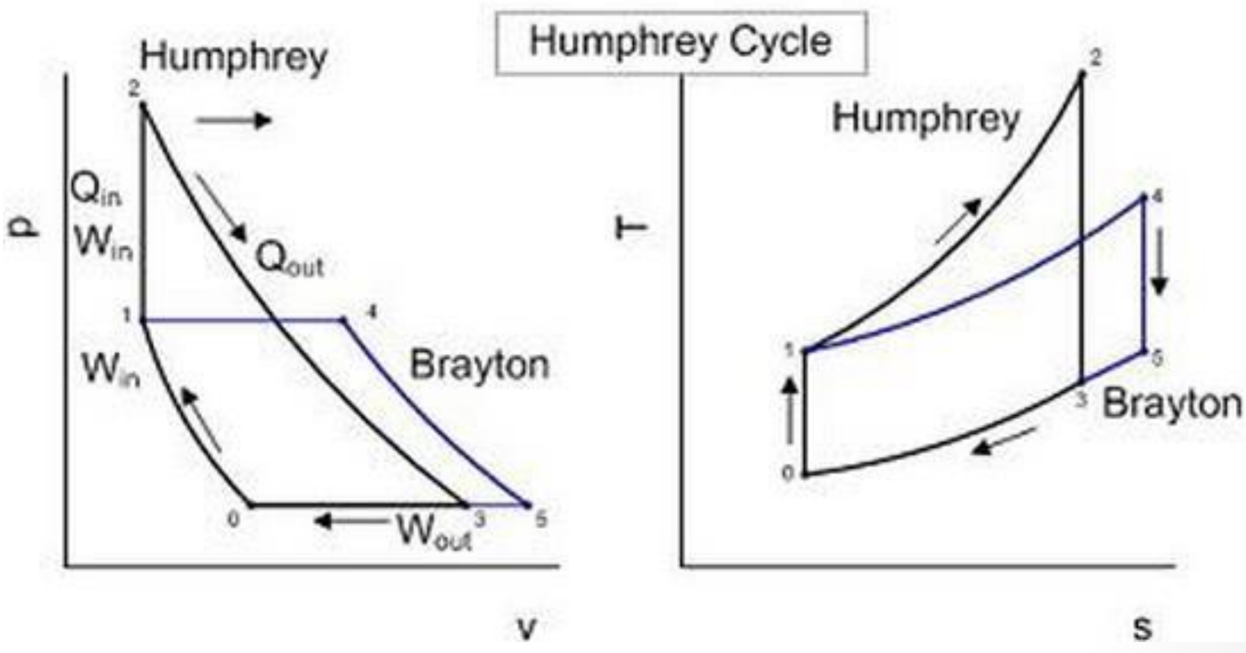
PDE CYCLE

- Similar to Brayton cycle except that the heat addition process occurs at constant volume because combustion takes place so rapidly, the charge (fuel/air mix) does not have time to expand during this process.



CONTD…

LIMITATIONS

- One of the factors affecting the practical implementation of PDEs is the difficulty in achieving consistent detonations within the combustion chamber, within a short tube length.
- Detonation is often difficult to initiate within fuel and air mixtures in shorter tubes, requiring the addition of large amounts of energy.
- A more useful method is to start a deflagrative combustion and then to drive the reaction to a detonation by placing obstacles within the path that will create turbulent mixing and also speed up the flow.
- The process of accelerating the pressure wave into a detonation wave is known as Deflagration to Detonation Transition (DDT). The most effective DDT inducing object is the Shchelkin spiral, which is similar to a helical spring. Other DDT devices include orifice plates and converging-diverging nozzles.

CONTD…

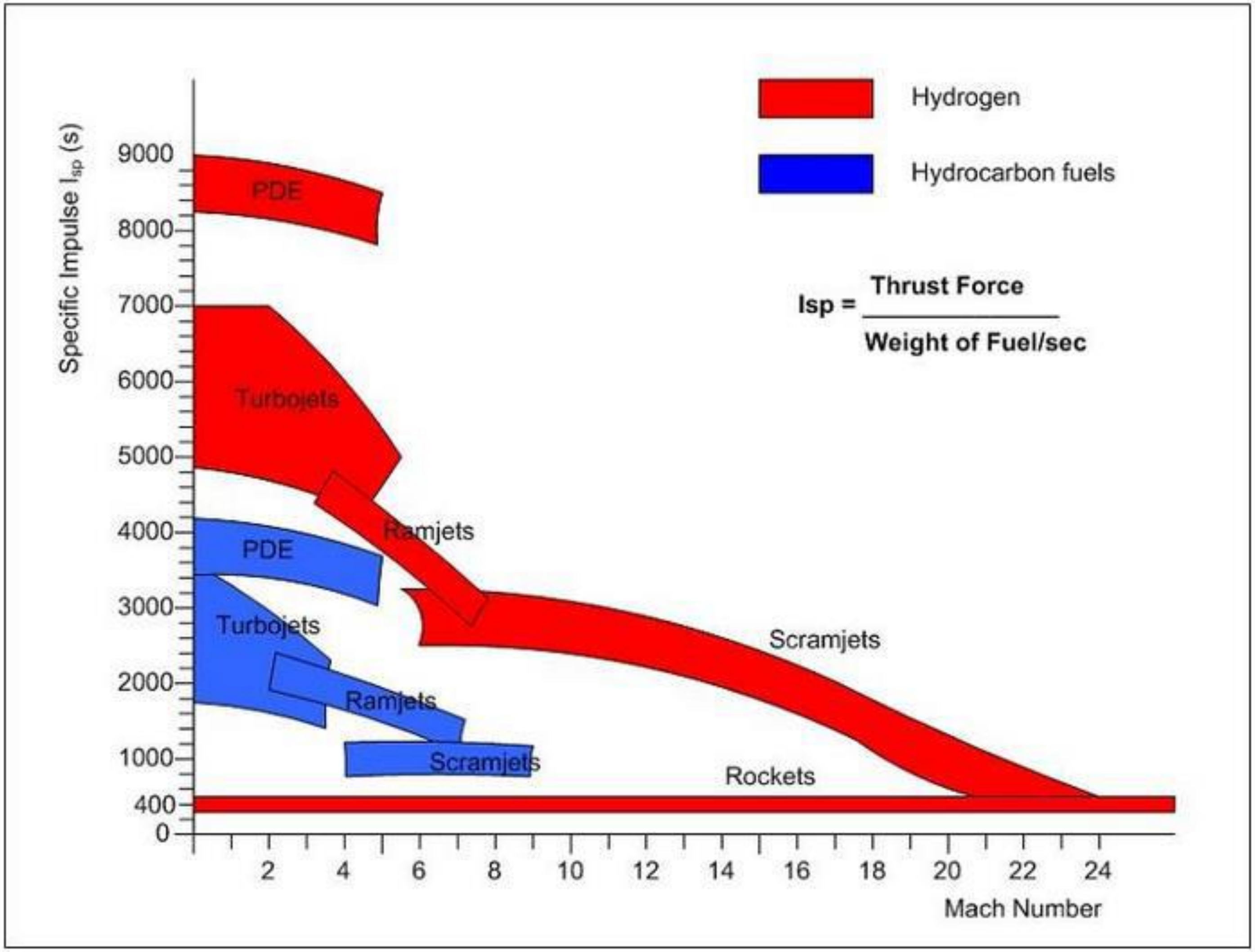


Figure 2: Mach Number versus Specific Impulse for Various Propulsion Systems

ROCKET PROPULSION

- It produces a high temperature reaction mass, as a hot gas which exhausts from high-expansion ratio nozzle to produce thrust.
- Exhaust speeds reaches nearly Mach 10 at sea level
- High specific thrust/ specific impulse
- Commonly called chemical rocket propulsion because of the use of fuel and oxidizer (oxygen is produced within the engine i.e. pure chemical rocket engine is non air breathing.)
- Uses: low-cost weapons, space propulsion, aerospace vehicle boost applications.
- Based on type of propellant (fuel + oxidizer):
  - Liquid Propellant
  - Gaseous Propellant
  - Solid Propellant (Propellant in the form of packed grain)
  - Hybrid propellant (fuel is solid, oxidizer is liquid or gas)

CONTD…

CHEMICAL ROCKET PROPULSION

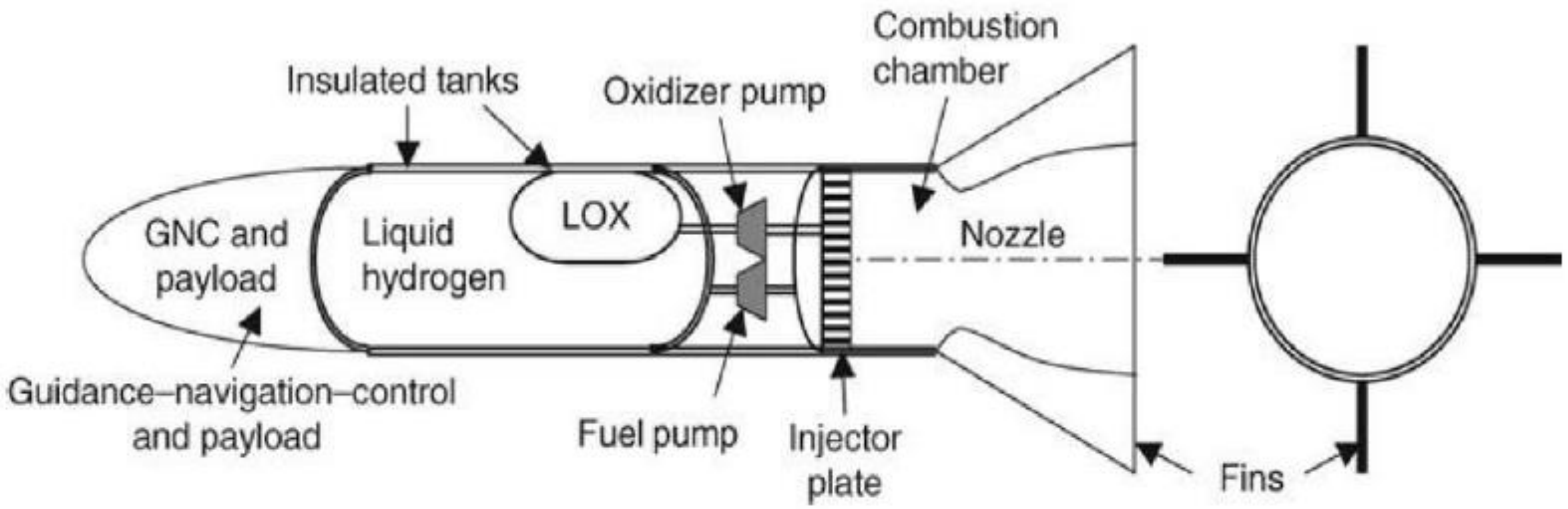


Fig: Schematic diagram of a (simplified) chemical rocket with liquid hydrogen as fuel and liquid oxygen (LO2)as the oxidizer (with turbo-pump feed system)

CONTD…

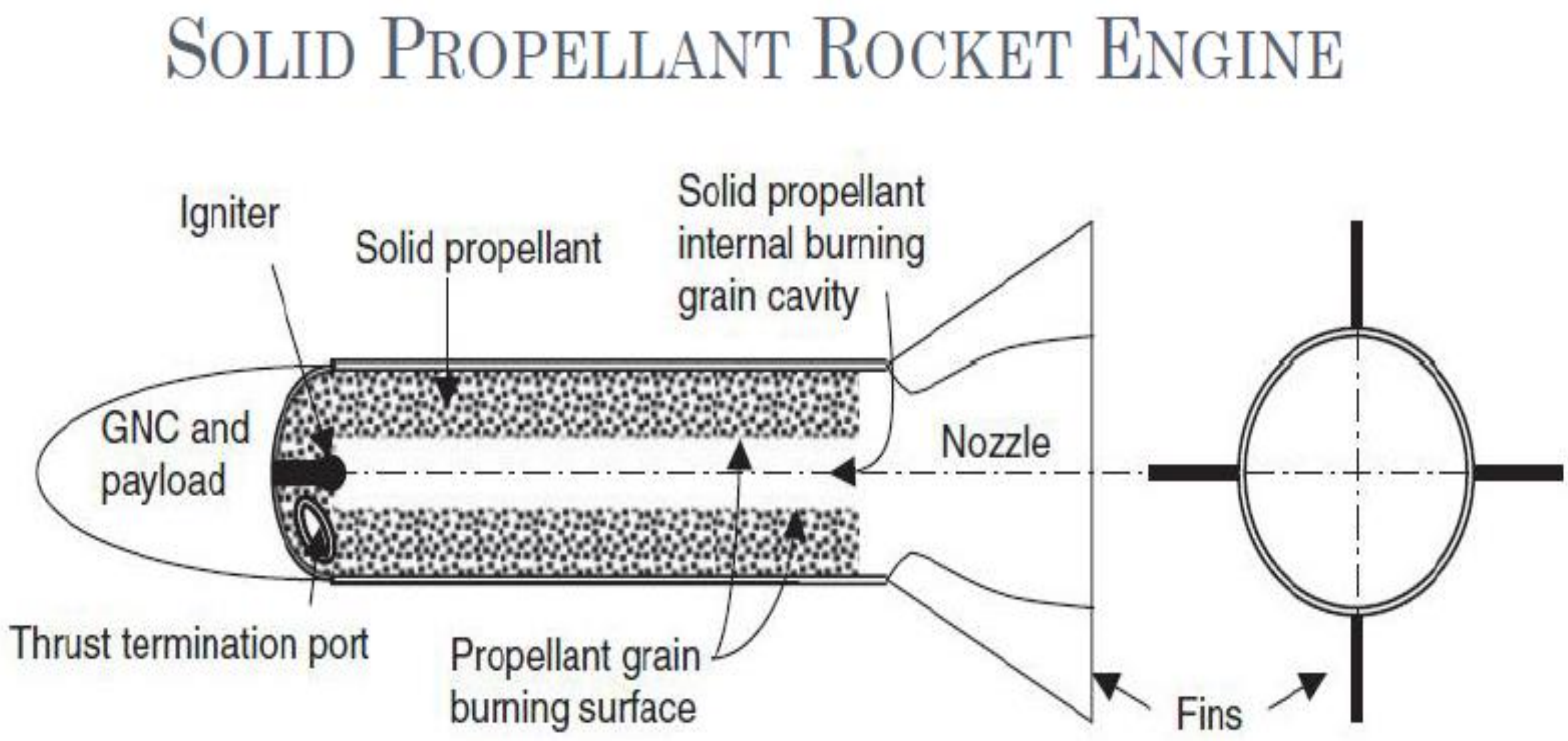


Fig: Schematic drawing of a solid-propellant chemical rocket with internal burning grain

CONTD…

ROCKET ENGINE LIMITATIONS

- The main drawback of rocket engines operating in the Earth's atmosphere is *their high propellant consumption rate per unit thrust produced* as compared to the fuel consumption rate in air-breathing engines.
- To reach LEO (low earth orbit) and maintain a circular orbit, we need to fly about Mach 25. For a single-stage to orbit aircraft (what is known as SSTO), the engine(s) have to produce takeoff thrust, maintain climb rate, and acceleration until the vehicle has achieved Mach 25.

CONTD…

- At takeoff, we could use a turbofan engine and gradually reduce its bypass ratio (as in a variable-bypass TF engine) with flight Mach number until it operates as a turbojet.
- Then, we should be able to shut down the gas generator all together near Mach 3 and switch over to a conventional (or subsonic combustion) ramjet for up to ∼Mach 6.
- The scramjet is to take over beyond Mach 6 and accelerate the vehicle through Mach 10–15, depending on the hydrocarbon or hydrogen fuel, respectively.
- At these Mach numbers, we are still too slow to maintain a circular orbit at LEO. Therefore, chemical rocket engines have to be fired for the last leg of our launch, which should take the vehicle to Mach 25 and low Earth orbit.
- The main challenge for such a *combination propulsion system* (CPS) is complex system integration into a vehicle and the mechanical complexities involved in transition from one set or class of engines to another.
- This gives rise to a *combined cycle engines (CCE or CCPS)*or *hybrid engines* which is completely different from CPS.

Hybrid jet Engines

COMBINED CYCLE PROPULSION SYSTEM (CCPS ENGINE)

- An engine system whose main element is the ramjet/PDE engine (with subsonic and or supersonic combustion) that is boosted to ramjet/PDE takeover speed by means of turbo engine (turbo-accelerator) or rocket based system and that uses ramjet/PDE propulsion at the higher speeds.
- A CCPS (combined cycle propulsion system) is defined as a single propulsion system assembly that has multiple operating modes using the same propulsion subsystems (compressor, combustor, and nozzle) interchangeably throughout the flight.
- The first mode of operation is low speed subsystem from Mach 0 to 3, supersonic subsystem from Mach 3 to 5, hypersonic subsystem from Mach 5 to 10, and finally the rocket subsystem from Mach 10 to orbital velocity.
- The basic subsystems are turbofan or turbojets, ramjets or pulsejets, and rockets.

CONTD…

- Types of CCPS
  - Rocket Based Combined cycle (RBCC)
  - Turbine Based Combined Cycle (TBCC)
- A typical TBCC propulsion system would utilize a turbofan or turbojet to produce thrust and accelerate the vehicle from rest to an intermediate Mach number.
- A secondary airstream would bypass the main combustor of the turbojet or turbofan and go to an afterburning ram duct which provides greater thrust at higher Mach numbers.
- Once the vehicle is at supersonic speeds, an inlet shock cone and turbo-compressor diffuse the air into the ramjet afterburner.
- A great example of a TBCC propulsion system, the Pratt & Whitney J-58, is used to power the supersonic Lockheed Martin SR-71 Blackbird.

CONTD…

- While the TBCC propulsion system would be extremely useful at relatively low Mach numbers, it is not suitable for use on an SSTO launch vehicle.
- In order to use a TBCC propulsion system on an SSTO vehicle, the fan and turbine components would have to be moved out of the main flight path and into stowage during high-speed flight through the atmosphere.
- However, they would be well suited for applications in a two-stage-to-orbit (TSTO) vehicle as the lower stage booster.

CONTD…

- RBCC is defined as any propulsion system which utilizes a rocket element as its primary propulsion element in achieving static thrust and ultimately trans-atmospheric insertion, while simultaneously using any number of complimentary propulsion system cycles (usually ramjet) to augment the performance throughout its mission profile.
- At takeoff where conventional ramjets are incapable of producing thrust, a rocket is fired (with an ejector nozzle configuration to get a thrust boost) that accelerates the vehicle to, say, Mach 2. At Mach 2, the rocket is turned off and air intakes are opened to start a subsonic ramjet engine operation.

CONTD…

- The air-breathing engine switches from the subsonic to supersonic combustion ramjet (scramjet) near Mach 5. The scramjet will accelerate the vehicle to, say, Mach 15.
- The air intakes close at Mach 15 and rocket operation resumes accelerating the vehicle to orbital speeds (~Mach 25 or higher).
- Also known as rocket based air-breathing propulsion.
- Example: SABRE (synergetic air breathing rocket engine)

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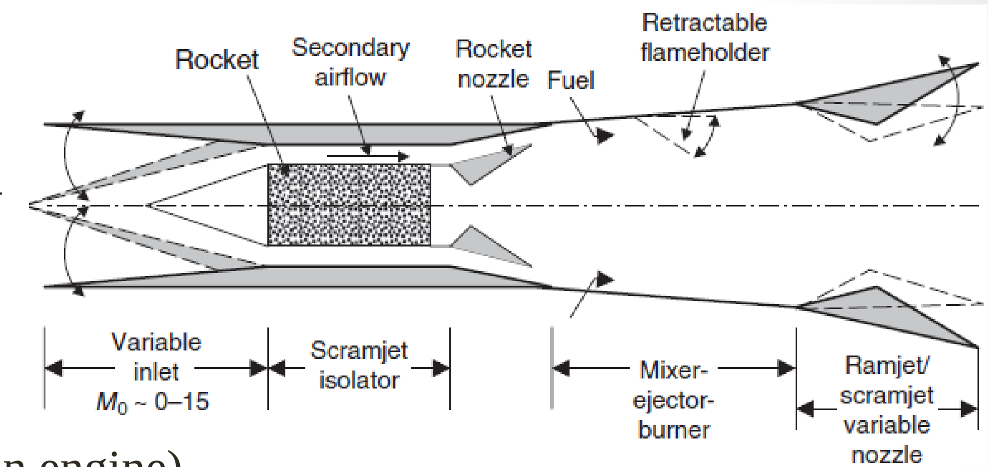
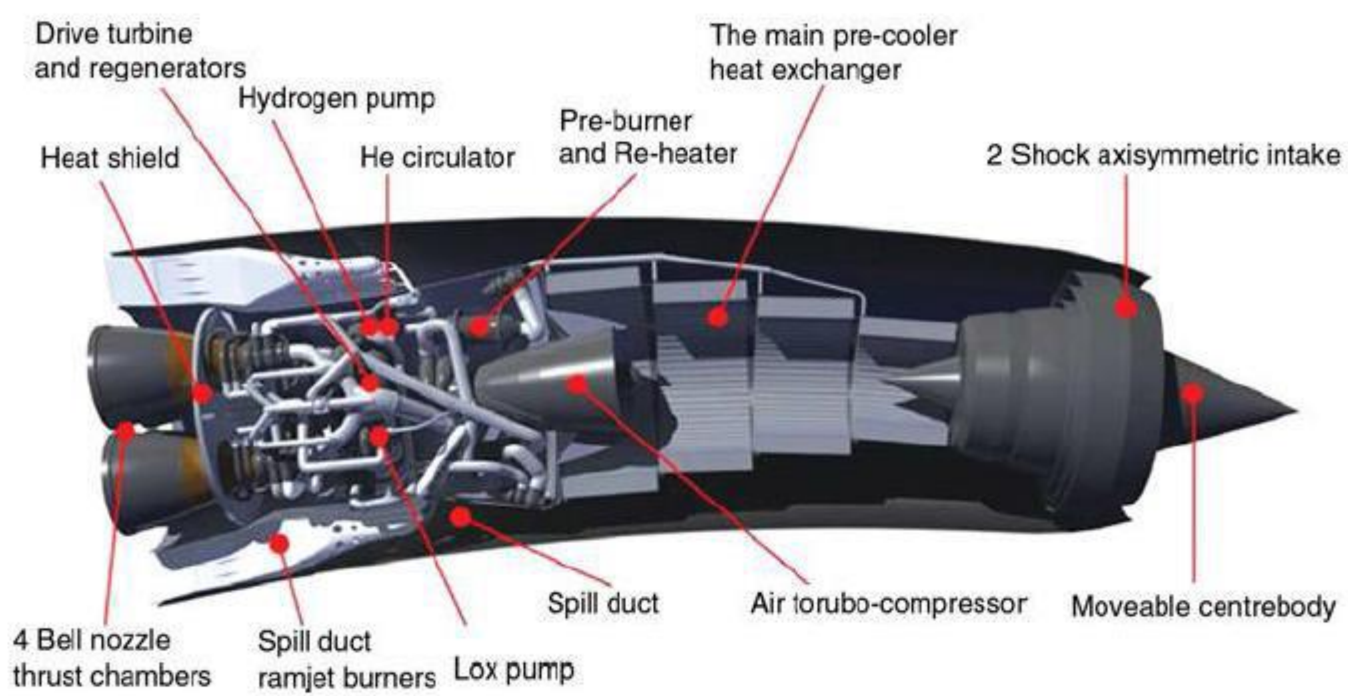
CONTD…

RBCC IN PROPULSION



OTHER VARIANTS OF CCPS

- PDTE (Pulsed detonation turbofan engine)
- TRCC (Turbo rocket combined cycle)



Engines used on Aircrafts Operating in Nepal

- Turbo prop
  - Examples: de Havilland Canada DHC-6 Twin Otter, ATR, Dronier Do 228, Beechcraft, Hawker Siddeley (HS) 748 (Nepal Army), etc.
- Turbo fan
  - Examples: B737, B757, B777, A330, A320 series, etc.
- Turbo shaft
  - Russian MI-17 and MI-8 (Nepal Army), Indian HAL Dhruv, etc

THANK YOU !!!