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DEPARTMENT OF AEROSPACE ENGINEERING

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UNIT II - JET ENGINE INTAKES AND EXHAUST NOZZLES

Real Flow Losses in Nozzles

Theory of flow in isentropic nozzles

The task of the exhaust nozzle is to convert gas potential energy into kinetic energy (i.e., gas velocity) necessary for the generation of thrust. This is accomplished solely by the geometrical shape of the nozzle, which is a tube of varying cross-section. Not every nozzle type performs in the same manner. Depending on the type of aircraft and design flight speed, different types of nozzles are employed. Ai

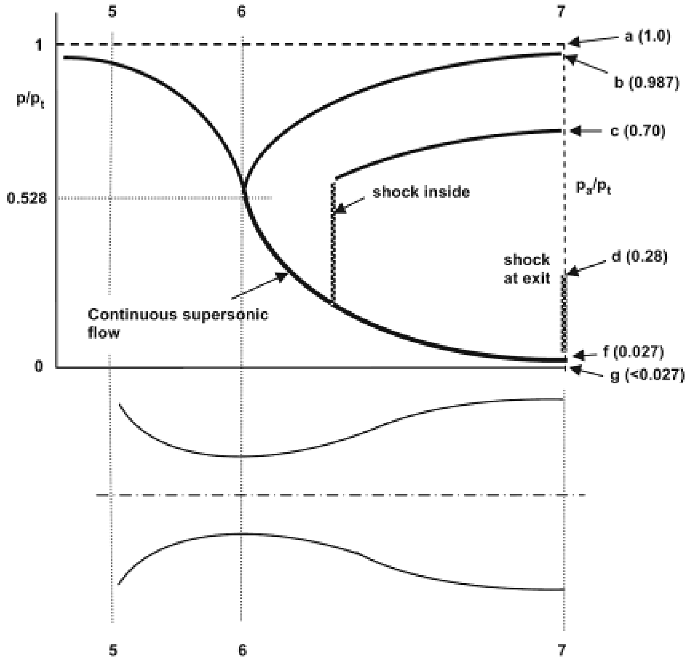


FIGURE 5.3

To illustrate the nature of the flow in the different regions of the Nozzle, we consider the case of a nozzle designed for air (Ɣ = 1.4) and at exit Mach number M = three under different back pressures.

- Pa/Pt, = I: The hack pressure is equal to the supply stagnation pressure, and there is no flow in the Nozzle.
- Pa/Pt = 0.987: The back pressure is low enough to have the flow accelerate and choke the throat
- Pa/Pt = 0.70: Here, the back pressure is low enough to ensure starting but not low enough to permit supersonic flow throughout the nozzle. The supersonic flow must "shock down." that is. A normal shock must appear to bring down the Mach number to an appropriate subsonic level so that a higher static pressure is produced behind the shock. Further diffusion through the increasing area duct serves to bring the pressure at the exit up to the appropriate level.
- Pa/Pt = 0.28: In this instance. The back pressure is low enough to ensure supersonic flow throughout the nozzle but still higher than the pressure at the end of the nozzle.
- 0.28 :> Pa/Pt > 027: In this range of hack pressure, the flow is continuously supersonic throughout the nozzle, and the adjustment of the exhaust pressure takes shock waves occurring outside the nozzle properly. Because the back pressure is higher than the exit pressure. The nozzle is said to be "over-expanded."
- Pa/Pt = 0.027: Here, the exit pressure is exactly equal to the back pressure, and the flow is continuously supersonic throughout. And the exhaust stream is perfectly adapted to the surrounding ambient pressure. This case is called the perfectly expanded nozzle.
- Pa/Pt< 0.027: For all back pressures below the perfectly expanded value, the flow through the nozzle is supersonic, and the adjustment to the low back pressure takes place outside the nozzle. This case is called the under-expanded' nozzle.

Functions of the Nozzles

- Accelerate the flow to a high velocity with minimum total pressure loss
- Match exit and atmospheric pressure as closely as desired
- Permit afterburner operation without affecting main engine operation

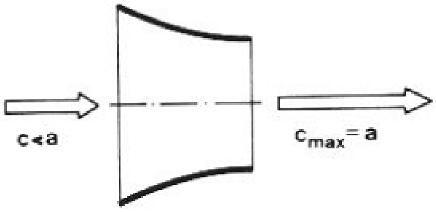
- Allow for cooling of blades
- Mix core and bypass streams of turbofan if necessary
- Allow for thrust vectoring
- Suppress jet noise and infrared radiation
- Thrust vector control.

Classifications of exhaust nozzles

- Convergent or C-D types
- Axisymmetric or two-dimensional types
- Fixed geometry or variable geometry types

Convergent nozzle:

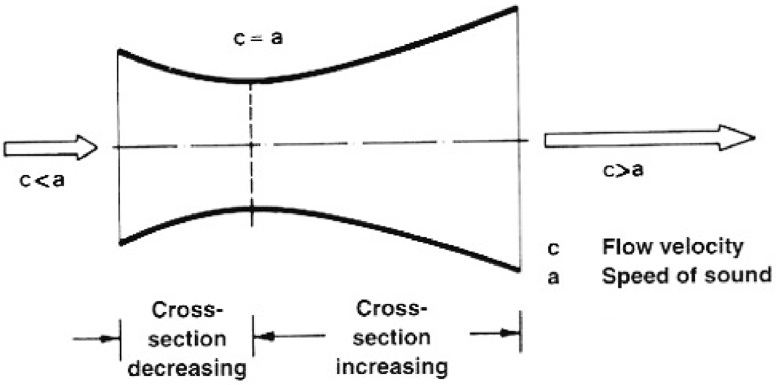
In a convergent nozzle, the cross-section of a duct decreases in the streamwise direction if a subsonic fluid flow is to be accelerated. A convergent nozzle is fitted to all airliners which fly at subsonic or transonic speeds. Thus, it is either of the axisymmetric ortannular geometry. All subsonic/ transonic turbojets and turboprop engines have one axisymmetric convergent nozzle.



Convergent-Divergent Nozzles:

For higher exhaust velocities above Mach 1.5. A convergent-divergent nozzle shape is required. The geometric characteristic of this nozzle is a decreasing cross-sectional area in its forward part (much like a convergent nozzle), followed by a cross-sectional increase in its rearward portion (the divergent section).

In this nozzle, the subsonic flow is accelerated in the converging section up to the minimum area or throat. It reaches a sonic speed exactly at the throat In the divergent section, pressure is allowed to decrease below its critical value, with fluid velocity continuing to accelerate to supersonic values.

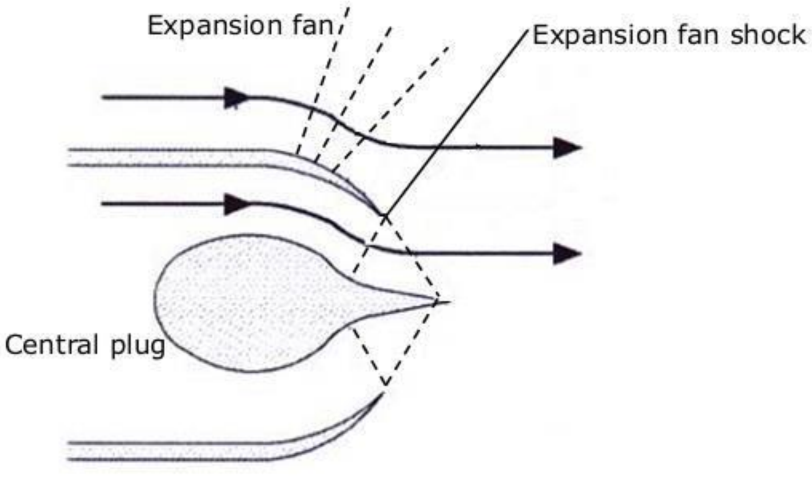


Variable Geometry Nozzles:

A variable area nozzle, which is sometimes identified as an adjustable nozzle, is necessary for engines fitted with afterburners. Generally, as the nozzle is reduced in area, the turbine inlet temperature increases, and the exhaust velocity and thrust increase. Three methods are available, namely:

- Central plug at nozzle outlet
- Ejector-type nozzle
- IRIS nozzle

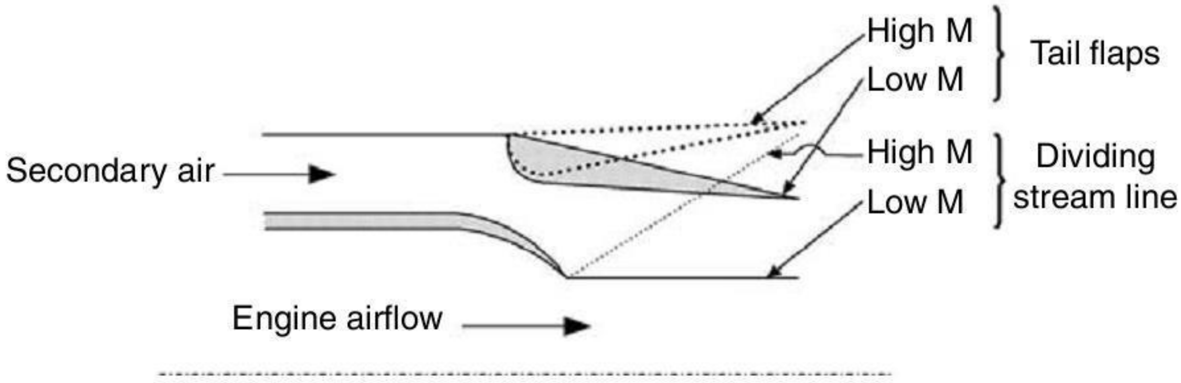
Central plug at nozzle outlet A



The plug nozzle is the exact analog of the isentropic spike inlet. The improvement in off-design performance results from the flow remaining attached to the spike at pressure ratios below design, while the stream tube leaving the nozzle contracts to satisfy the requirements for a lower expansion ratio.

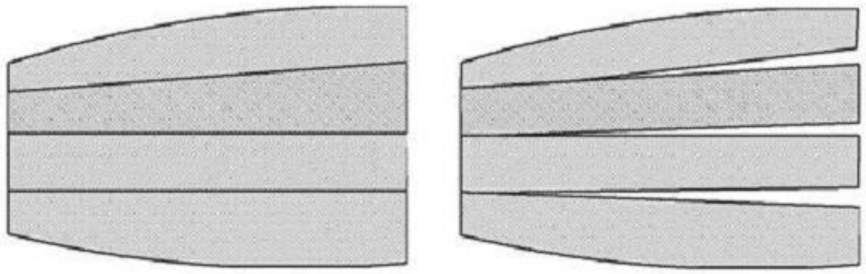
Variable geometry ejector nozzle with tail flaps

This type of nozzle is effective through a secondary airflow and spring-loaded petals. At subsonic speeds, the airflow constricts the exhaust to a convergent shape. As the aircraft speeds up, the two nozzles dilate, which allows the exhaust to form a C-D shape, speeding the exhaust gases past Mach 1 Advantages of the ejector nozzle are relative simplicity and reliability. Disadvantages are average performance (compared to the other nozzle types) and relatively high drag due to the secondary airflow.



IRIS nozzle

Iris nozzle, which is used for higher-performance nozzles. This type uses overlapping, hydraulically adjustable "petals." Although more complex than the ejector nozzle, it has significantly higher performance and smoother airflow. It is employed primarily on high-performance fighters such as F-16. Some modern iris nozzles can change the angle of the thrust.



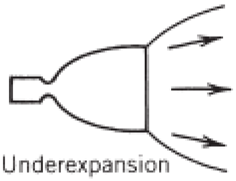
Losses in a Nozzle

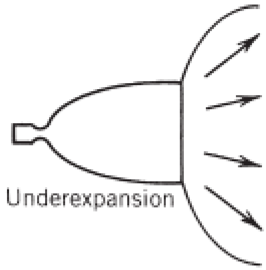
- Thrust loss due to exhaust velocity vector angularity.
- Thrust loss due to the reduction in velocity magnitude caused by friction in the boundary layers
- Thrust loss due to loss of mass flow between nozzle entry and exit from leakage through the nozzle walls
- Thrust loss due to flow no uniformities.

The behavior of the Nozzles at different altitudes

When the exit pressure, Pe, is greater than the ambient pressure, Pa, the expansion process to the ambient pressure is incomplete. The nozzle is then said to be an under-expanded nozzle. The opposite conditions prevail when Pe<Pa The exit pressure is lower than the ambient pressure, and the nozzle is said to be over-expanded.

A rocket traverses different altitudes, and the ambient pressure decreases as the rocket moves away from the surface of the Earth. If the area ratio of the nozzle is designed for optimum conditions at a given altitude of operation, it will be operating in an 'under-expanded' condition for altitudes higher than the design altitude (Pe=Pa), whereas it will function as an 'over-expanded' nozzle for the lower altitudes (Pe<Pa).





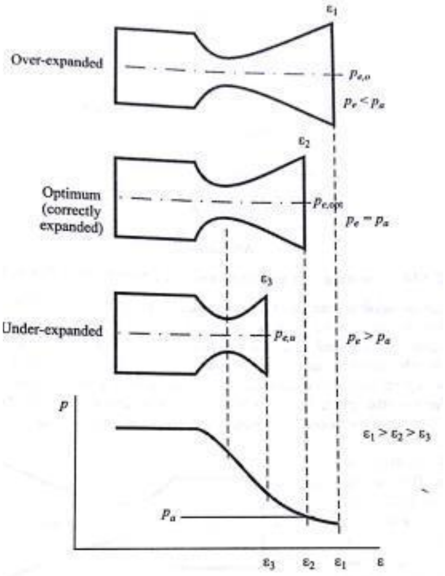


Fig. 3.17 Under-expanded and Over-expanded Nozzles

Nozzle choking

Fluid flows through a restricted area whose rate reaches a maximum when the fluid velocity reaches the sonic velocity at some point along the flow path.

The phenomenon of choking exists only in incompressible flow and can occur in several flow situations.

Through Varying-Area Duct:

Choked flow can occur through a convergent flow area or nozzle attached to a huge reservoir. Flow exits the reservoir through the nozzle if the back pressure is less than the reservoir pressure. When the back pressure is decreased slightly below the reservoir pressure, a signal from beyond the nozzle exit is transmitted at sonic speed to the reservoir.

The reservoir responds by sending fluid through the nozzle. Further, the maximum velocity of the fluid exists at the nozzle throat where the area is smallest. When the back pressure is further decreased, fluid exits the reservoir more rapidly. Eventually, however, the velocity at the throat reaches the sonic velocity.

Then, the fluid velocity at the throat is sonic, and the velocity of the signal is also sonic. Therefore, further decreases in back pressure are not sensed by the reservoir and correspondingly will not induce any greater flow to exit the reservoir. The nozzle is thus said to be choked, and the mass flow of fluid is a maximum.

With Friction:

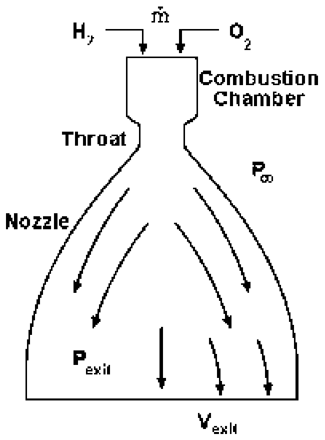
Choked flow can also occur through a long, constant-area duct attached to a reservoir. As fluid flows through the duct, friction between the fluid and the duct wall reduces the pressure acting on the fluid.

As pressure is reduced, other fluid properties are affected, such as sonic velocity, density, and temperature. The maximum Mach number occurs at the nozzle exit and choked flow results when this Mach number reaches 1.

With Heat Addition:

A reservoir with a constant-area duct attached may also be considered in the case that the flow through the duct is assumed to be frictionless, but heat is added to the system along the duct wall.

Over - Under Expanded Nozzle

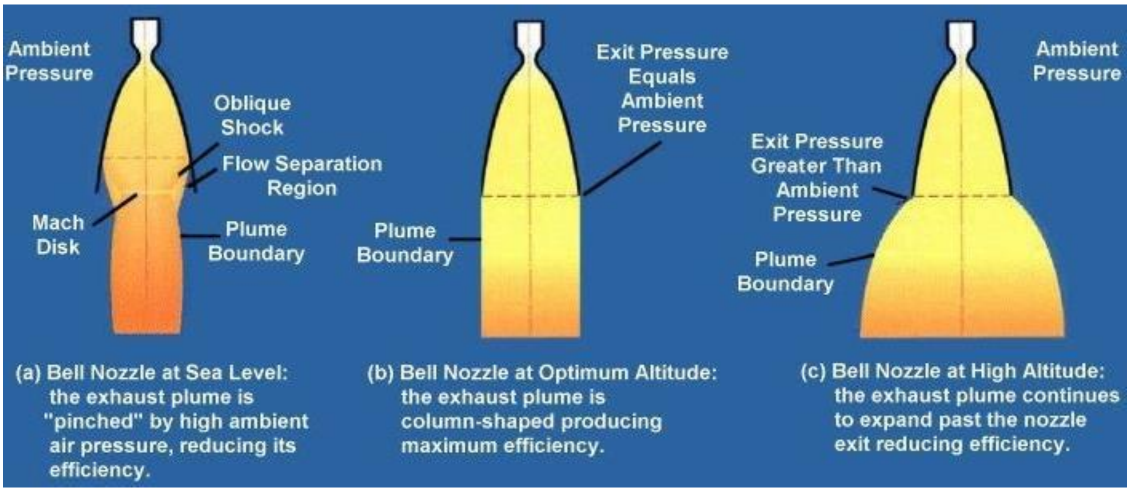


Flow passing though a rocket nozzle

Expansion is the process that converts the thermal energy of combustion into kinetic energy to move an object forward. In other words, the hot gases created by burning fuel inside a jet or rocket engine are exhausted through a nozzle to produce thrust. It is the shape of this nozzle that is key to the expansion process. As that high-temperature flow is exhausted, it expands against the walls of the nozzle to create a force that pushes the vehicle forward.

The behavior of this expansion process is largely dictated by pressure--both the pressure of the exhaust itself as well as the pressure of the external environment into which it exhausts. Of greatest concern is to design the shape and length of the nozzle so that it converts as much of that thermal energy into thrust as possible. In an ideal nozzle that optimizes performance, the exit pressure (Pexit) will be equal to the ambient pressure of the external atmosphere (P¥). The flow, in this case, is perfectly expanded inside the nozzle and maximizes thrust.

Unfortunately, this situation can only occur at one specific atmospheric pressure on a fixed-geometry nozzle. As we have seen previously, pressure decreases as altitude increases. Nozzle designers typically must select a shape that is optimum at only one altitude but minimizes the losses that occur at lower or higher altitudes. These losses result from the fact that the atmospheric pressure will either be higher than the exit pressure of the exhaust gases, i.e., at low altitudes, or lower than the exit pressure, i.e., at high altitudes.



This first case, where the external pressure is higher than the exit pressure, is referred to as over-expanded. When an over-expanded flow passes through a nozzle, the higher atmospheric pressure causes it to squeeze back inward and separate from the walls of the nozzle. This "pinching" of the flow reduces efficiency because that extra nozzle wall is wasted and does nothing to generate any additional thrust. Ideally, the nozzle should have been shorter to eliminate this unnecessary wall.

The opposite situation, in which the atmospheric pressure is lower than the exit pressure, is called under-expanded. In this case, the flow continues to expand outward after it has exited the nozzle. This behavior also reduces efficiency because that external expansion does not exert any force on the nozzle wall. This energy can, therefore, not be converted into thrust and is lost. Ideally, the nozzle should have been longer to capture this expansion and convert it into thrust.