Chapter 4

Gas Turbine Engine Cycle Analysis

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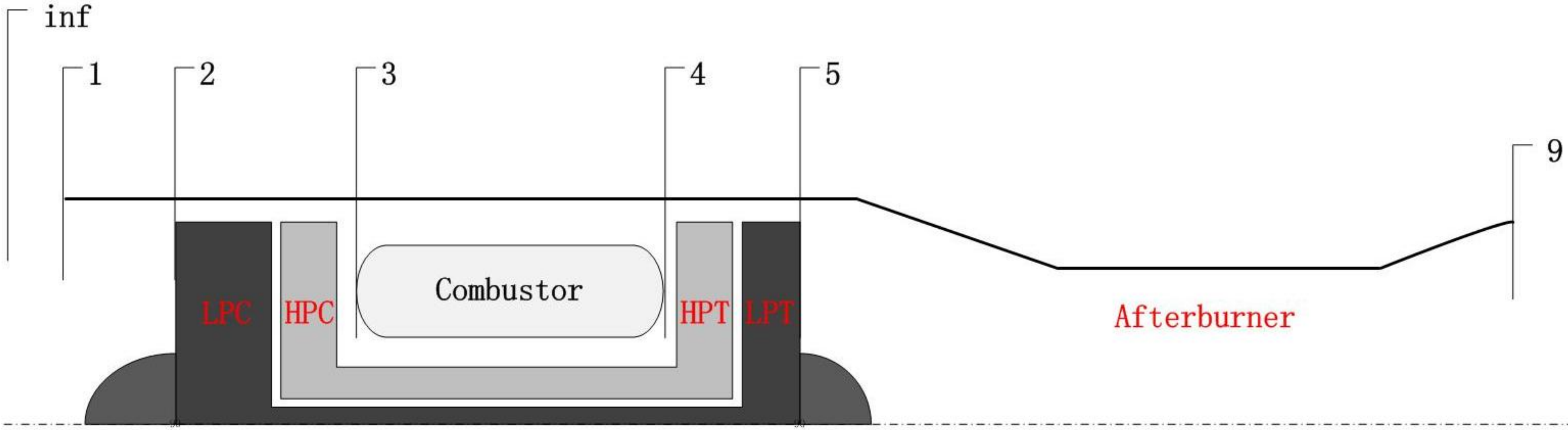
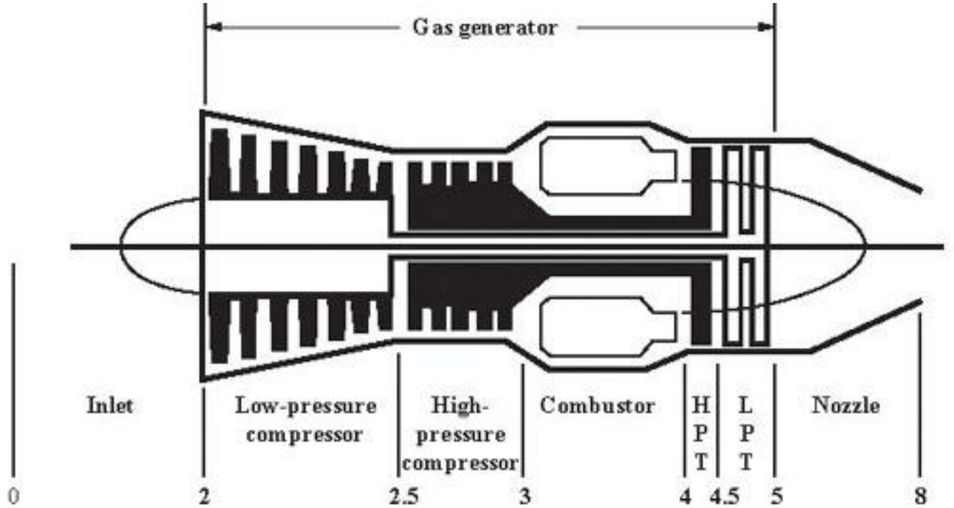
Gas Turbine Engine Parameters

- **Compressor pressure ratio** (*design* parameter): dictate the number and type of compressor stages.
  - The higher the Mach number, the lower the compressor pressure ratio requirement;
  - Above Mach 3, no mechanical compression is needed (ramjet).
- **Compressor air mass flow rate** (*size* parameter).
- **Combustor fuel flow rate/turbine entry temperature** (*temperature limit* parameter): dictate the material and cooling technologies to be employed in the engine hot section, i.e. the turbine and nozzle sections, at the design stage.
- **Fuel heating value** (*ideal fuel energy* parameter)
- **Component efficiency** (*irreversibility* or loss parameter)

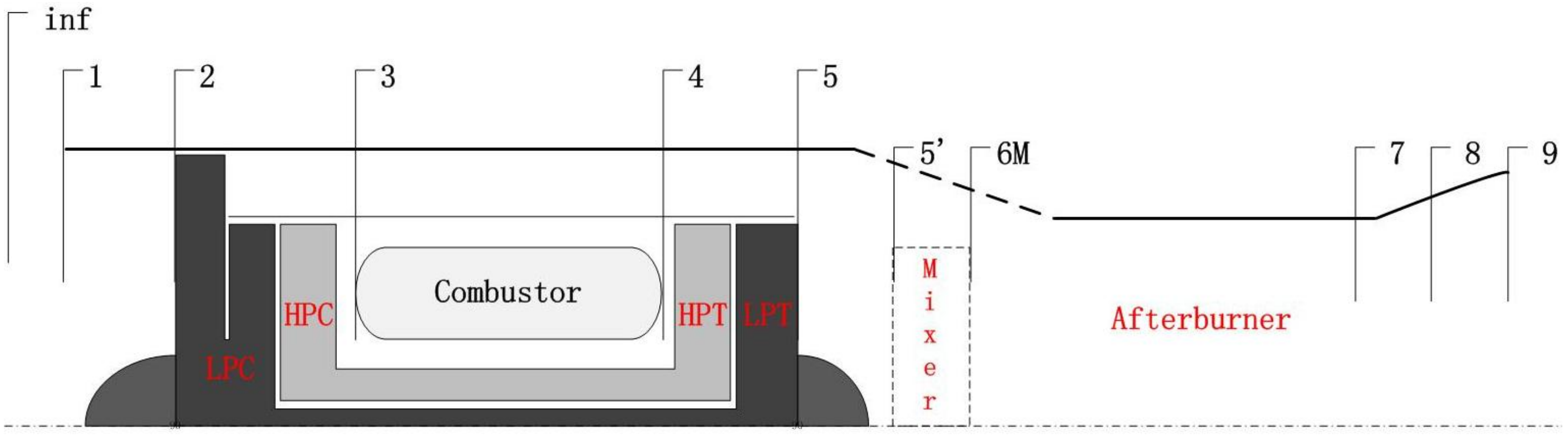
Engine Station Numbers



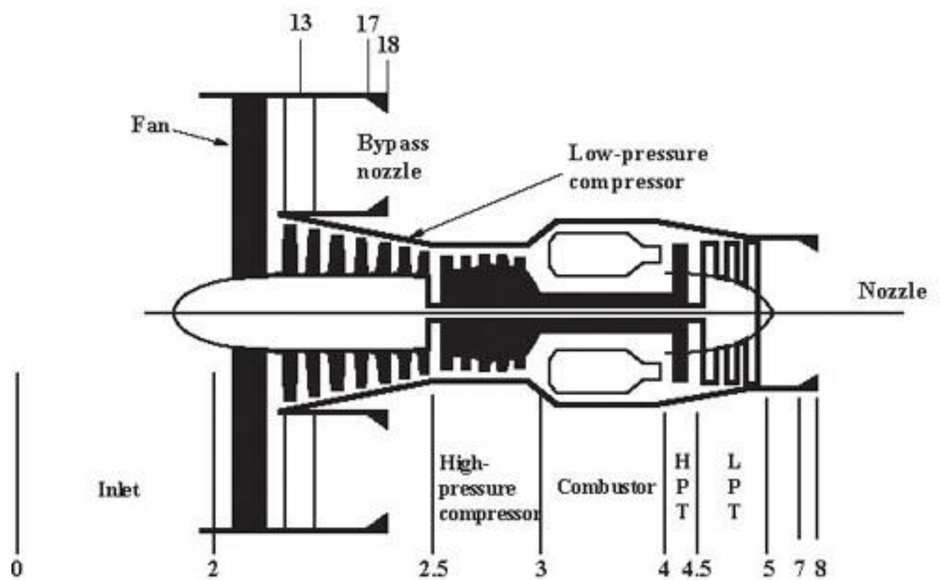
Turbojet Engine Stations



Engine Station Numbers



Turbofan Engine Stations

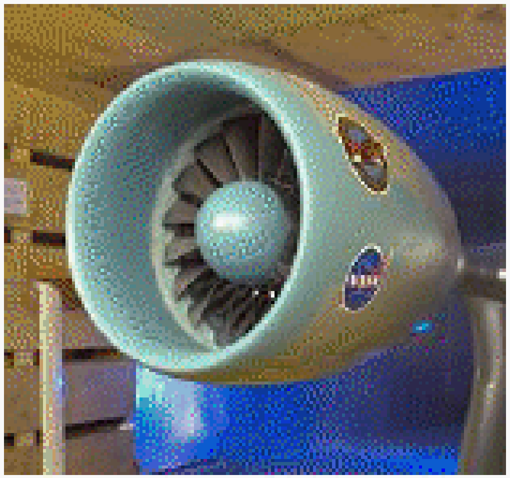


1. The Turbojet Engine

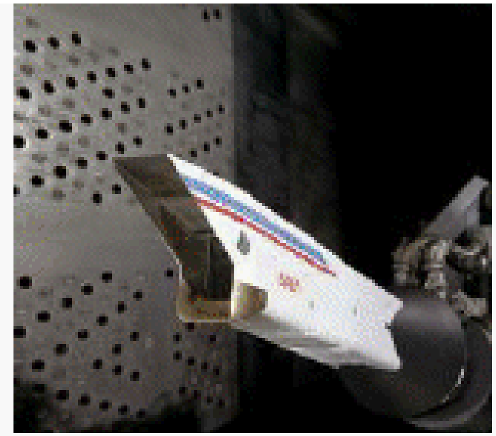
➢ **The Inlet**

1. The Turbojet Engine

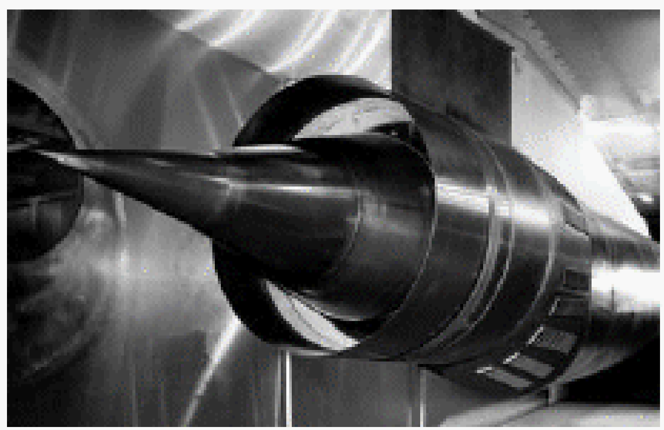
- **The Inlet**



Subsonic



Rectangular Supersonic



Axisymmetric Supersonic

1. The Turbojet Engine

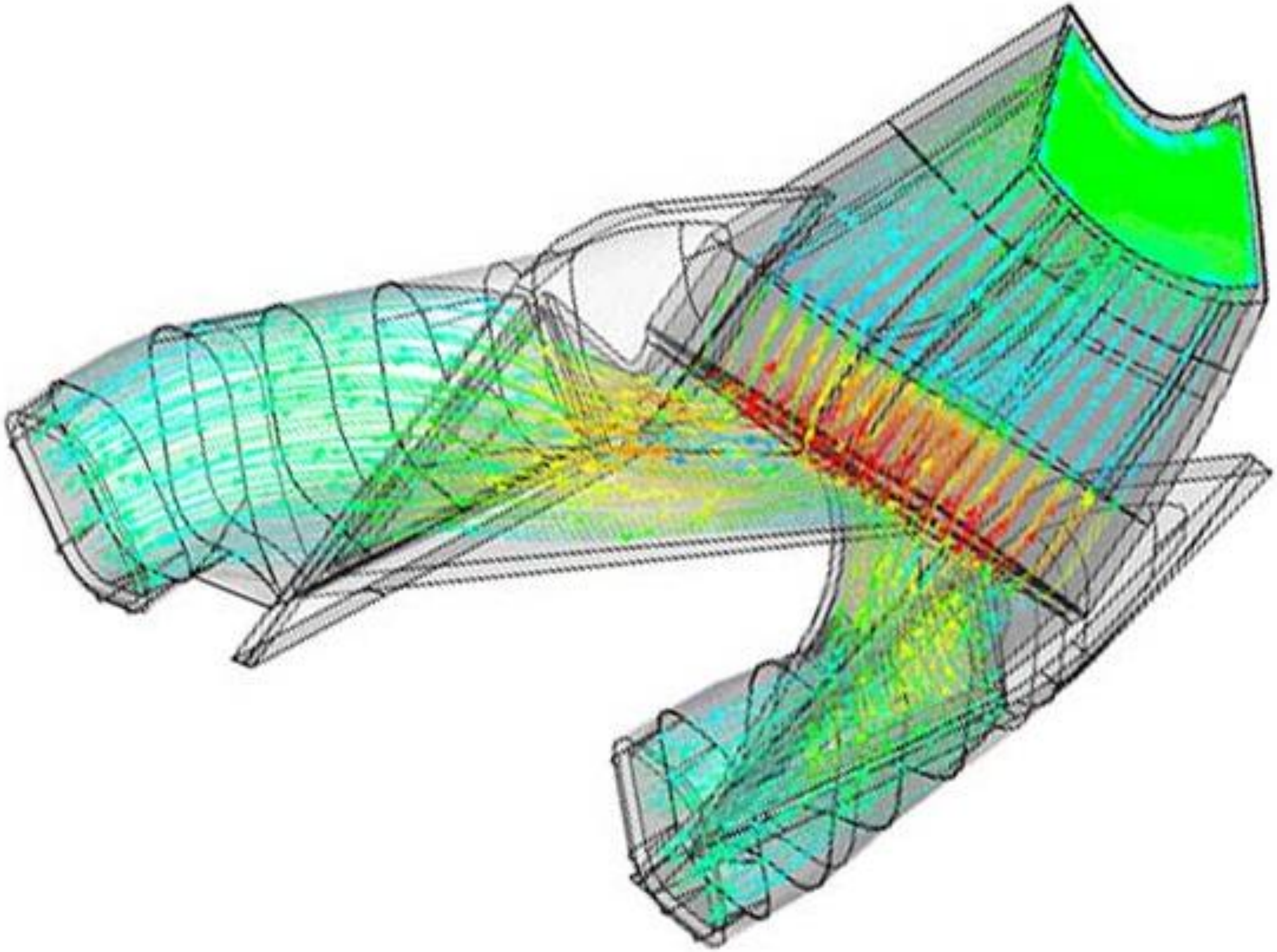
➢ **The Inlet**

1. The Turbojet Engine

➢ **The Inlet**

1. The Turbojet Engine

- **The Inlet**



1. The Turbojet Engine

➢ The Inlet

- ➢ Inlet is a necessary component.
- ➢ Engine requires intake axial speed less than $M = 0.7$; however, suitably designed inlets can enable the airplane to fly at $M > 1$ in design condition.
- ➢ In off-design condition, engine intake Mach number and flight Mach number are different. Therefore, an intake is needed to reduce speed and increase pressure to adapt to the engine.
- ➢ Inlet is a component of the engine, even if though it is a structural part of the airplane.
- ➢ Engine factory does not manufacture inlets. It’s a separately designed and optimized component of the airframe, installed into the engine.

1. The Turbojet Engine

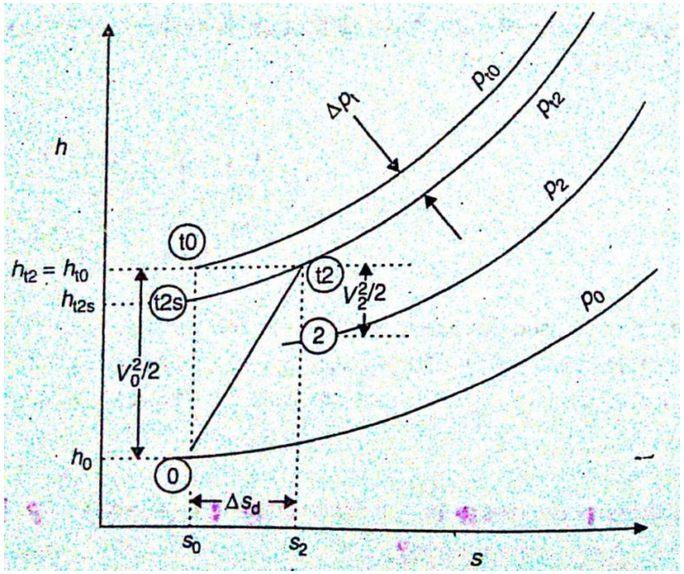
➢ The Inlet

- ➢ Subsonic compressors are designed for an axial Mach number of 0.5-0.6. Therefore, for flight Mach numbers greater than 0.5 or 0.6 (all fixed wing military and commercial aircrafts), then the inlet is required to decelerate the air efficiently.
- ➢ Hence, the main function of an inlet is to ***diffuse*** or *decelerate* the flow.
- ➢ One of the main challenges facing a inlet designer is to **control the inlet boundary layer separation**, caused by the adverse pressure gradient that incur during the diffusion process.
- ➢ This can be achieved by tailoring the inlet geometry to avoid rapid diffusion or possibly through variable geometry inlet design.

1. The Turbojet Engine

➢ The Inlet

- An ideal inlet is considered to provide isentropic compression of the captured flow to the engine.
- In an actual inlet the adiabatic condition is actually met, but the reversible aspect of an ideal inlet flow assumption is not.
- Actual inlets suffer from the realities of wall friction, and any shocks invariably present in the supersonic flows.

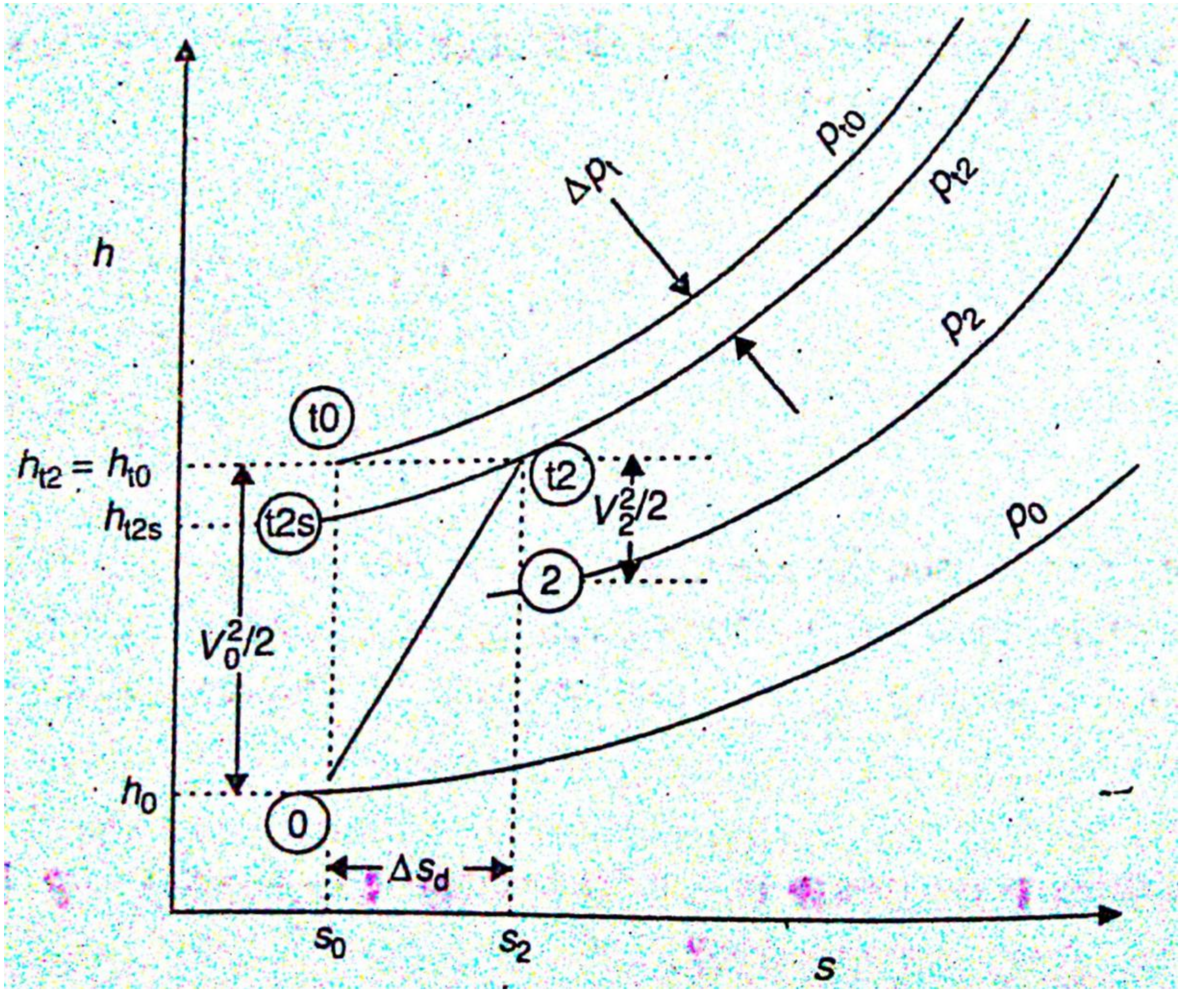


1. The Turbojet Engine

➢ The Inlet

The states 0 (static) and t0(total) are measured by a pitot-static tube on the aircraft, and the static and total pressures at the engine face are measured by a pressure rake or inlet pitot tubes.

Total enthalpy of the real inlet is the same as the total enthalpy of the flight.



Inlet Total Pressure Recovery

$$\pi_d = \frac{p_{t2}}{p_{t0}}$$

1. The Turbojet Engine

➢ The Inlet

- ➢ The inlet adiabatic efficiency (keeping the adiabatic assumption) is given by:

$$n_d = \frac{h_{t2s} - h_0}{h_{t2} - h_0} = \frac{\left[\dfrac{V_2^{\,2}}{2}\right]_{ideal}}{\dfrac{V_2^{\,2}}{2}} \Rightarrow n_d = \frac{\dfrac{h_{t2s}}{h_0} - 1}{\dfrac{h_{t2}}{h_0} - 1} = \frac{\left(\dfrac{p_{t2}}{p_0}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\dfrac{\gamma-1}{2} M_0^{\,2}}$$

$$\frac{p_{t2}}{p_0} = \left\{1 + \eta_d \frac{\gamma-1}{2} M_0^{\,2}\right\}^{\frac{\gamma}{\gamma-1}}$$

1. The Turbojet Engine

➢ The Inlet

- The two inlet parameters η_d and π_d are not independent from each other.

$$\pi_d = \frac{p_{t2}}{p_{t0}} = \frac{\left\{1+\eta_d \dfrac{\gamma-1}{2} M_0^{\ 2}\right\}^{\frac{\gamma}{\gamma-1}}}{\dfrac{p_{t0}}{p_0}} = \left\{\frac{1+\eta_d \dfrac{\gamma-1}{2} M_0^{\ 2}}{1+\dfrac{\gamma-1}{2} M_0^{\ 2}}\right\}^{\frac{\gamma}{\gamma-1}}$$

- When $\eta_d \to 1$, then $\pi_d \to 1$ as well.

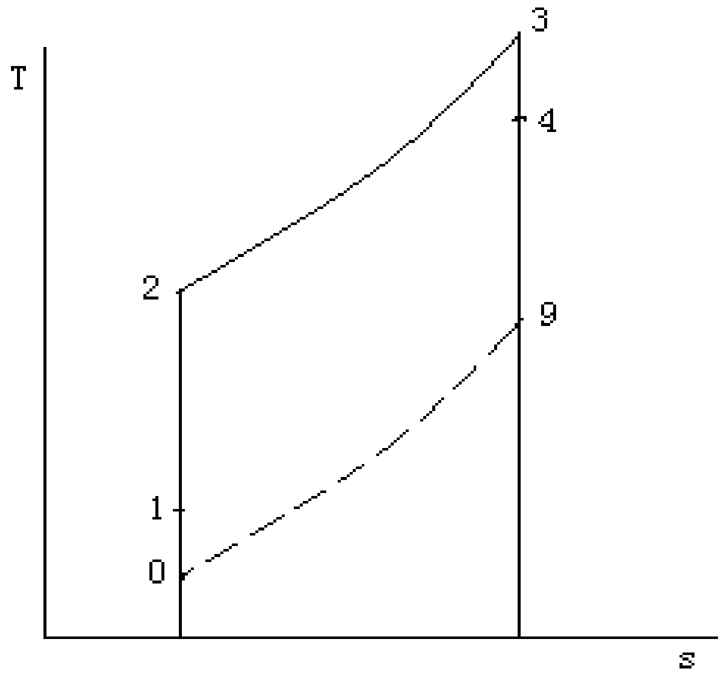
1. The Turbojet Engine

➢ The Inlet

- The inlet flow may be considered to be adiabatic.
- The inlet flow is always irreversible, with viscous dissipation in the boundary layer and shock as the sources of irreversibility.
- The two figures of merit that describe the extent of losses in the inlet are the total pressure recovery and the inlet adiabatic efficiency.
- The two figures are related through a simple mathematical relation.
- At cruise $A_0 < A_2$, and at low speed take off $A_0 > A_2$.
- The outer nacelle geometry of an inlet dictates the drag divergence and high angle of attack characteristics of the inlet and is crucial for the installed performance.

1. The Turbojet Engine

➢ The Compressor

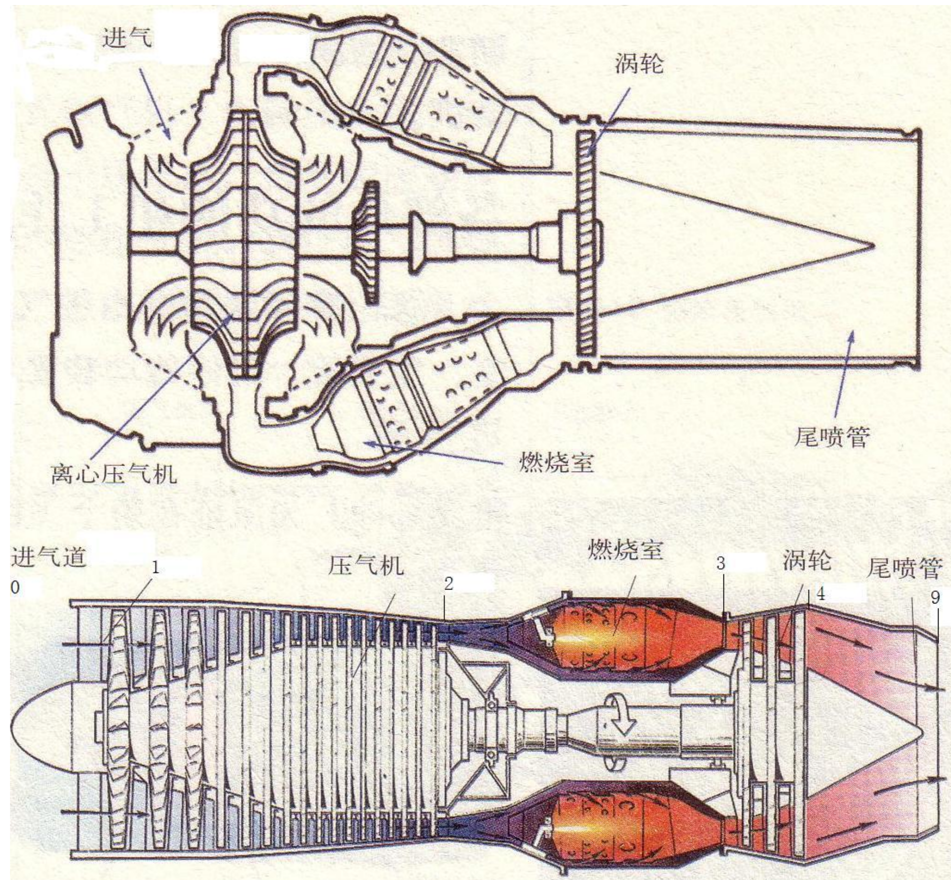


Process: Station point 1-2

- ➢ Role of the compressor
  - ➢ According to thermal cycle analysis, compressor is a important component which increases gas pressure so that the cycle can output mechanical work.

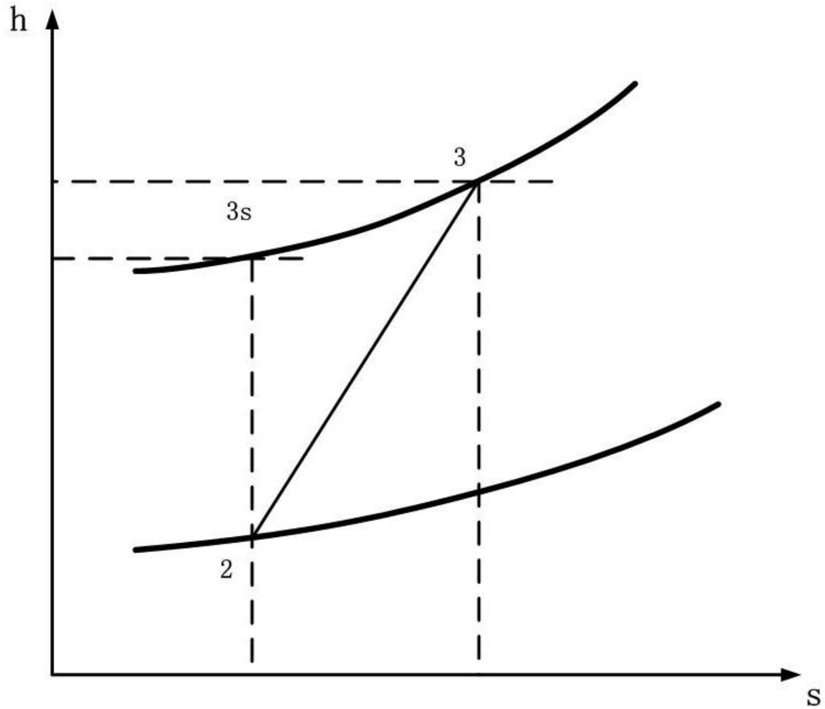
1. The Turbojet Engine

- **The Compressor**
  - Often seen types
    - Centrifugal
    - Axial



1. The Turbojet Engine

➢ The Compressor



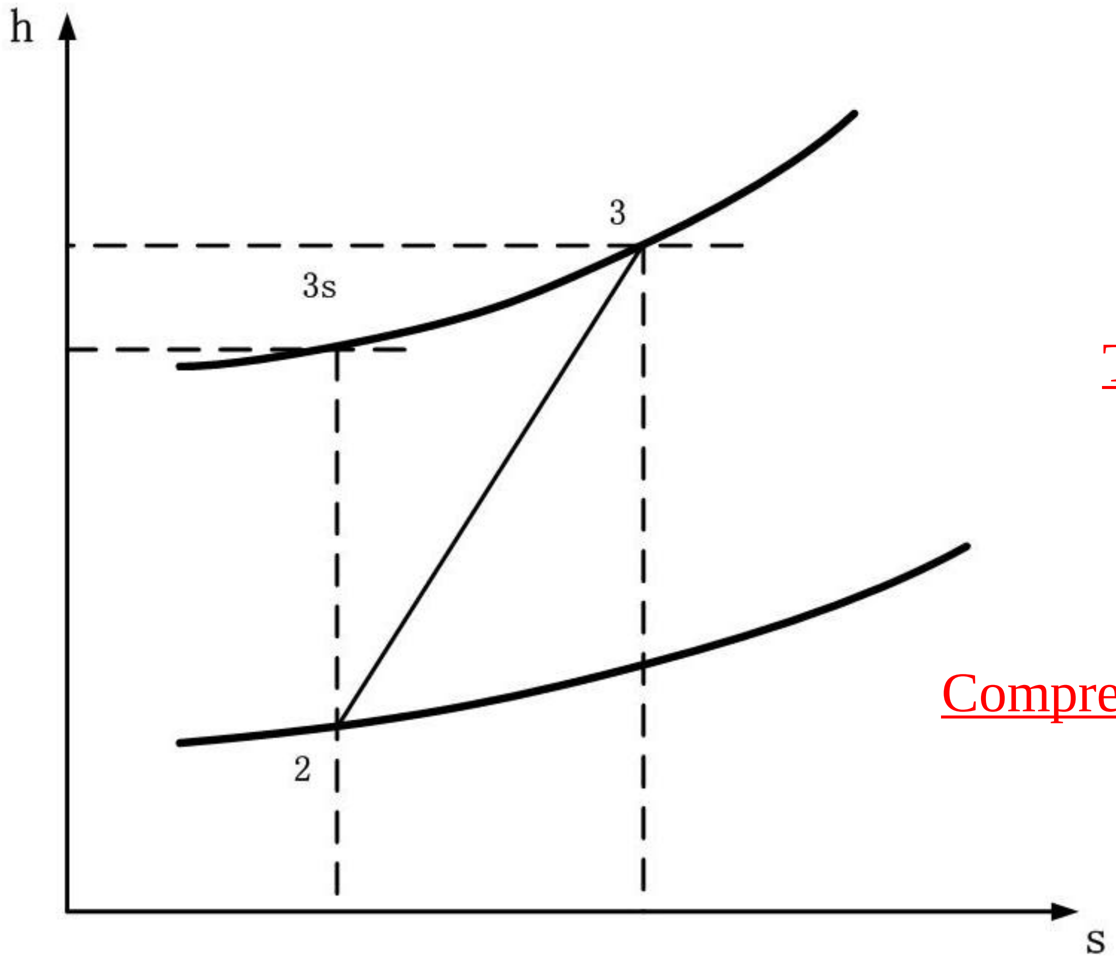
Total Pressure Ratio

$$\pi_c = \frac{p_{t3}}{p_{t2}}$$

- The power delivered to the medium in a compressor is achieved by one or more rows of rotating blades (rotors) attached to one or more spinning shafts (typically referred to as spools).

1. The Turbojet Engine

➢ The Compressor



Total Pressure Ratio

$$\pi_c = \frac{p_{t3}}{p_{t2}}$$

Total Temperature Ratio

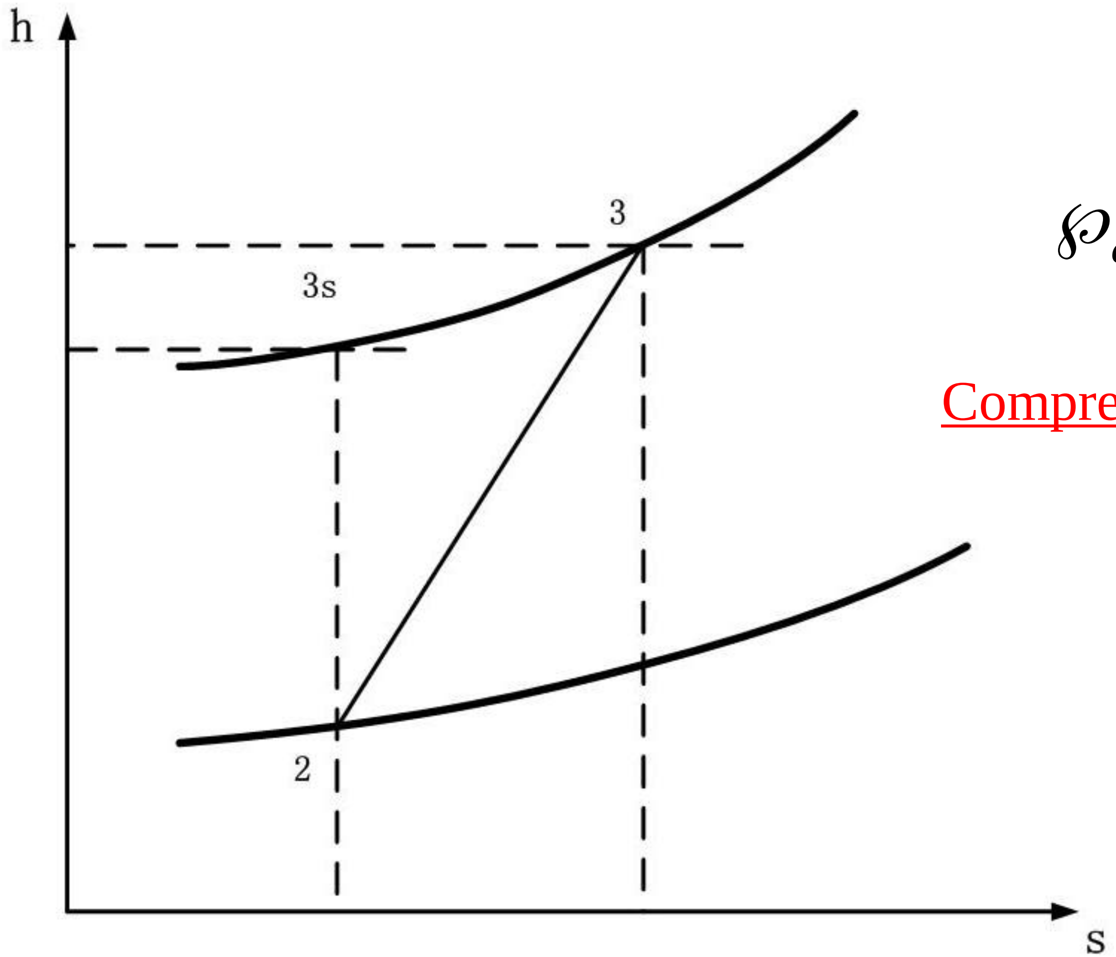
$$\tau_c = \frac{T_{t3}}{T_{t2}}$$

Compressor Adiabatic Efficiency

$$n_c = \frac{h_{t3s} - h_{t2}}{h_{t3} - h_{t2}}$$

1. The Turbojet Engine

➢ The Compressor



Power Generated

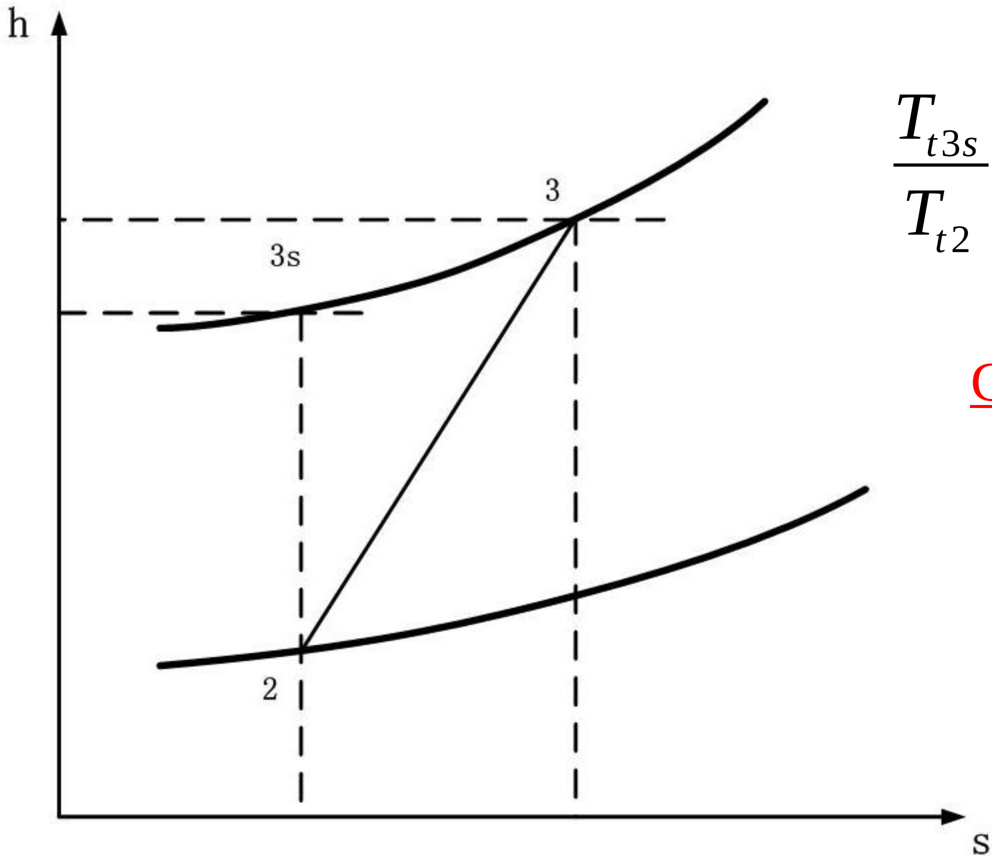
$$\wp_c = \dot{m}_o \left(h_{t3} - h_{t2} \right)$$

Compressor Adiabatic Efficiency

$$n_c = \frac{\dfrac{T_{t3s}}{T_{t2}} - 1}{\dfrac{T_{t3}}{T_{t2}} - 1}$$

1. The Turbojet Engine

➢ The Compressor



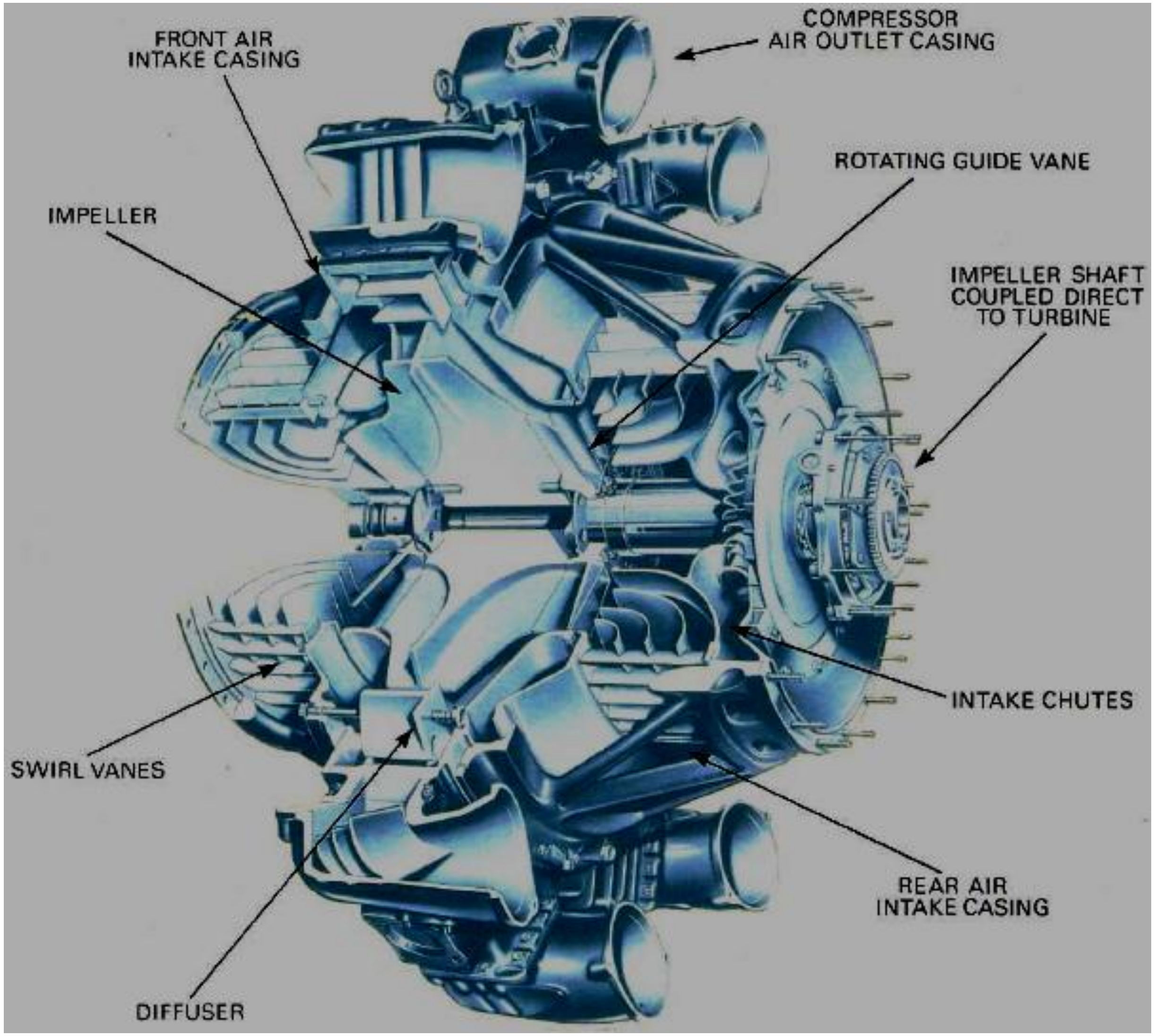
$$\frac{T_{t3s}}{T_{t2}} = \left(\frac{p_{t3s}}{p_{t2}}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{p_{t3}}{p_{t2}}\right)^{\frac{\gamma-1}{\gamma}} = \pi^{\frac{\gamma-1}{\gamma}}$$

Compressor Adiabatic Efficiency

$$n_c = \frac{\frac{T_{t3s}}{T_{t2}} - 1}{\frac{T_{t3}}{T_{t2}} - 1} = \frac{\pi_c^{\frac{\gamma-1}{\gamma}} - 1}{\tau_c - 1}$$

1. The Turbojet Engine

➢ **The Compressor**

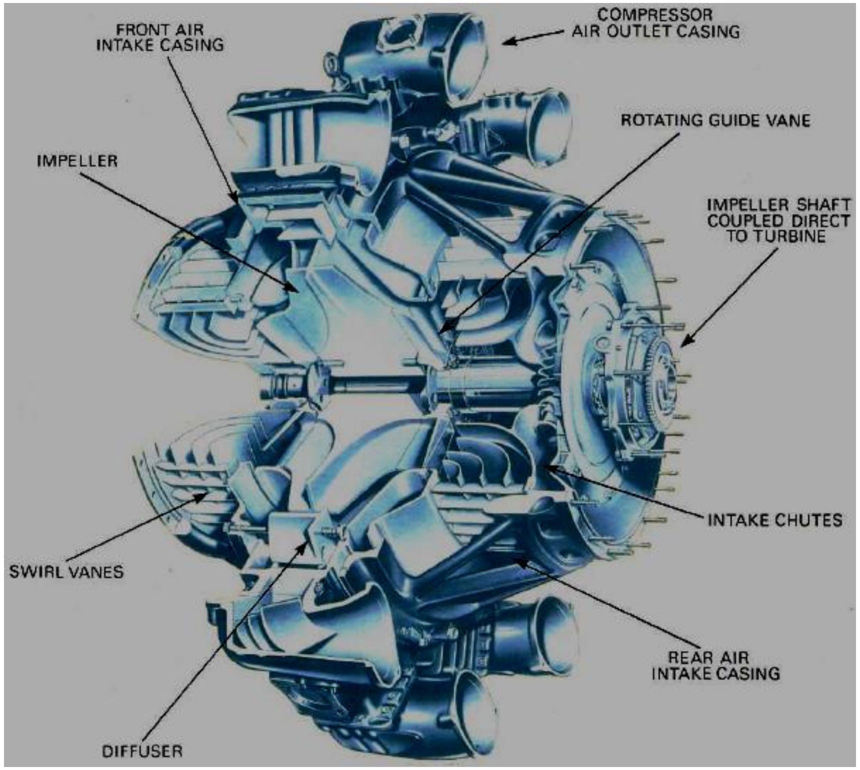


Centrifugal
Compressor

1. The Turbojet Engine

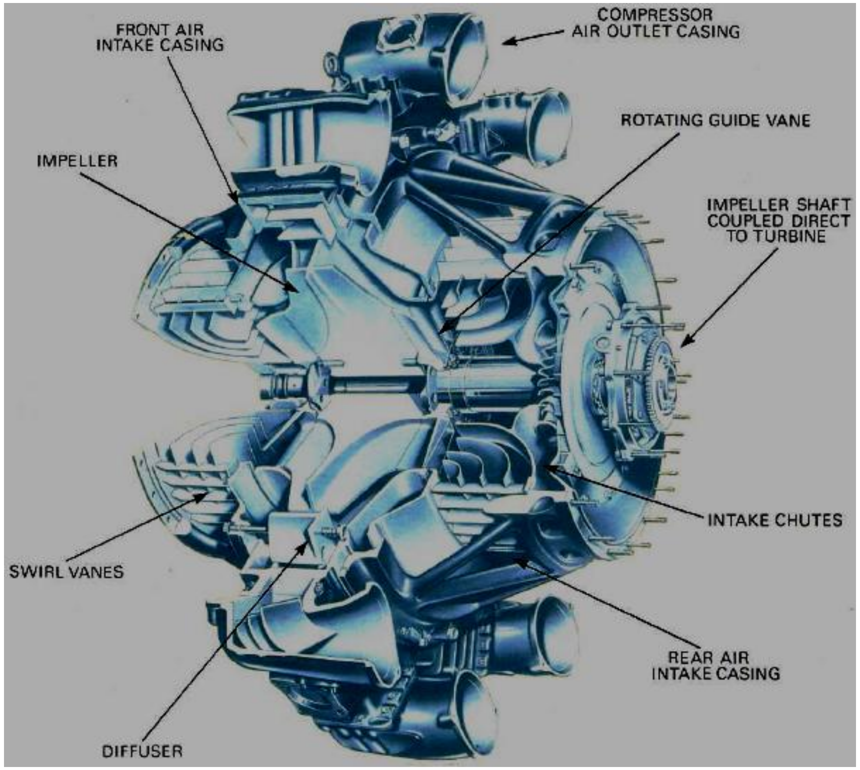
- **The Compressor**
  - Centrifugal Compressor
    - Shaft is coupled directly to turbine.
    - Impeller can be single or double sided.

    - **Rotating guide vane:** Air goes in axially. It can be made in one piece with impeller.
    - **Impeller:** Radial blades that increase air speed and pressure.



1. The Turbojet Engine

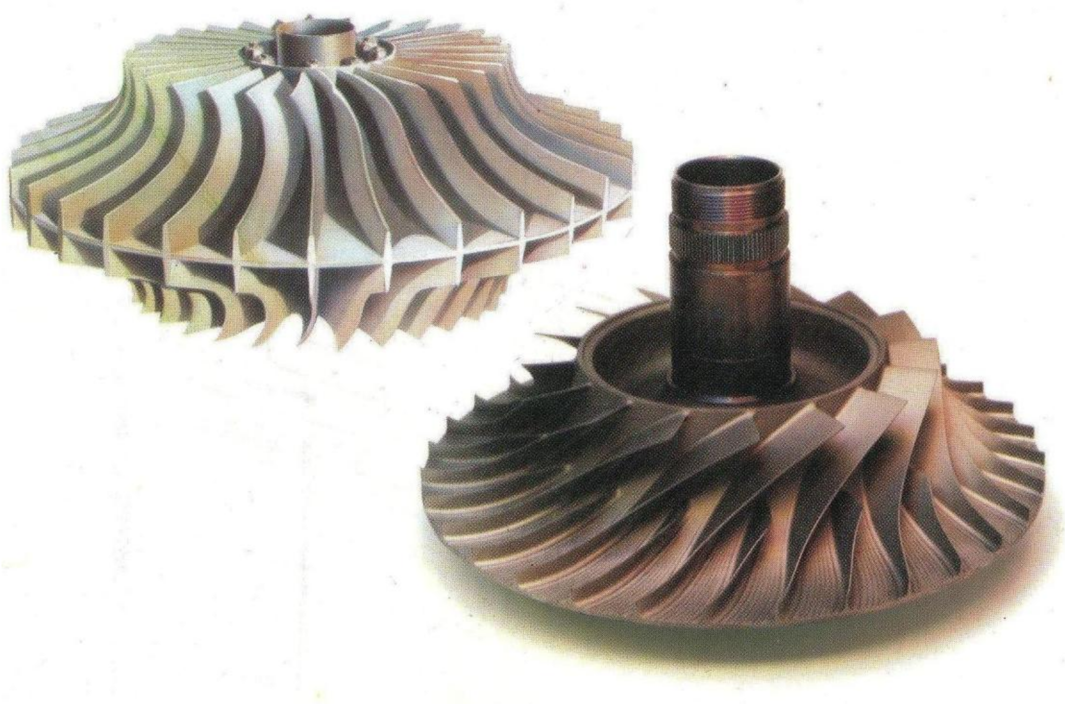
- **The Compressor**
  - Centrifugal Compressor
    - **Diffuser:** Reduces speed and gets pressure rise.
    - **Air outlet casing:** Turns air to adapt combustion chamber.



1. The Turbojet Engine

➢ The Compressor

- ➢ Centrifugal Compressor Characteristic
  - ➢ Simple and reliable structure
  - ➢ Single stage pressure ratio is high（typically 2-4)
  - ➢ Stable performance
  - ➢ Lower efficiency
  - ➢ Larger frontal area



1. The Turbojet Engine

- **The Compressor**
  - Centrifugal Compressor Characteristic
    - **Small power**
      - Cruise missiles
      - UAV’s or small airplanes
    - **Helicopters**
      - Often compressor is in combined form with axial and centrifugal types (last stage)

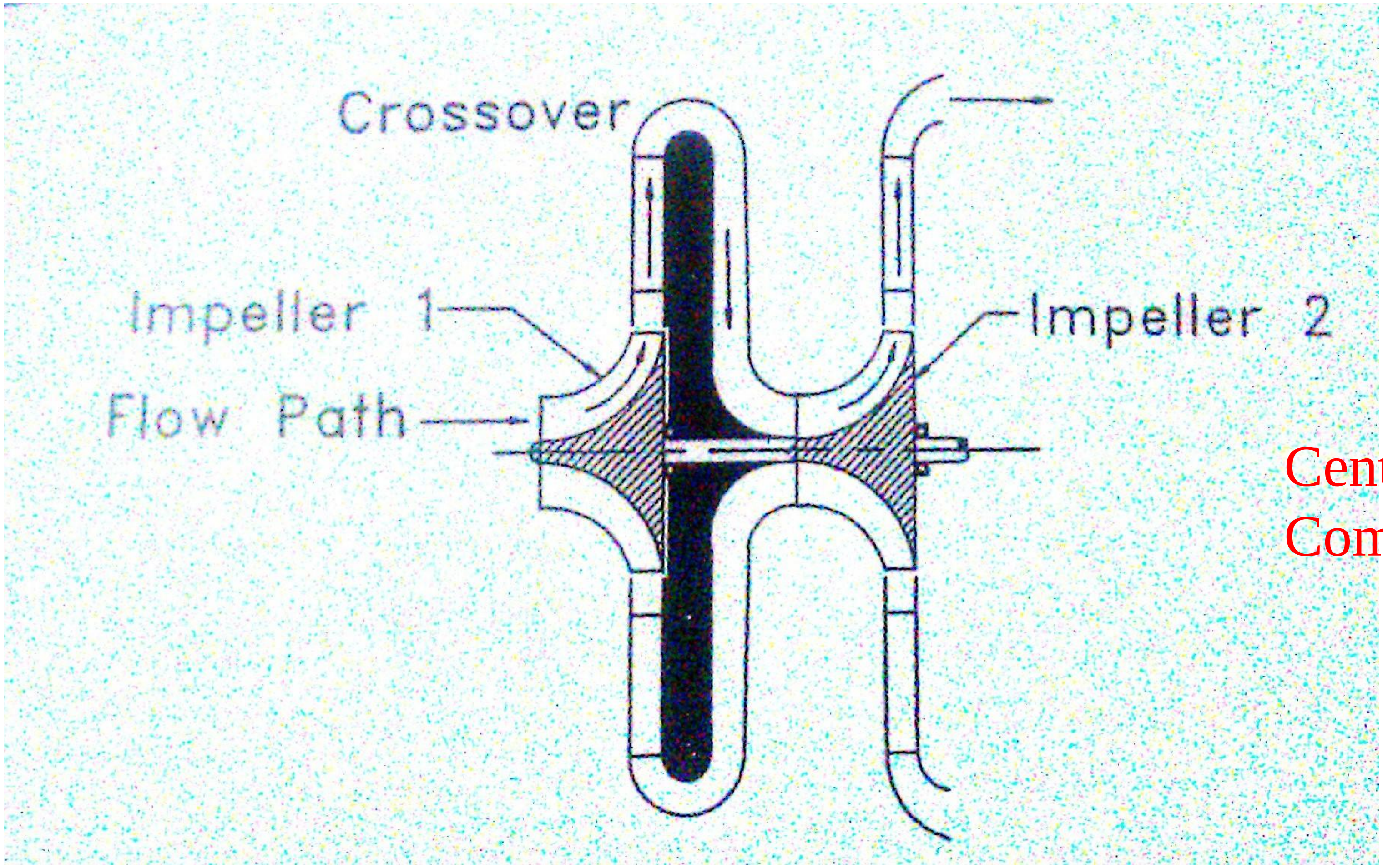
1. The Turbojet Engine

➢ The Compressor

- ➢ Centrifugal compressors have higher single-stage pressure ratios than axial compressors. As a result, centrifugal compressors have lower cross-sectional flow areas per mass flow rate than do axial compressors.
- ➢ They also have a larger diameter but shorter length per unit mass flow rate.
- ➢ The rotating element (impeller) of the compressor is an integral unit of blades and a disk, and thus if one blade is damaged the entire unit is replaced.
- ➢ They are physically small units with low flow rates, which makes them ideal for helicopter and small aircraft application.
- ➢ They cost less in manufacturing.

1. The Turbojet Engine

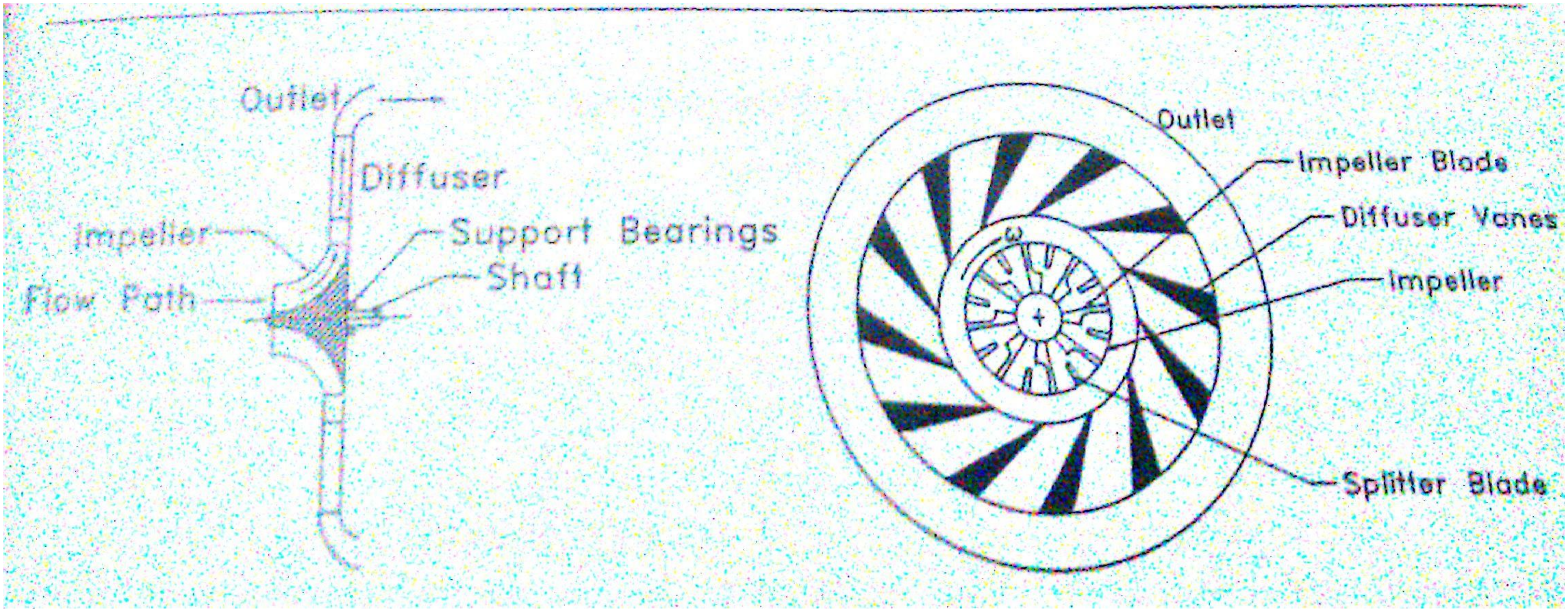
➢ The Compressor



Centrifugal Compressor

1. The Turbojet Engine

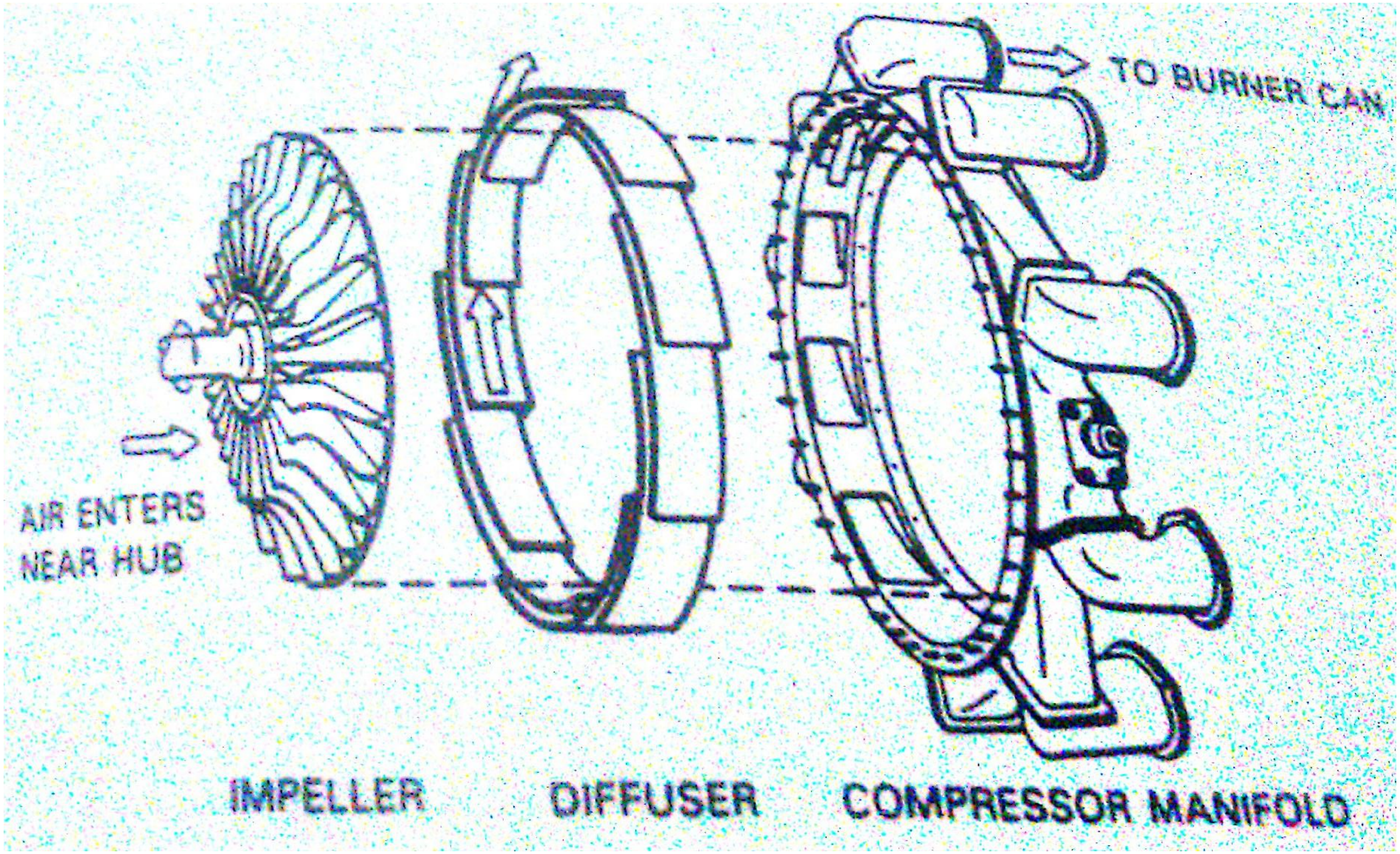
➢ **The Compressor**



Centrifugal Compressor

1. The Turbojet Engine

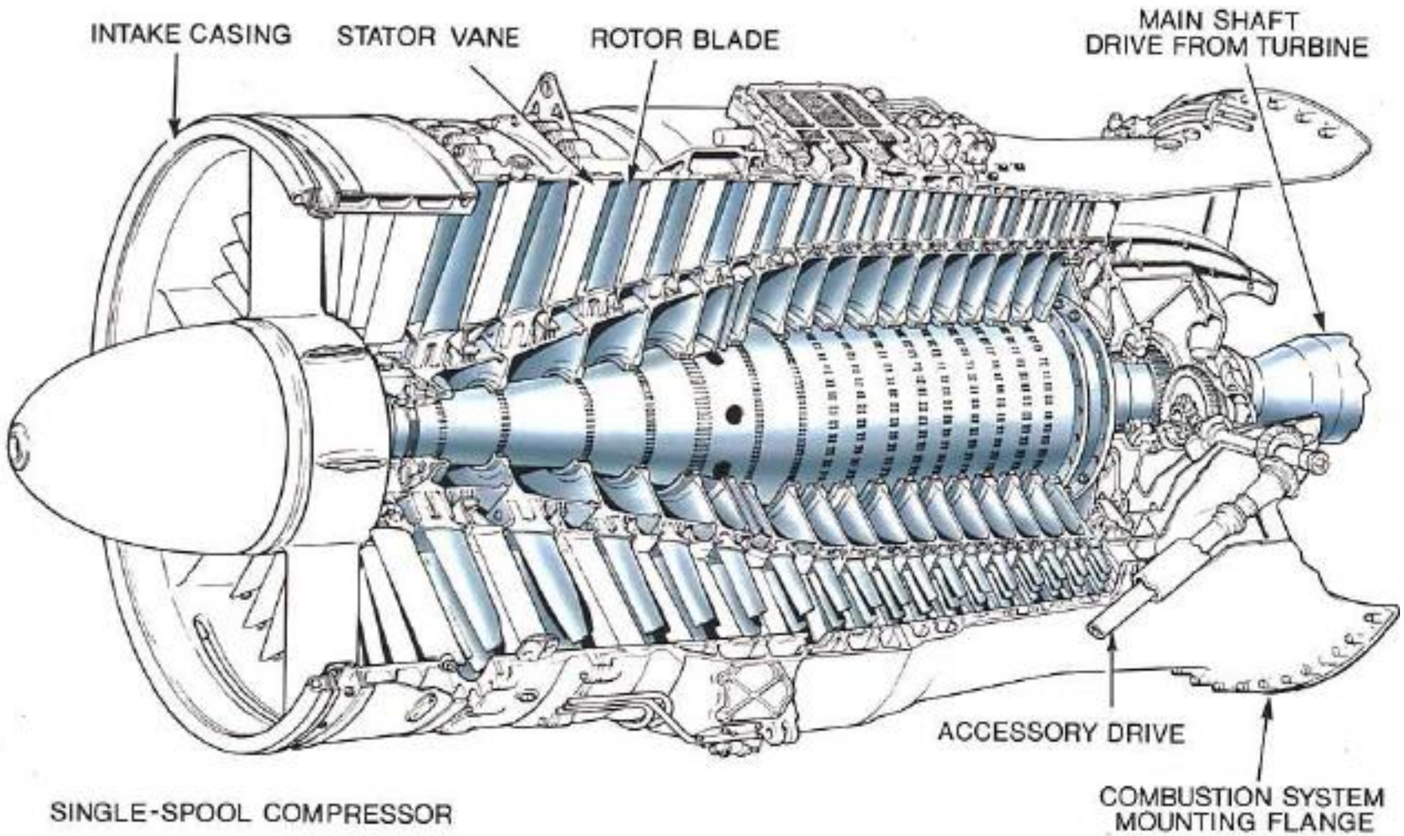
➢ **The Compressor**



Centrifugal Compressor

1. The Turbojet Engine

➢ The Compressor



Single Spool

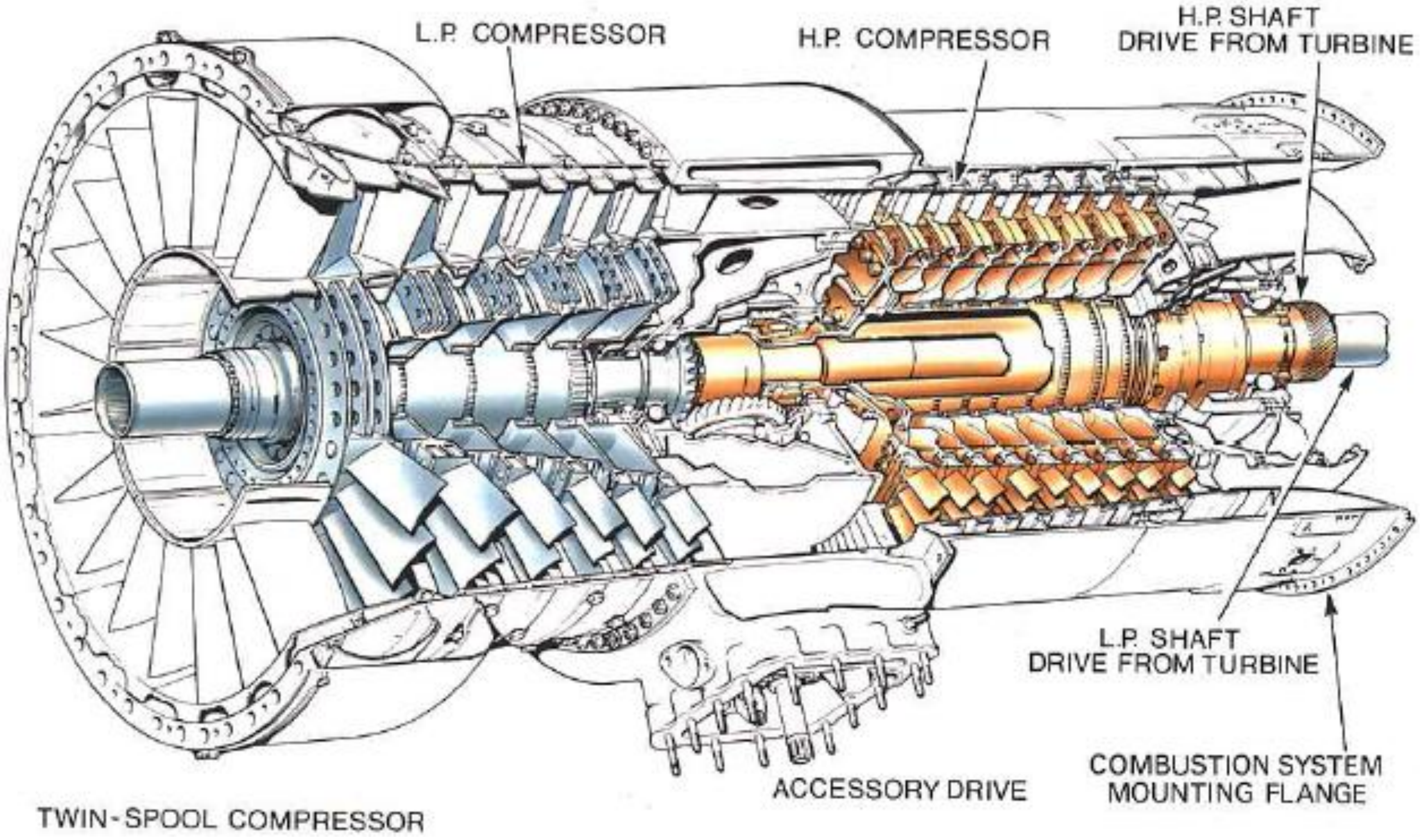
Axial Compressor

1. The Turbojet Engine

- **The Compressor: Axial Compressors**
  - Single spool
    - Consists of one rotor and one stator.
    - The rotor may includes blades, disks drum and shaft. They are assembled together and sit on 2 bearings.
    - Stator has guide vanes and casing.
    - Axial compressor has pressure ratio lower than centrifugal compressor, normally 1.15~1.35. That why multiple stage axial compressor.

1. The Turbojet Engine

➢ The Compressor: Axial Compressors



Twin Spool

1. The Turbojet Engine

- **The Compressor: Axial Compressors**

  - Twin spool compressors
    - The same axle, but different shafts.
    - Front row is low pressure (LP) compressor, and it rotates with LP Turbine;
    - Rear one is high pressure (HP) compressor coupled with HP turbine.
    - **Two rotors have no mechanical connection, and they have their own rotational speed.**

1. The Turbojet Engine

- **The Compressor: Axial Compressors**

  - Compressor rotors

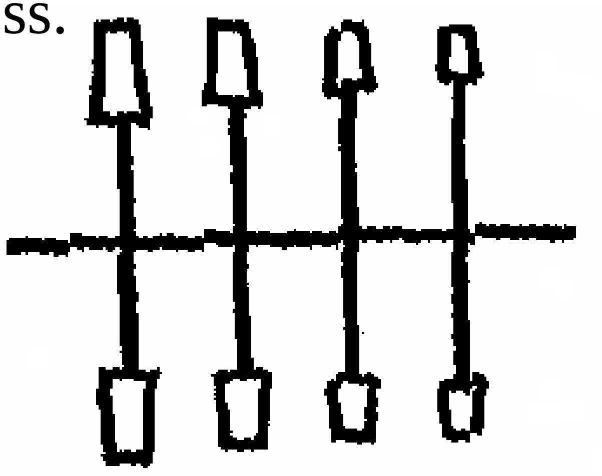
    - Have a high thermal resistances and suffer from less fatigue.
    - Work under very high rotational speeds(thousands ~ hundreds k rpm)
    - Are able to withstand bending moment, torque, centrifugal forces, and vibrations.
    - Require light weight construction with enough strength and stiffness

1. The Turbojet Engine

➢ The Compressor: Axial Compressors

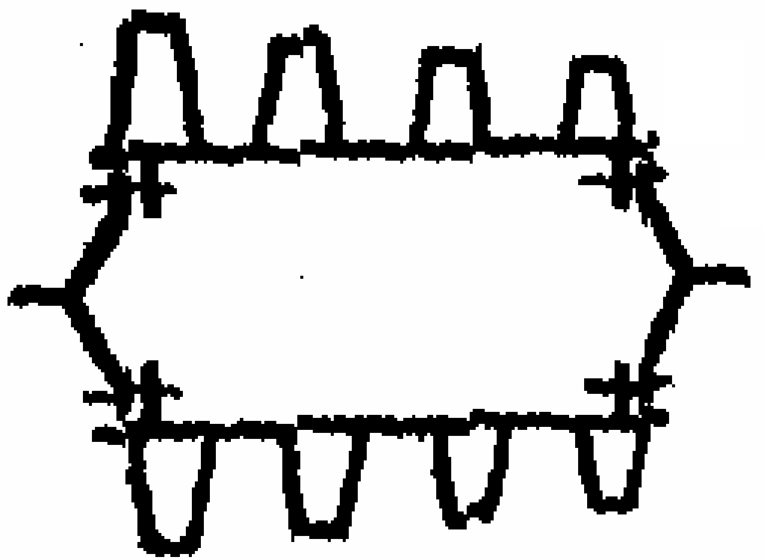
➢ Structure

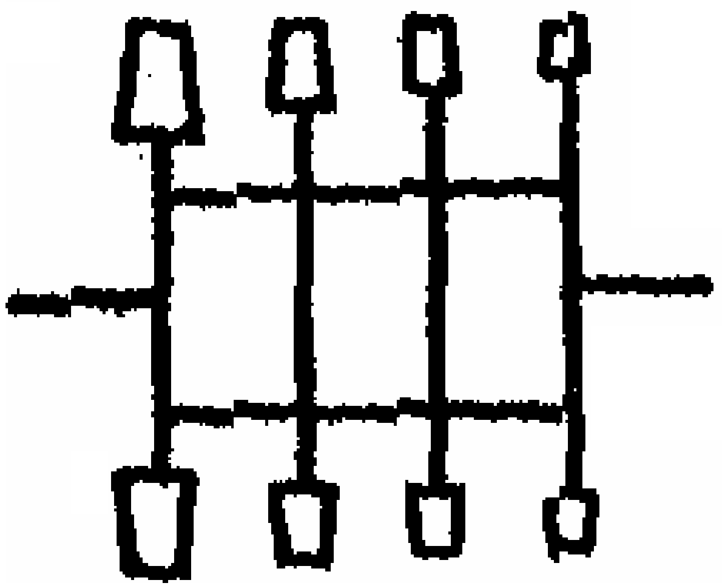
- ➢ **Disks + shaft**: Consists of one shaft and many disks where blades are installed.
- ➢ Centrifugal forces of blades and disks are borne by the disks and bending stiffness depends on the shaft.
- ➢ This type of construction is no more used because of the inherently weak bending stiffness.



1. The Turbojet Engine

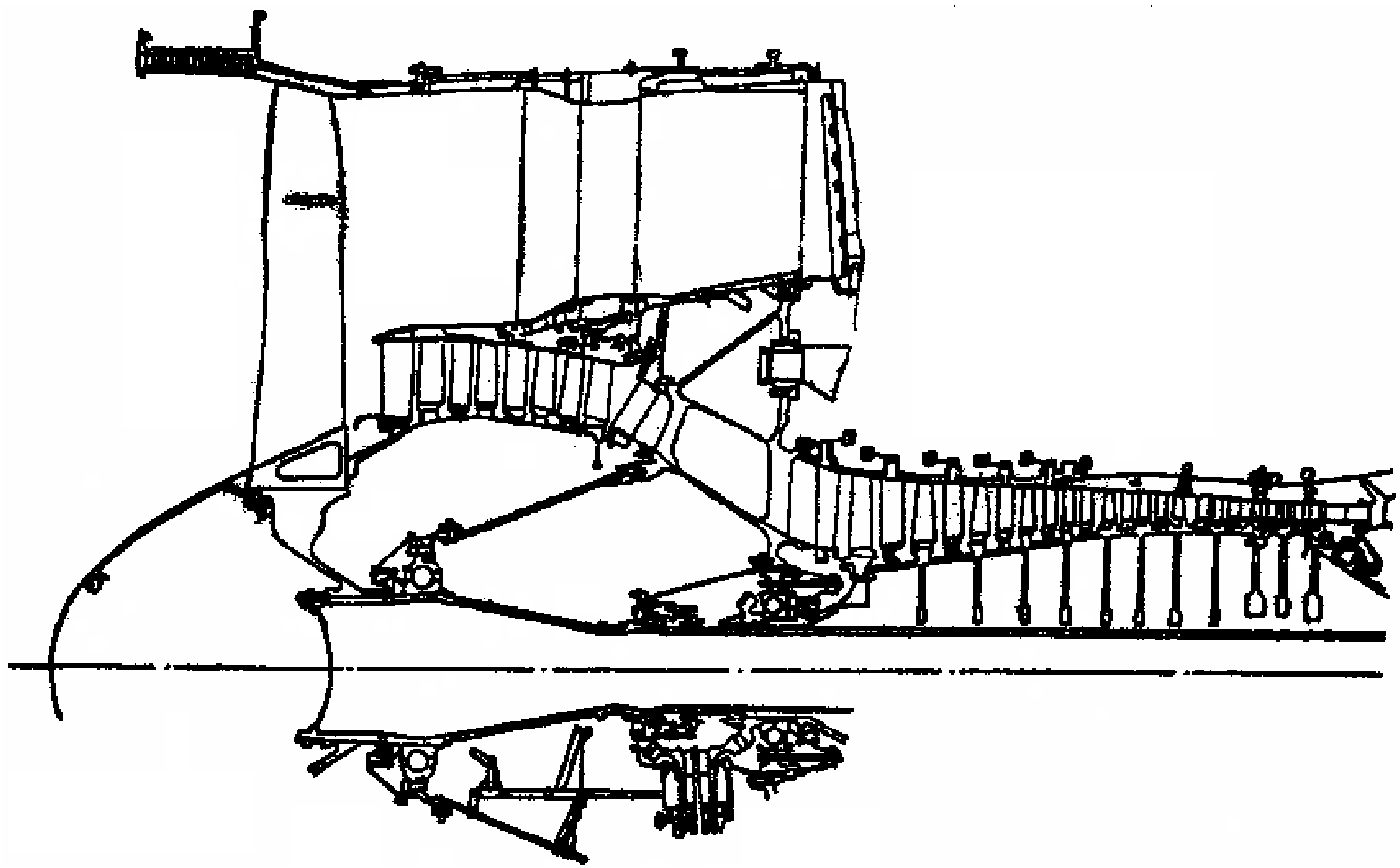
- **The Compressor: Axial Compressors**
  - Structure
    - **Drum and drum + disks:** Blades are attached circumferentially or axially in drum or disk. Forces are transferred through the drum and disks.
    - **The drum insures the bending stiffness.**





1. The Turbojet Engine

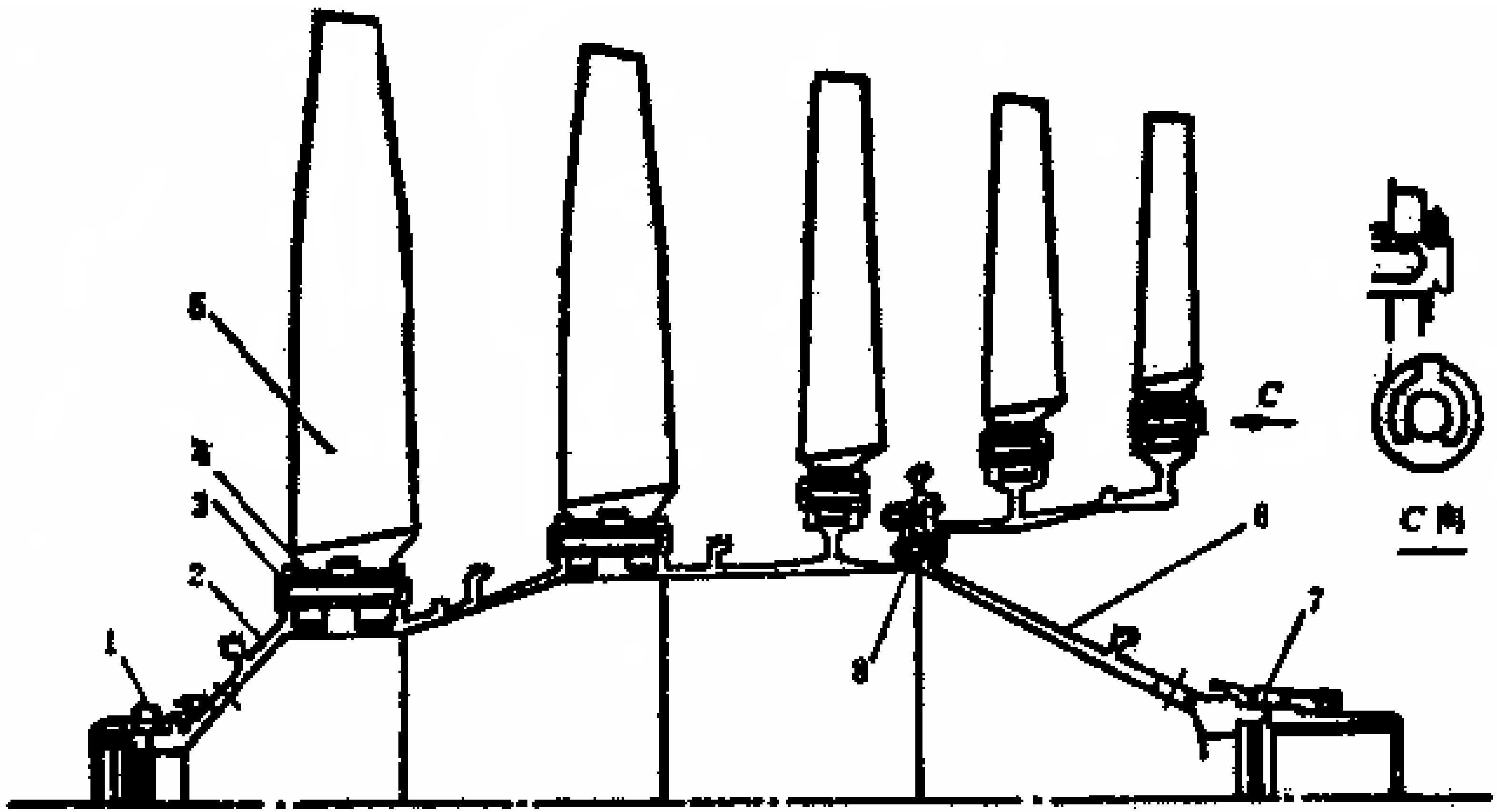
➢ The Compressor: Axial Compressors



Rolls Royce Structure

1. The Turbojet Engine

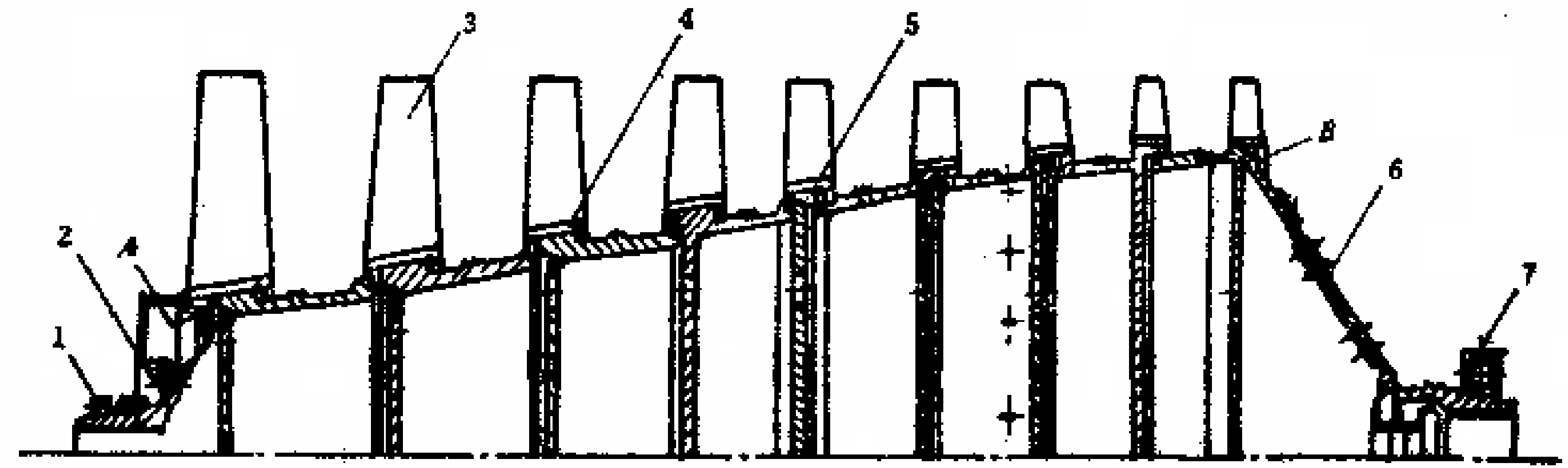
➢ The Compressor: Axial Compressors



Drum

1. The Turbojet Engine

➢ The Compressor: Axial Compressors



Drum + Disks

1. The Turbojet Engine

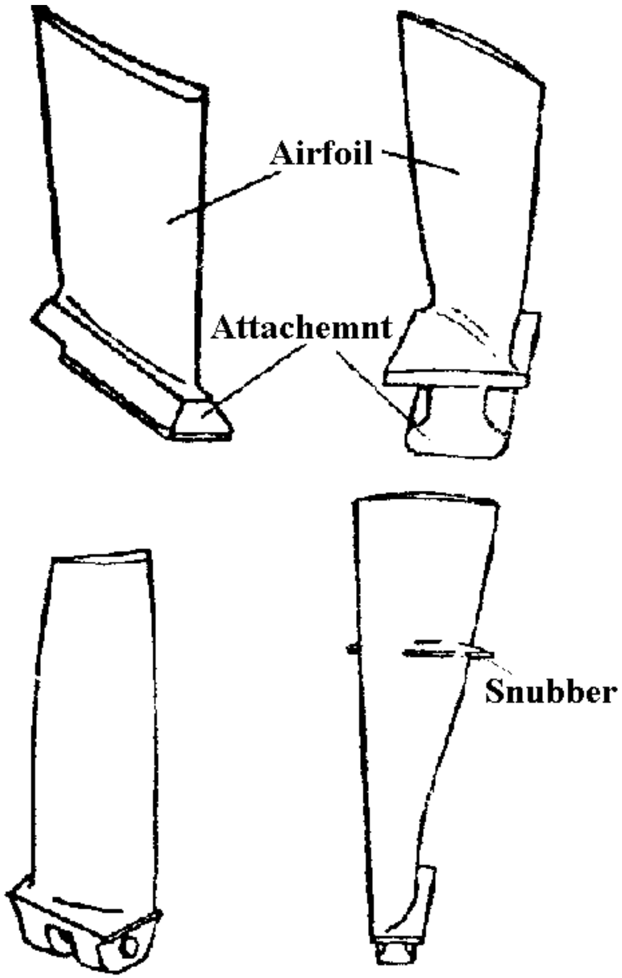
➢ **The Compressor: Axial Compressors**

- ➢ Blades
  - ➢ These are very important parts in axial compressors, composed of airfoil and attachment (fixing) system.

1. The Turbojet Engine

➢ The Compressor: Axial Compressors

- ➢ Blades suffer centrifugal, aerodynamic and vibrating forces.
- ➢ Attachment is also important.
  - ➢ **Swallow tail attachment**: easy fabrication.
  - ➢ **Pivot attachment**: No bending stress.



Airfoils and Attachments

1. The Turbojet Engine

➢ The Compressor: Axial Compressors

- Blades may be broken due to fatigue, especially from fatigue due to vibration .
- To reduce vibration amplitude, long blades are often made with a mid-span support called **snubber or clapper**.
- ↑ centrifugal force, ↓ efficiency.
- At the end of compressor, temperature can reach up to 500 ~ 600 ℃, or even higher.
- The materials normally used for the blades are titanium, aluminum alloys, steels and composites.

1. The Turbojet Engine

- **The Compressor: Axial Compressors**

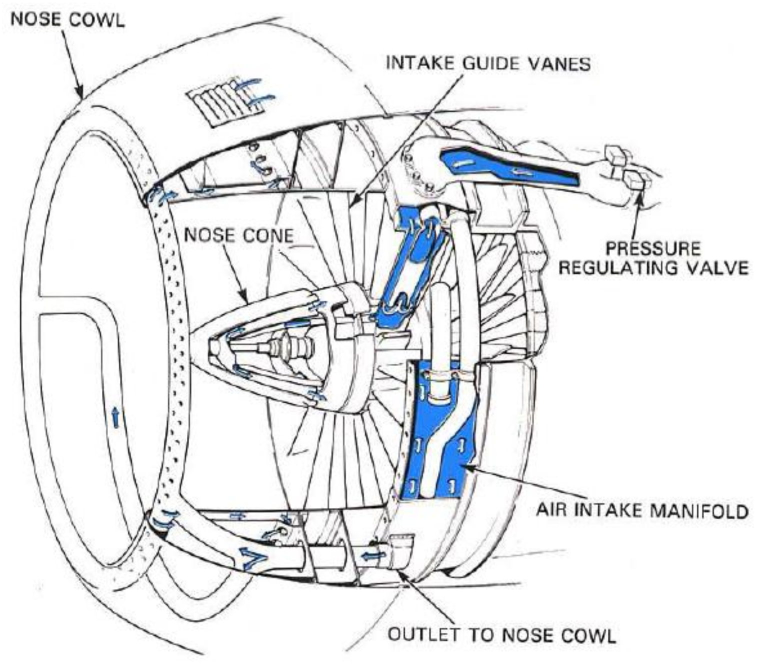
  - **Compressor stator** is the part which does not rotate and consists of vanes and casings.
  - It bears axial forces, torques, vibration and rotor’s forces transferred by bearings. It is a part of air passage, and hence bears pressure forces as well as thermal stress caused by temperature.
  - **Half-half Casing:** Good stiffness; No need disassemble the rotor while assembling; Heavier.
  - **Entire Casing:** Must disassemble rotor (blades); Normally used in few stages compressor; Lighter.

1. The Turbojet Engine

➢ The Compressor: Axial Compressors

➢ Anti-icing

- ➢ Water droplets may become ice. They may reduce air passage and break blades when detached.
- ➢ Anti-icing methods
  - ➢Heating (electricity or hot air).
  - ➢Hydrophobic coating.



1. The Turbojet Engine

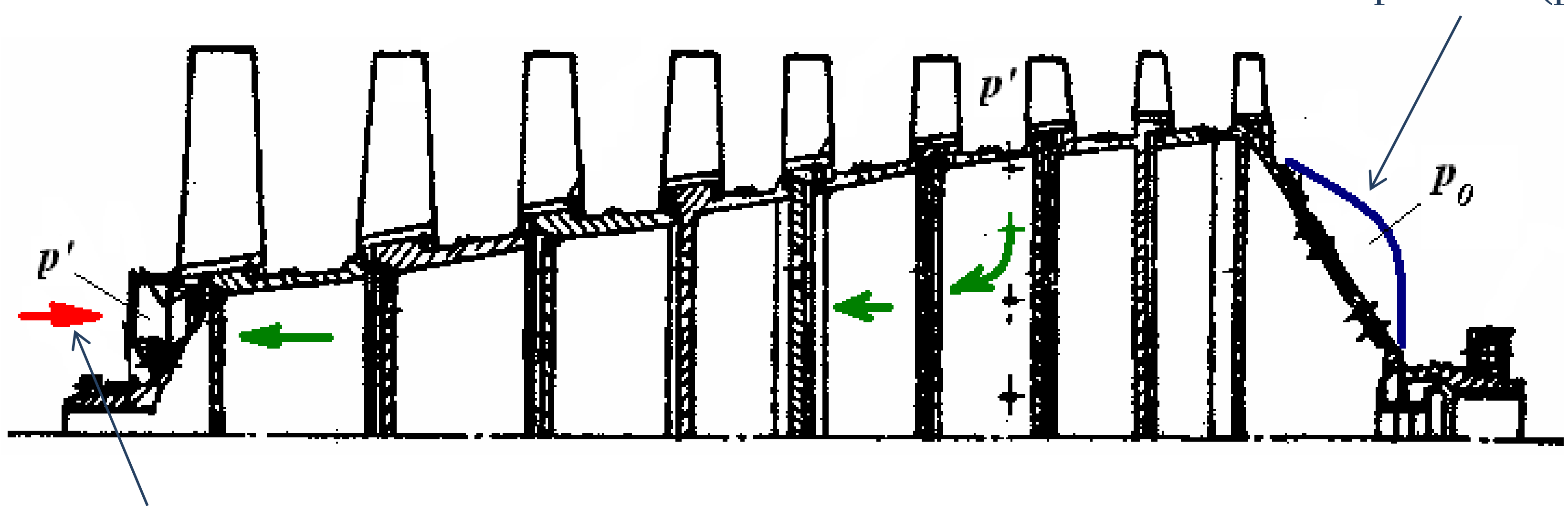
➢ The Compressor: Axial Compressors

- ➢ Axial force redistribution
  - ➢ Bearing
    - ➢ Ball (Axial and radial forces)
    - ➢ Roller (Journal bearing, Radial force only)
  - ➢ Compressor axial force (> total thrust) is too big for balls.
    - ➢ Coupling with turbine
    - ➢ Creating rooms (Not in air passage; inside the drum space)

1. The Turbojet Engine

➢ The Compressor: Axial Compressors

Low pressure (pull)



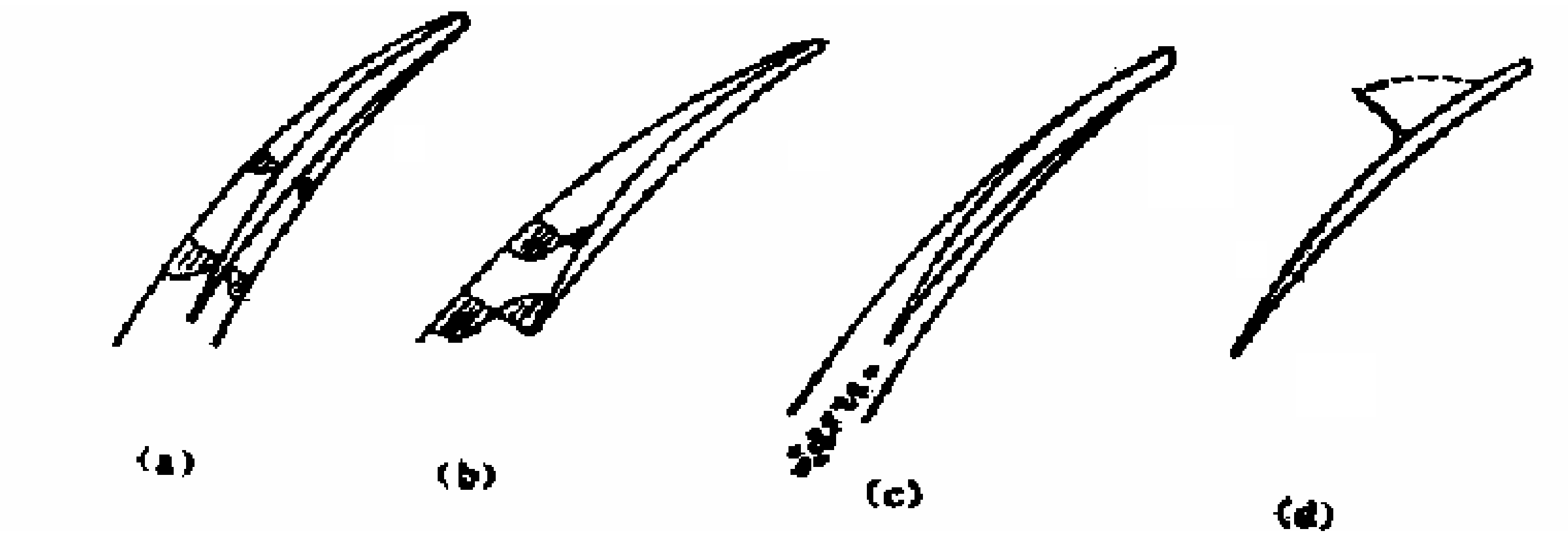
High pressure (push)

Rooms have rotor on one side and stator on another. They are sealed. The pull and push forces acting on the cross-section redistribute the compressor axial force.

1. The Turbojet Engine

➢ The Compressor: Axial Compressors

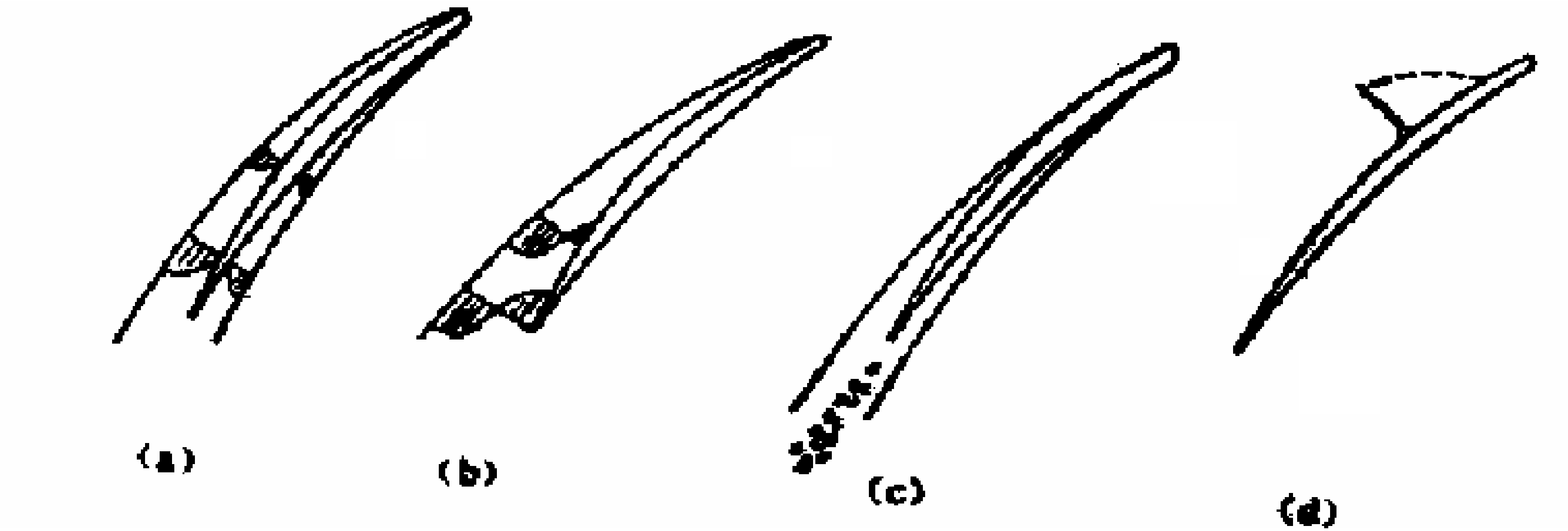
- **Efficiency and losses:** Due to viscosity, gas flowing in turbomachines will produce many kinds of losses and they can classed into two major types:
  - **Airfoil Losses**
  - **Circumferential Losses**



Airfoil Losses

1. The Turbojet Engine

➢ The Compressor: Axial Compressors



Airfoil Losses

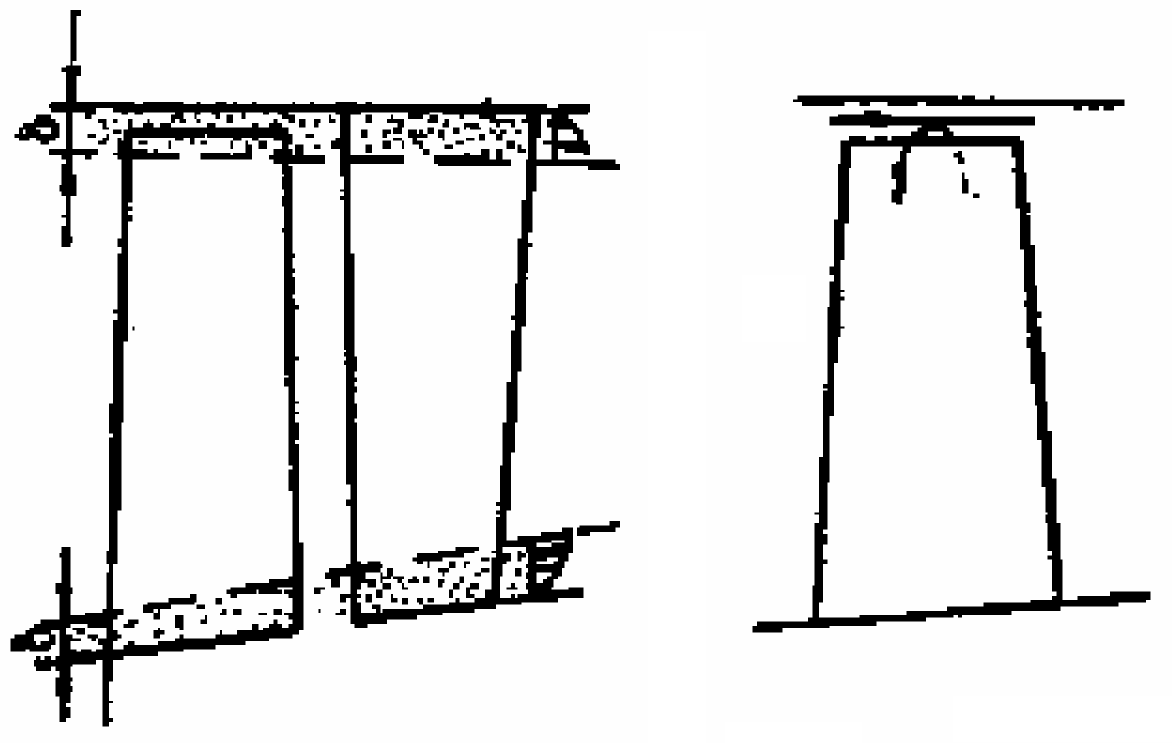
- Boundary layer loss- Friction (**a**)
- Separation loss (**b**)
- Tail trace vortexes (**c**)
- Shockwave losses (**d**)

1. The Turbojet Engine

➢ The Compressor: Axial Compressors

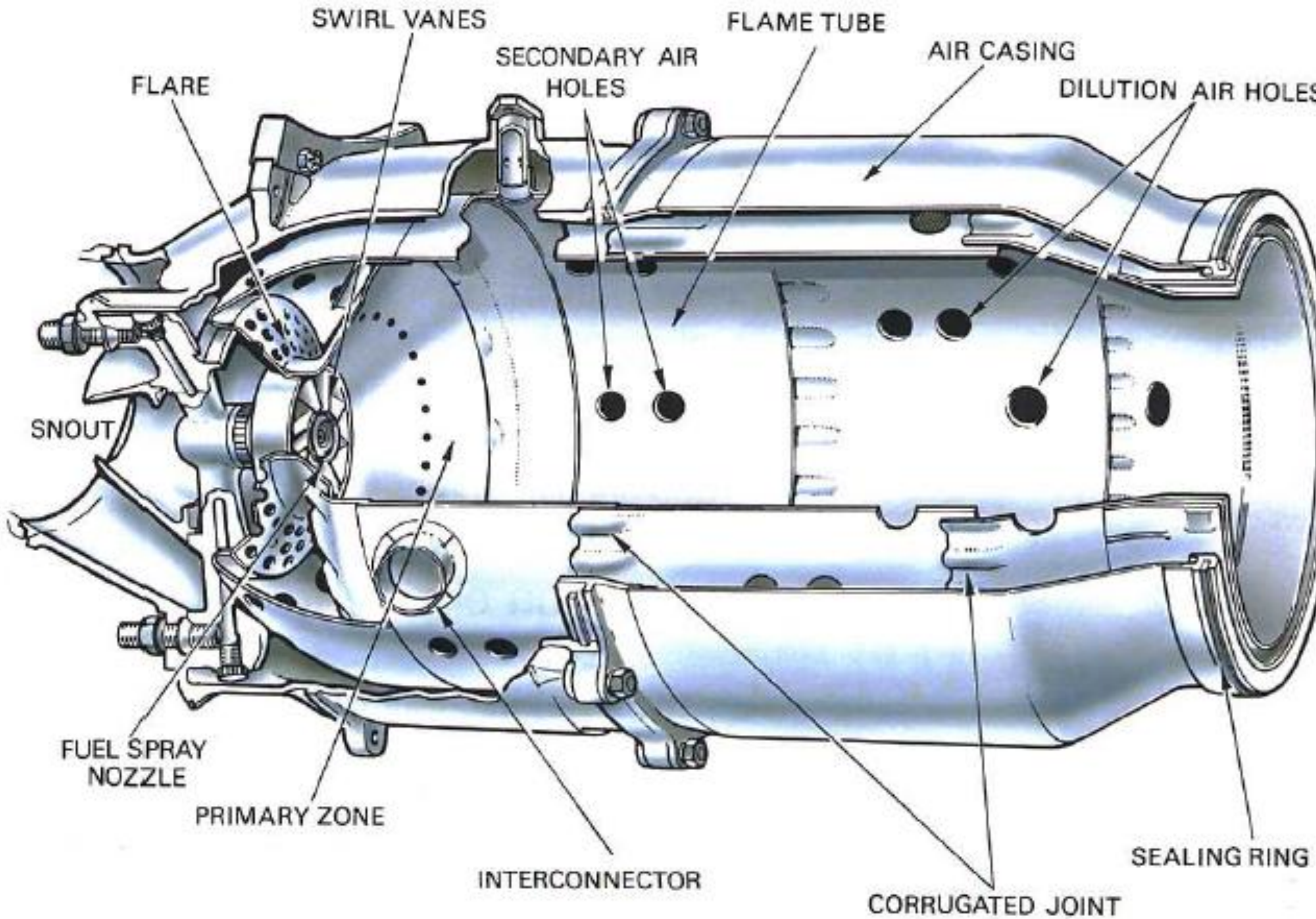
- ➢ Circumferential losses (secondary flow)
  - ➢Tip and hub circumferential boundary layers
  - ➢Tip clearance leaking and passage vortices

Circumferential losses



1. The Turbojet Engine

➢ The Combustor



1. The Turbojet Engine

The Combustor

- Combustion chamber changes chemical energy to heat energy by burning fuel-air mixture. Cold air comes from compressor and hot gas goes to turbine. Thus, combustor operation is also tied up to other components.
- Compressor exit-diffuser reduces Mach number of the air to a suitable combustor inlet value before it reaches the combustor.
- Combustion requires slow flow velocity for a sufficiently long residence time so that a necessary level of combustion can take place before the gases leave the combustor.

1. The Turbojet Engine

- **The Combustor**

- Desirable Combustor Specifications
  - Reliable ignition.
  - Stable flame.
  - Complete combustion.
  - Minimum total pressure loss.
  - Appropriate temperature distribution on exit.
  - Compact and small combustor size.
  - High combustion intensity.

1. The Turbojet Engine

- **The Combustor**
  - Reliable ignition and flame stability
    - On ground, it is easy to ignite the combustion because of higher pressure and temperature of the combustor intake flow.
    - However, in flight, especially at high altitude, it is difficult to reignite an extinguished combustion because compressor is in **windmill state**, has high velocity at the exit and p, T are low. The airplane must dive to get high pressure.
    - Ignition reliability refers to whether ignition succeeds in certain (bad) conditions (e.g. at high altitudes).

1. The Turbojet Engine

- **The Combustor**
  - Reliable ignition and flame stability
    - Fuel-to-air ratio:

$$f = \frac{\dot{m}_f}{\dot{m}_0}$$

- Good design has large domain for *f*.
- Air coefficient

$$\alpha = \frac{\dot{m}_0}{\dot{m}_f l_0}$$

- l_0 - air needed to burn 1 kg fuel.
- For kerosene, l_0 = 14.7.

1. The Turbojet Engine

- **The Combustor**
  - Reliable ignition and flame stability
    - $\alpha = 1$， complete burning
    - $\alpha < 1$， rich fuel burning
    - $\alpha > 1$， poor fuel burning
    - Air coefficient is 2.5~3.5 for turbo-engine.
    - However its value is almost 1 in central region of the combustion cross-section.

1. The Turbojet Engine

- **The Combustor**
  - Complete combustion
    - In combustor, most fuel is burnt so that chemical energy changes to heat to increase total enthalpy of the gas. But, a portion of fuel may not be burnt in the combustor because the flow residence time is not long enough to allow a complete combustion.
    - Directly effects the *sfc*.
    - Combustion efficiency, η_b:

$$\eta_b = \frac{Q_{R,actual}}{Q_{R,Ideal}}$$

1. The Turbojet Engine

- **The Combustor**
  - Complete combustion
    - Combustion efficiency, η_b:

$$\eta_b = \frac{Q_{R,actual}}{Q_{R,Ideal}}$$

- $Q_{R,Ideal} = \dot{m}_f LHV$
- $Q_{R,actual} = \left(\dot{m}_0 + \dot{m}_f\right) h_{t3} - \dot{m}_a h_{t2}$
- For kerosene, LHV = 42.9 MJ/kg
- For JP-10, LHV= 42.2 MJ/kg

1. The Turbojet Engine

- **The Combustor**
  - Complete combustion

$$\eta_b = \frac{\left(\dot{m}_0 + \dot{m}_f\right)h_{t4} - \dot{m}_a h_{t3}}{\dot{m}_f LHV}$$

- Under design condition, η_b is around 95%~98%. Because of low pressure at high altitude, η_b goes down.

1. The Turbojet Engine

➢ The Combustor

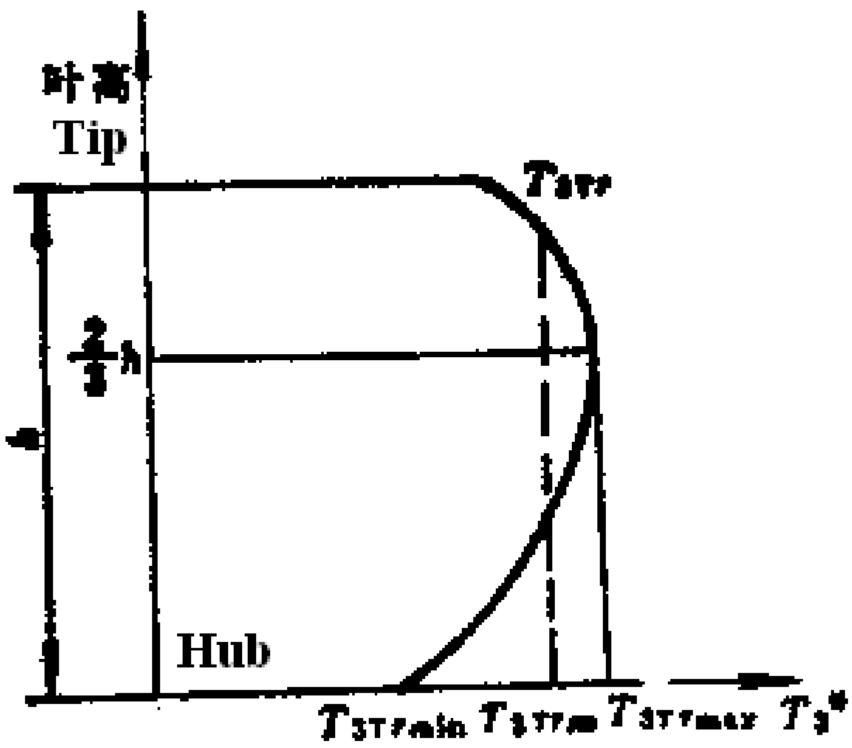
- Less total pressure loss
  - When air passes through the combustor, a part of it is used in burning the fuel, while the remaining is heated. Because of viscosity, losses are unavoidable so that total pressure goes down.
  - From cycle analysis, we know that this reduces the thrust and increases the *sfc*.
  - Combustor total pressure recovery:

$$\sigma_b = \frac{p_{t4}}{p_{t3}}$$

Usually for turbo-engines, σ_b is around 0.94.

1. The Turbojet Engine

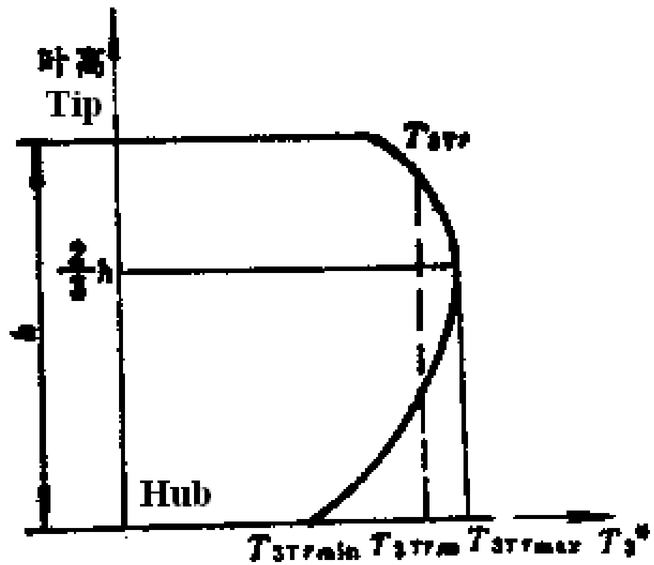
- **The Combustor**
  - Distribution of temperature at the combustor outlet
    - To protect turbine rotating blades, temperature field must follow a distribution as shown in the figure.



1. The Turbojet Engine

➢ The Combustor

- Distribution of temperature at the combustor outlet
  - Because of centrifugal force, stress is greater in blade root. So, temperature is lower.
  - At the tip, the blade is thin, temperature is also lower.
  - Temperature reaches max at 2/3 height so that the blade has a equi-strength.



1. The Turbojet Engine

- **The Combustor**
  - Small combustor size
    - To increase T/W ratio, we need a shorter length of combustion chamber so that the shafts and casings are shorter (and lighter).
    - It is difficult to reduce the combustor diameter.
    - Shorter combustor size implies that the volume of the chamber is smaller.
    - In the other hand, burning more fuel is better and combustion of optimum fuel mass is necessary.

1. The Turbojet Engine

- **The Combustor**
  - High combustion intensity
    - Burning strength Q_{vf} is used to measure heat released per hour per unit volume under unit pressure.

$$Q_{vf} = \frac{3600\eta_b \dot{m}_f LHV}{p_{t2} V_f}$$

    - V_f - volume of flame tube.
    - Usually for turbo-engines:
    - Q_{vf} = (1.2~2)×10^3 kJ/m^3.h.Pa.

1. The Turbojet Engine

- **The Combustor**

  - Design Considerations
    - Design must consider the above previously discussed desirable combustor specifications.
    - Pollution problem: limit concentration of CO, NO, NO_2 … (NO_x) in the emission gases.
    - Structural problem: crack in flame tubes and thermal fatigue.

1. The Turbojet Engine

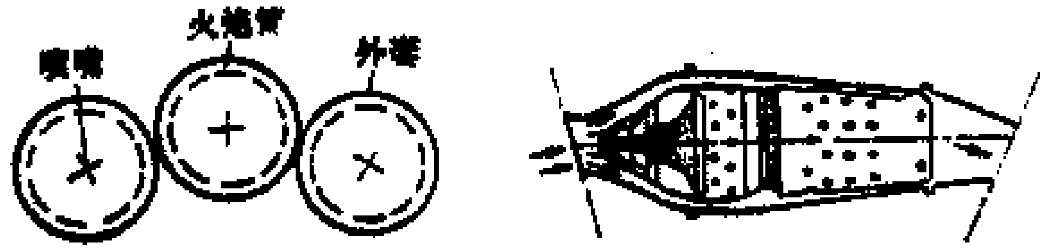
➢ The Combustor: Structure

- Casings,
- Flame tubes,
- Casing,
- Can Interconnectors (Cannular chamber),
- Snout,
- Spray nozzles,
- Swirl vanes,
- Dilution Air Holes,
- etc.

1. The Turbojet Engine

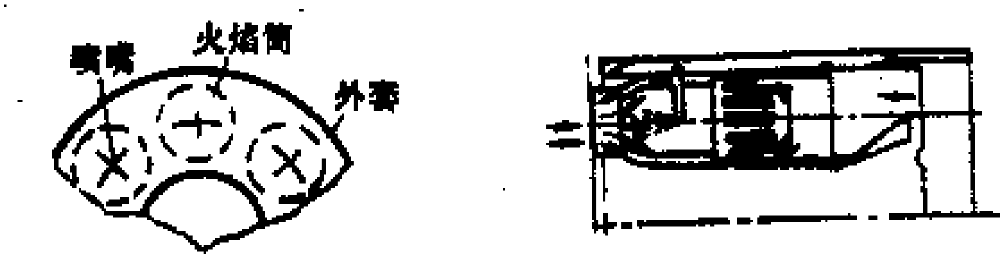
➢ The Combustor: Structure

➢ Single pipe



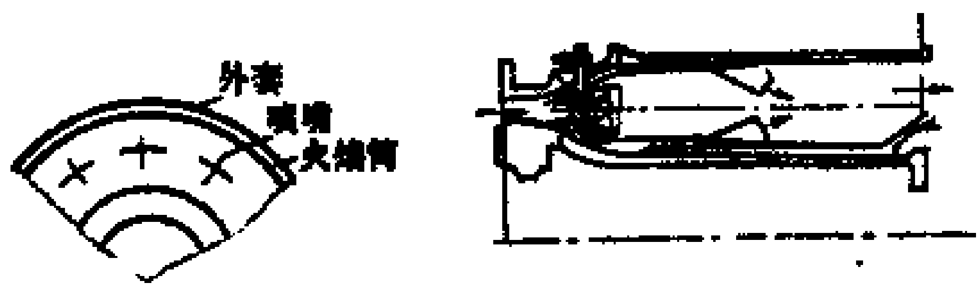
单管燃烧室

➢ Cannular



联管燃烧室

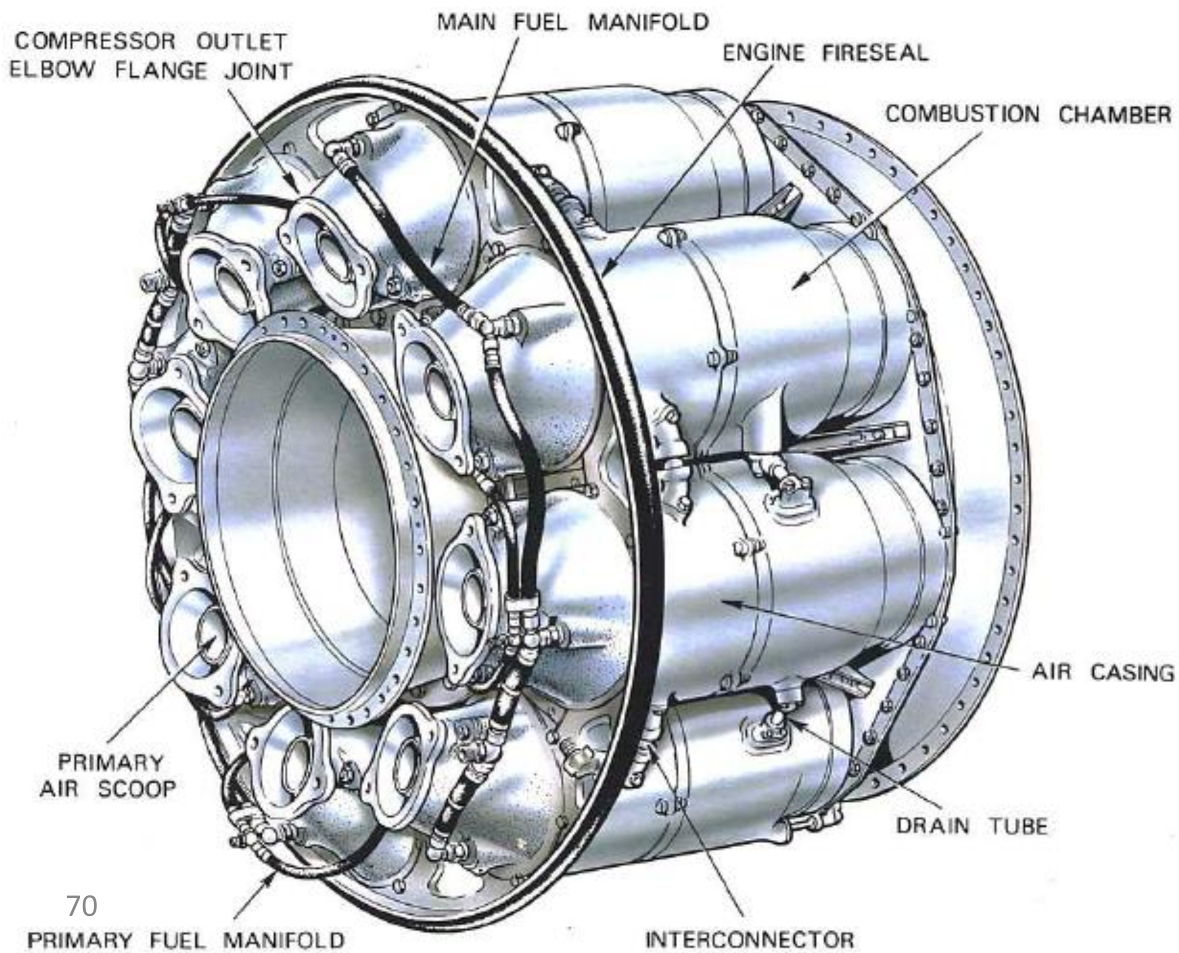
➢ Annular



环形燃烧室

1. The Turbojet Engine

- **The Combustor: Structure**
  - Single pipe

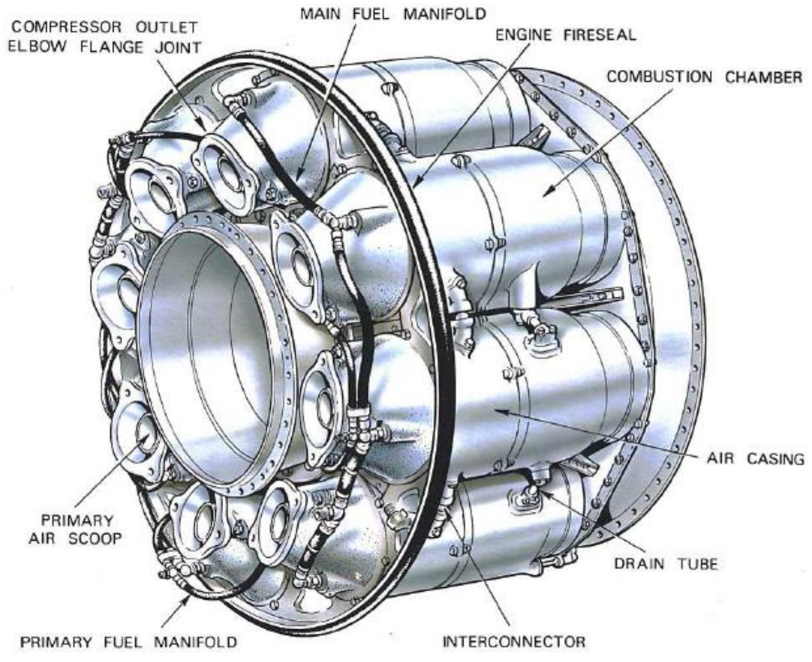


1. The Turbojet Engine

➢ The Combustor: Structure

➢ Single pipe

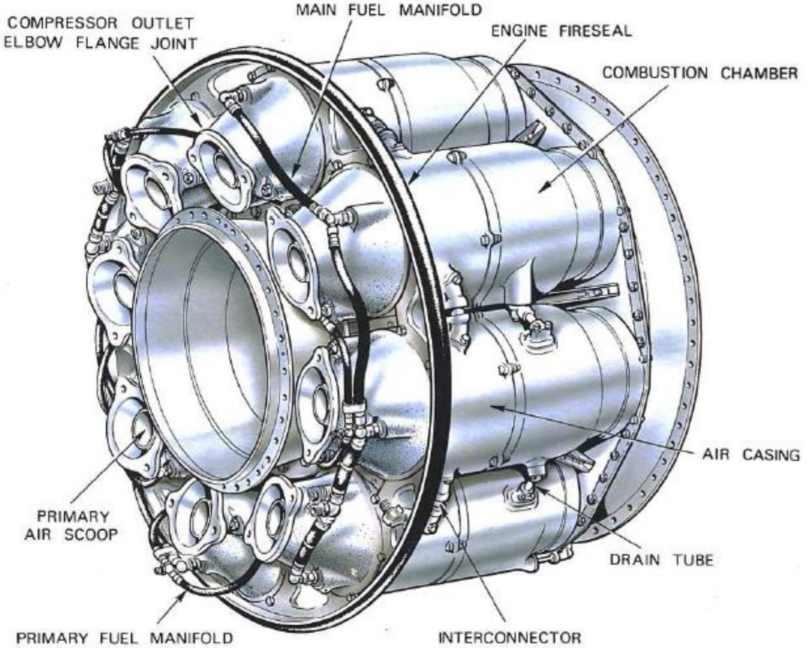
- ➢ It consists of many combustion chambers(8~16). Interconnectors connect them to pass flame and make pressure equal.
- ➢ Each chamber has a casing so that it is easy to test in lab.
- ➢ Require less air.



1. The Turbojet Engine

➢ The Combustor: Structure

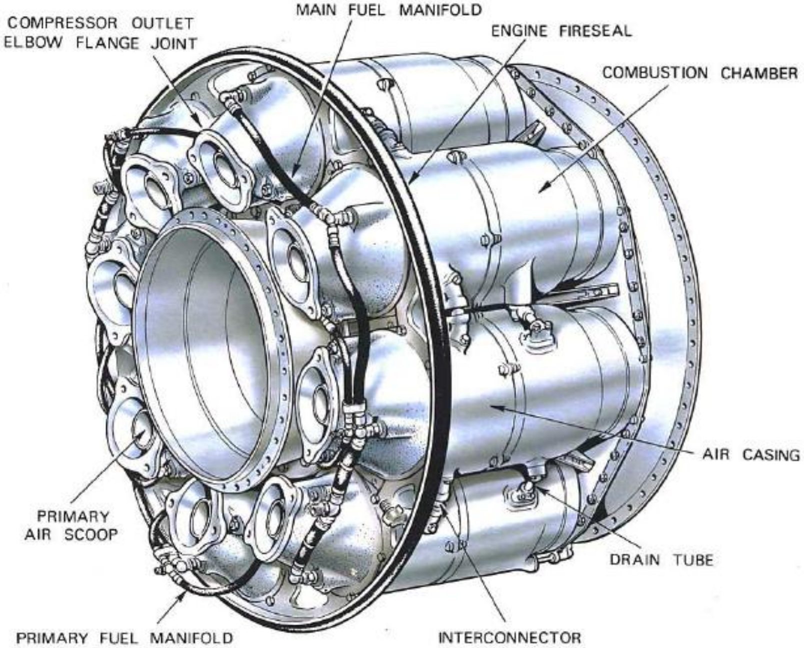
- ➢ Single pipe
  - ➢ It was widely used in early engines, especially in combination with centrifugal compressor.
  - ➢ Simple structure，easy to replace or maintain.



1. The Turbojet Engine

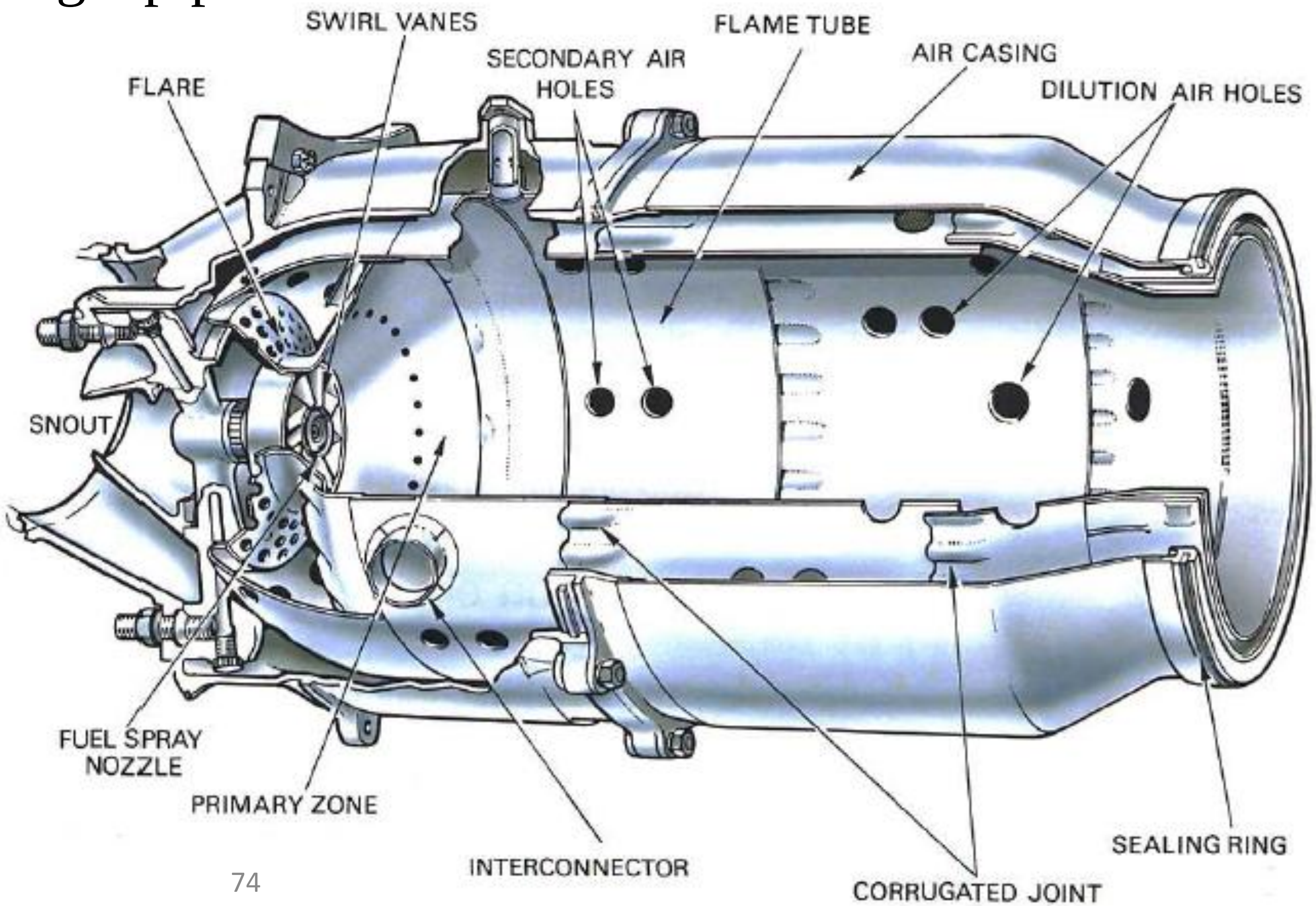
➢ The Combustor: Structure

- ➢ Single pipe
  - ➢ Not efficient in terms of the use of space.
  - ➢ Heavy.
  - ➢ Casing cannot transfer mechanical forces.
  - ➢ Its use increases the resulting part weight of other components.



1. The Turbojet Engine

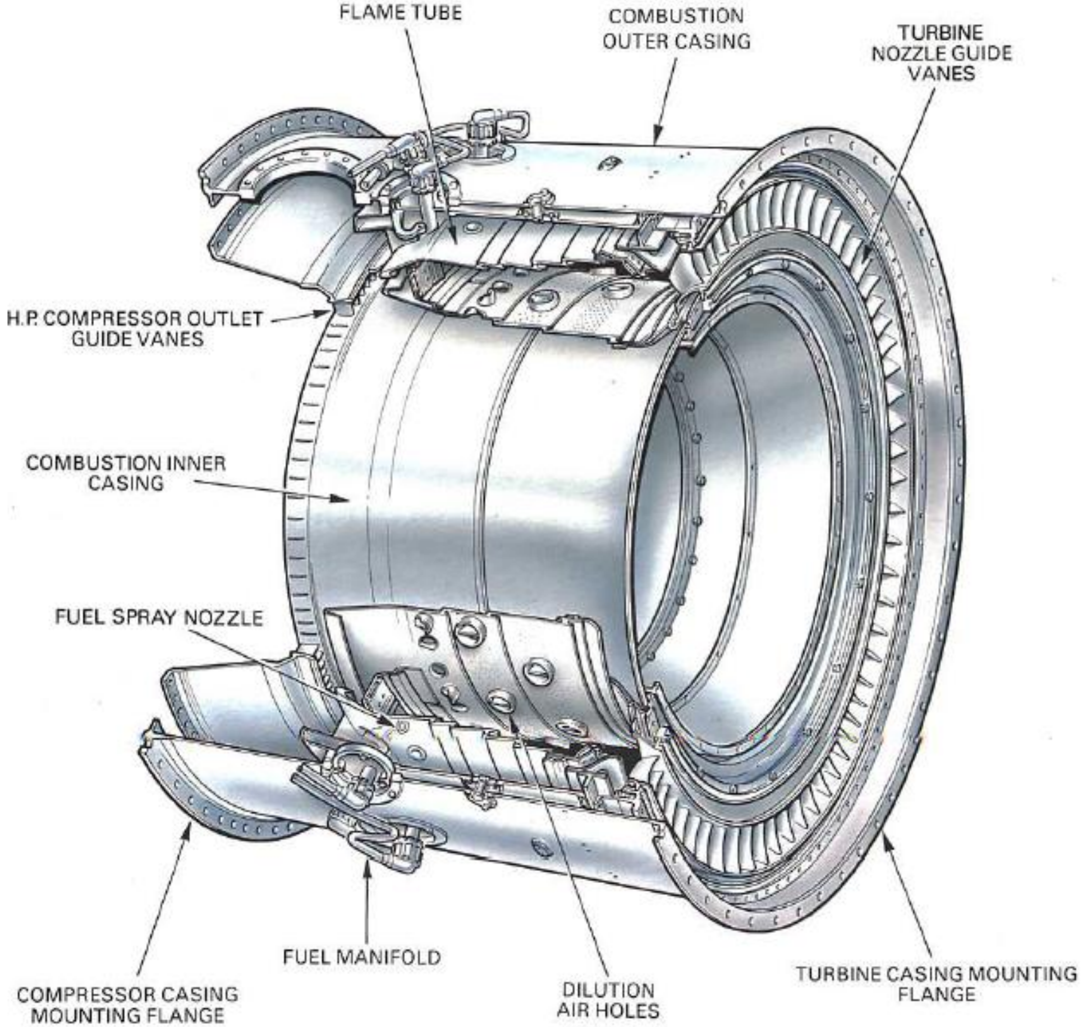
- **The Combustor: Structure**
  - Single pipe



1. The Turbojet Engine

➢ The Combustor: Structure

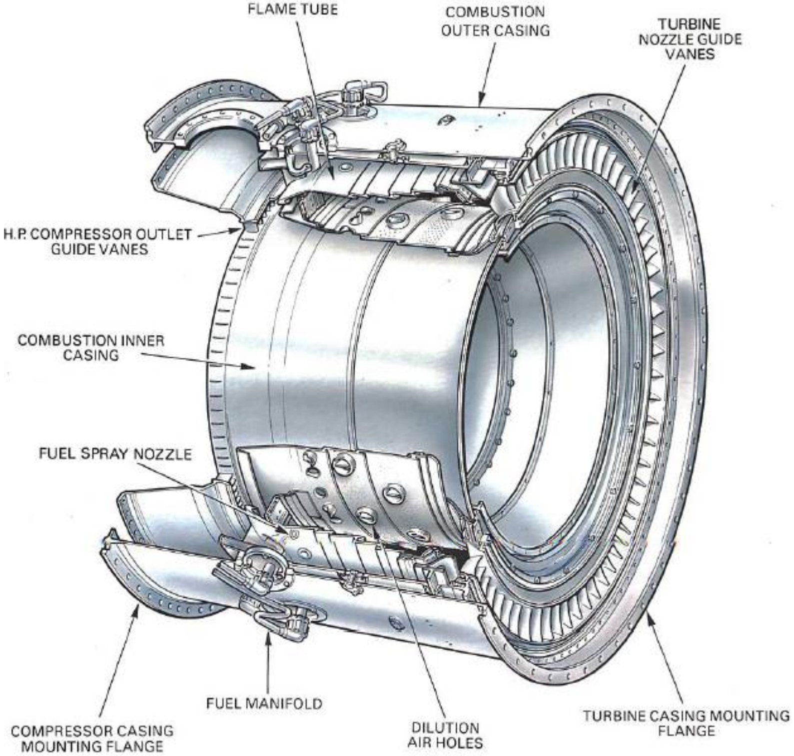
- ➢ Annular



1. The Turbojet Engine

➢ The Combustor: Structure

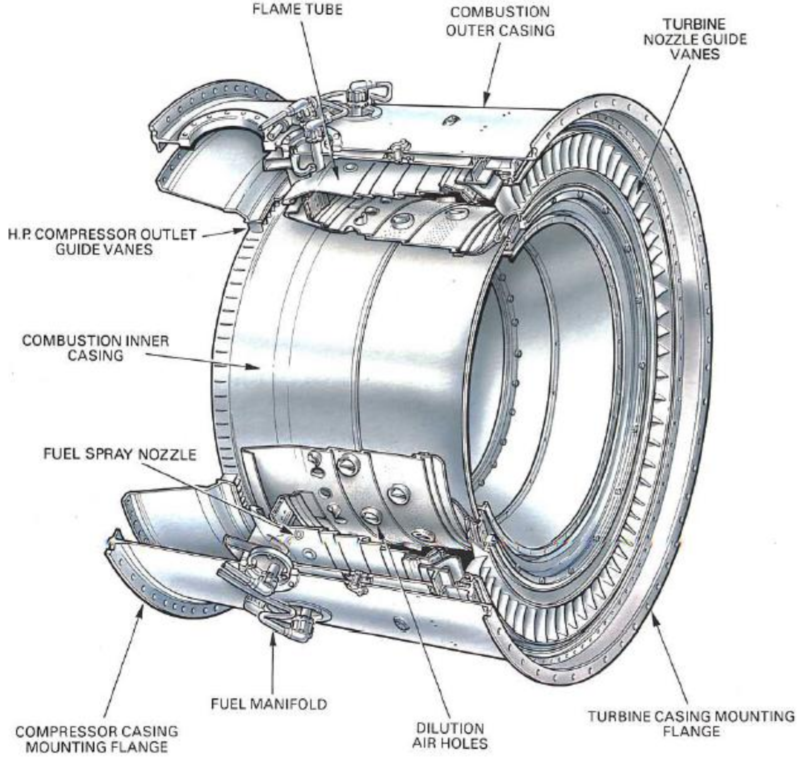
- ➢ Annular
  - ➢ Typical annular combustors consist of 4 concentric cylinders
  - ➢ Widely used nowadays.
  - ➢ Efficient use of space.
  - ➢ Casing can transfer forces.



1. The Turbojet Engine

➢ The Combustor: Structure

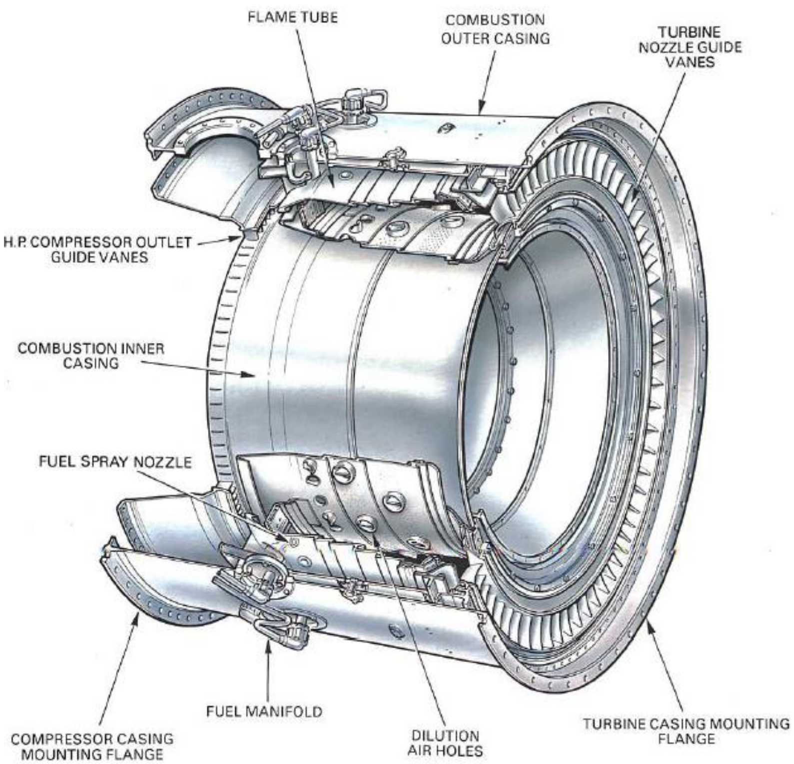
- ➢ Annular
  - ➢ It matches geometrically and aerodynamically with compressor outlet and turbine inlet, so less losses and uniform temperature field.
  - ➢ It's lighter in weight.



1. The Turbojet Engine

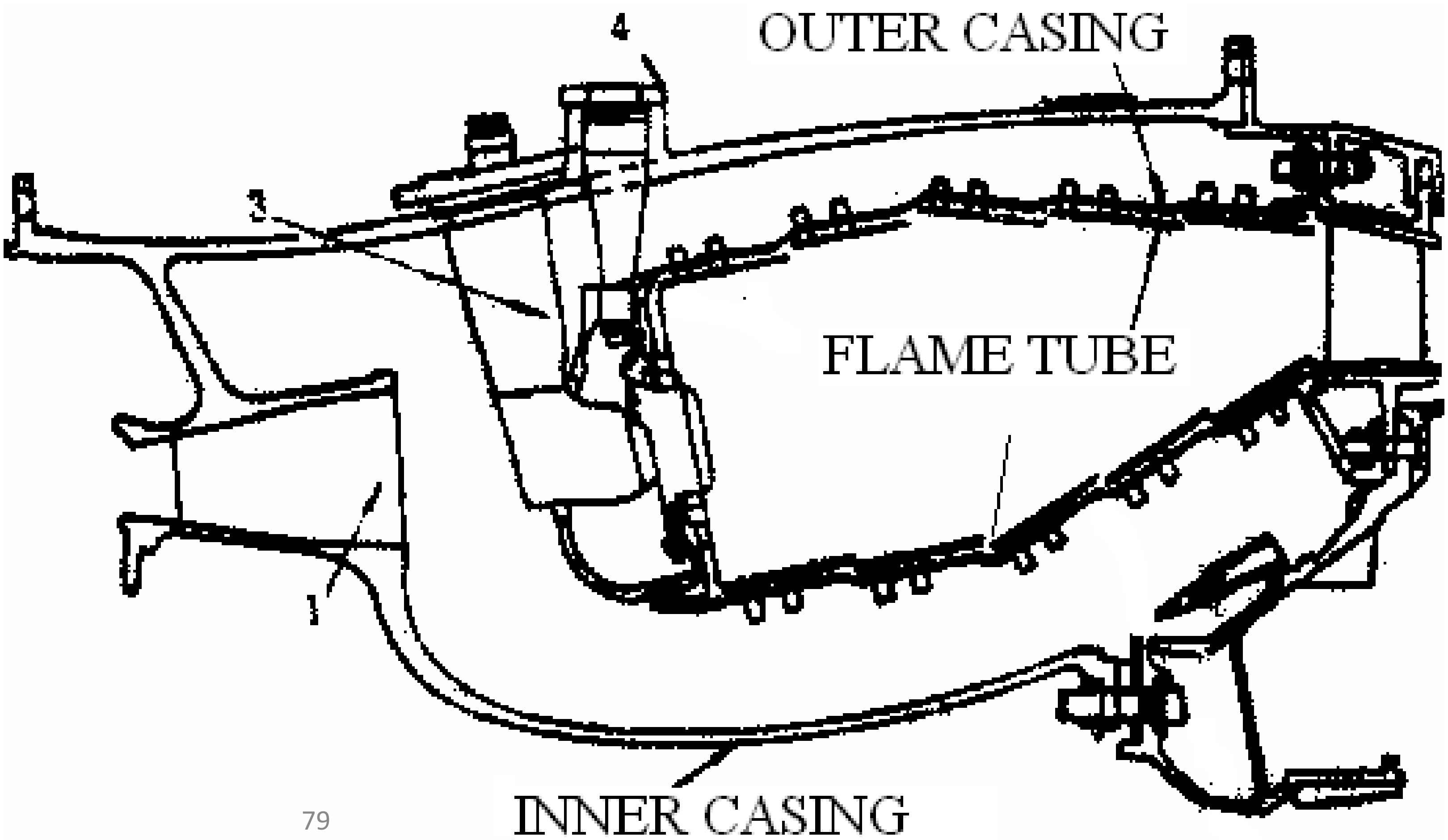
➢ The Combustor: Structure

- ➢ Annular
  - ➢ Difficult to test in lab, and need large quantity of flow to test.
  - ➢ Difficult to maintain.



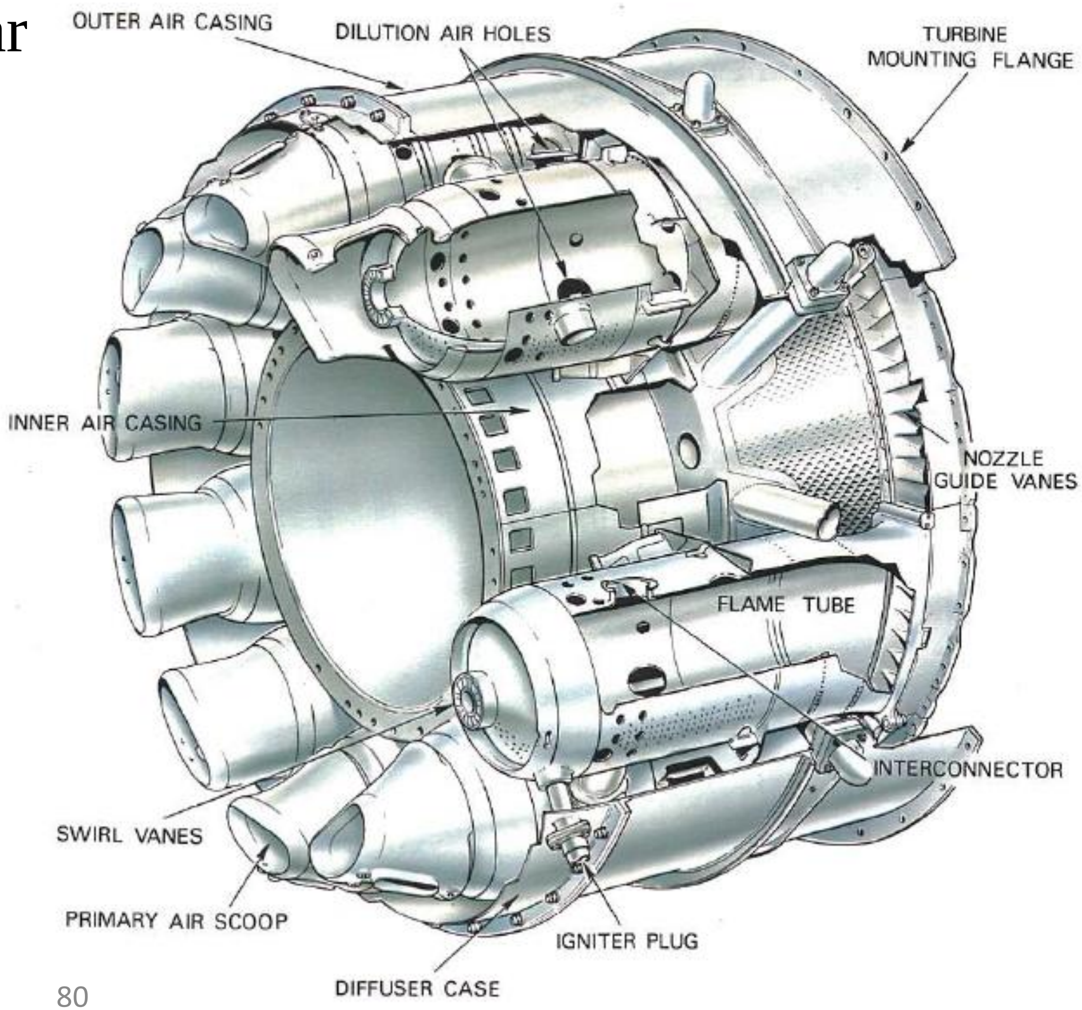
1. The Turbojet Engine

- **The Combustor: Structure**
  - Annular



1. The Turbojet Engine

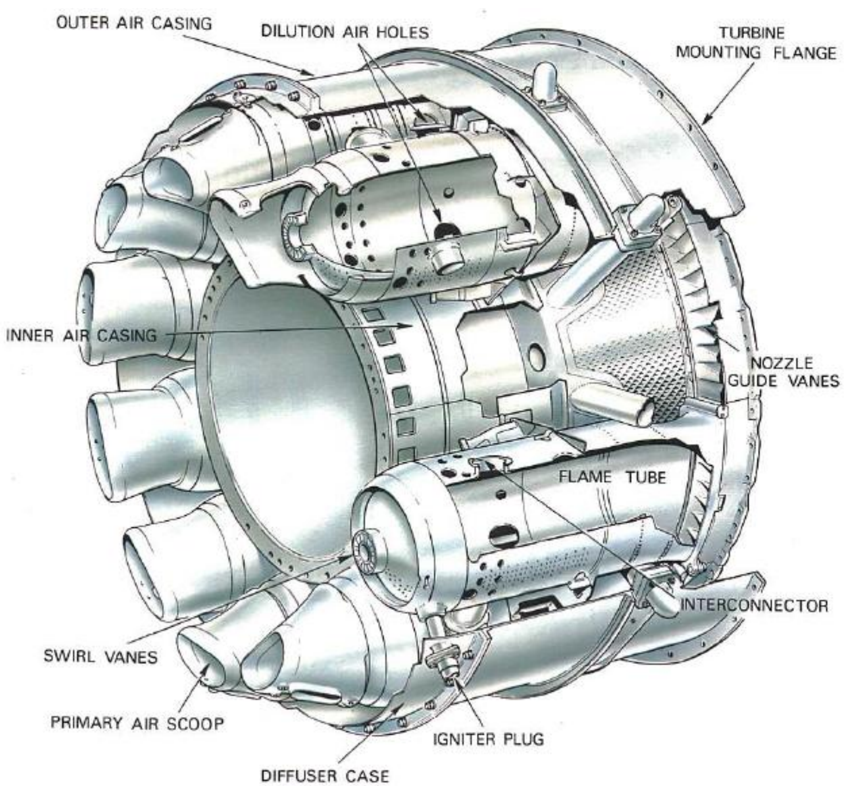
- **The Combustor: Structure**
  - Cannular



1. The Turbojet Engine

➢ The Combustor: Structure

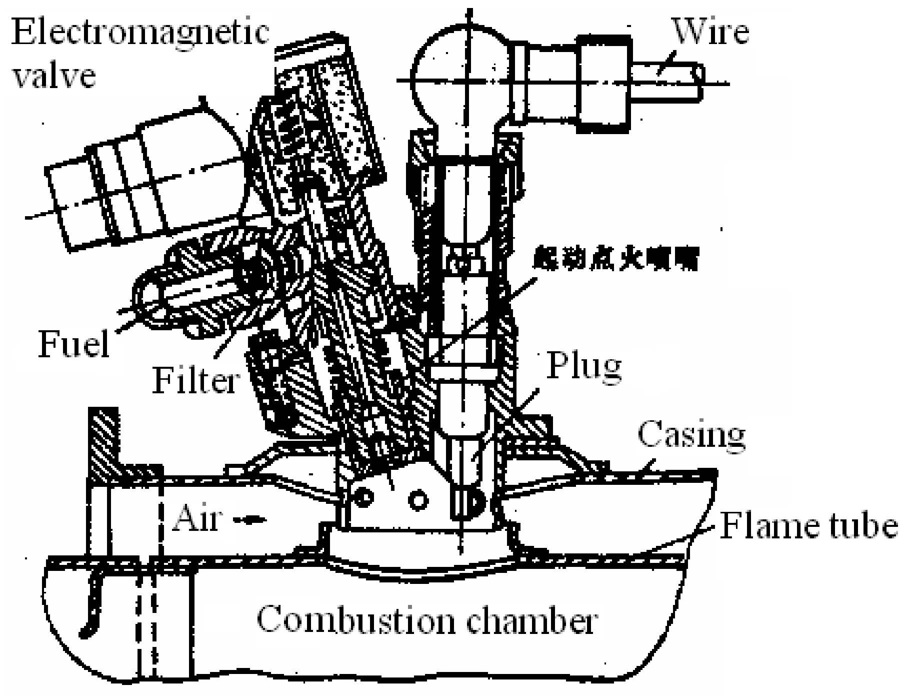
- ➢ Cannular
  - ➢ There are several single flame tubes within the same casing.
  - ➢ Casing can be used to transfer forces.
  - ➢ Compact structure.
  - ➢ It is lighter in weight.
  - ➢ A single-tube is easy to test.



1. The Turbojet Engine

➢ The Combustor: Ignition

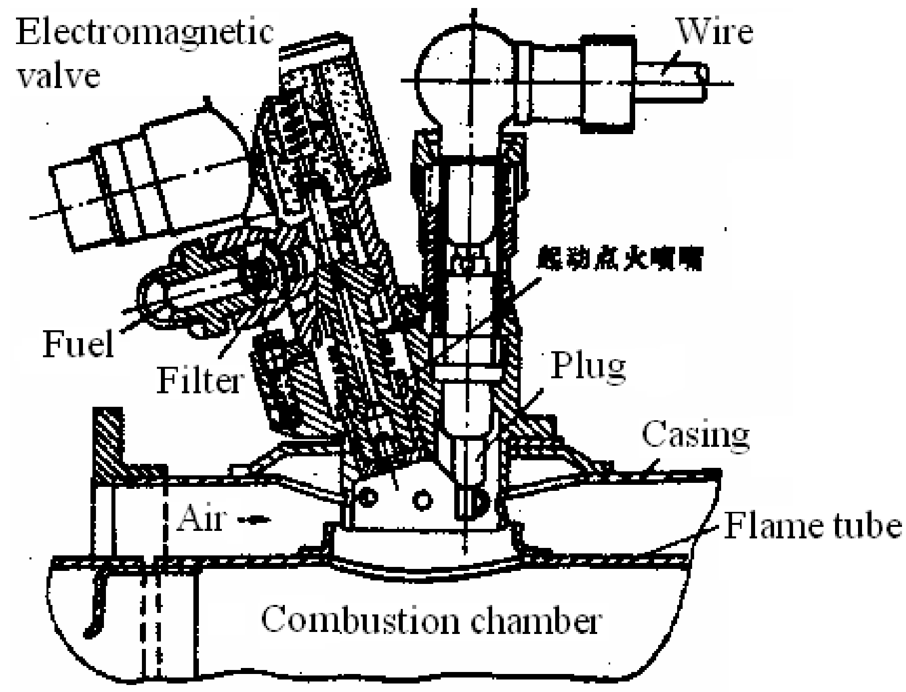
- ➢ Ignition process is the same as in an automobile engine, where a high voltage plug is used to ignite fuel-mixture. The resulting flame then propagates into the whole premixed combustion zone.



1. The Turbojet Engine

➢ The Combustor: Ignition

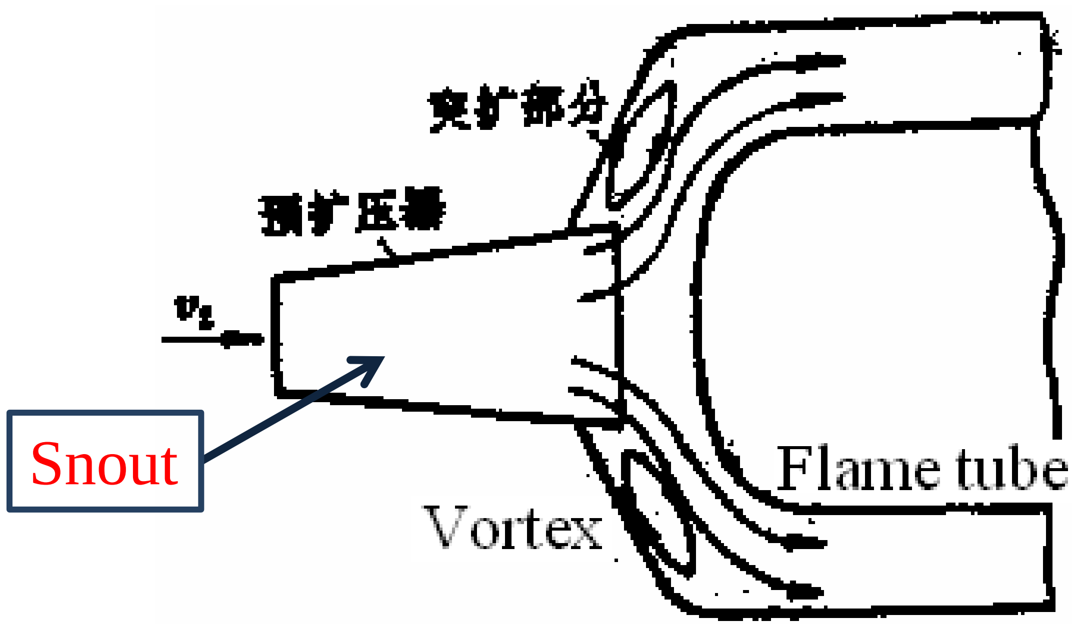
- ➢ Igniters stop working once burning zone is flamed.
- ➢ In general, one engine has at least 2 igniters to insure ignition success.
- ➢ For multiple flame tube structure, interconnectors pass flame from one to others.



1. The Turbojet Engine

➢ The Combustor: Speed Reduction

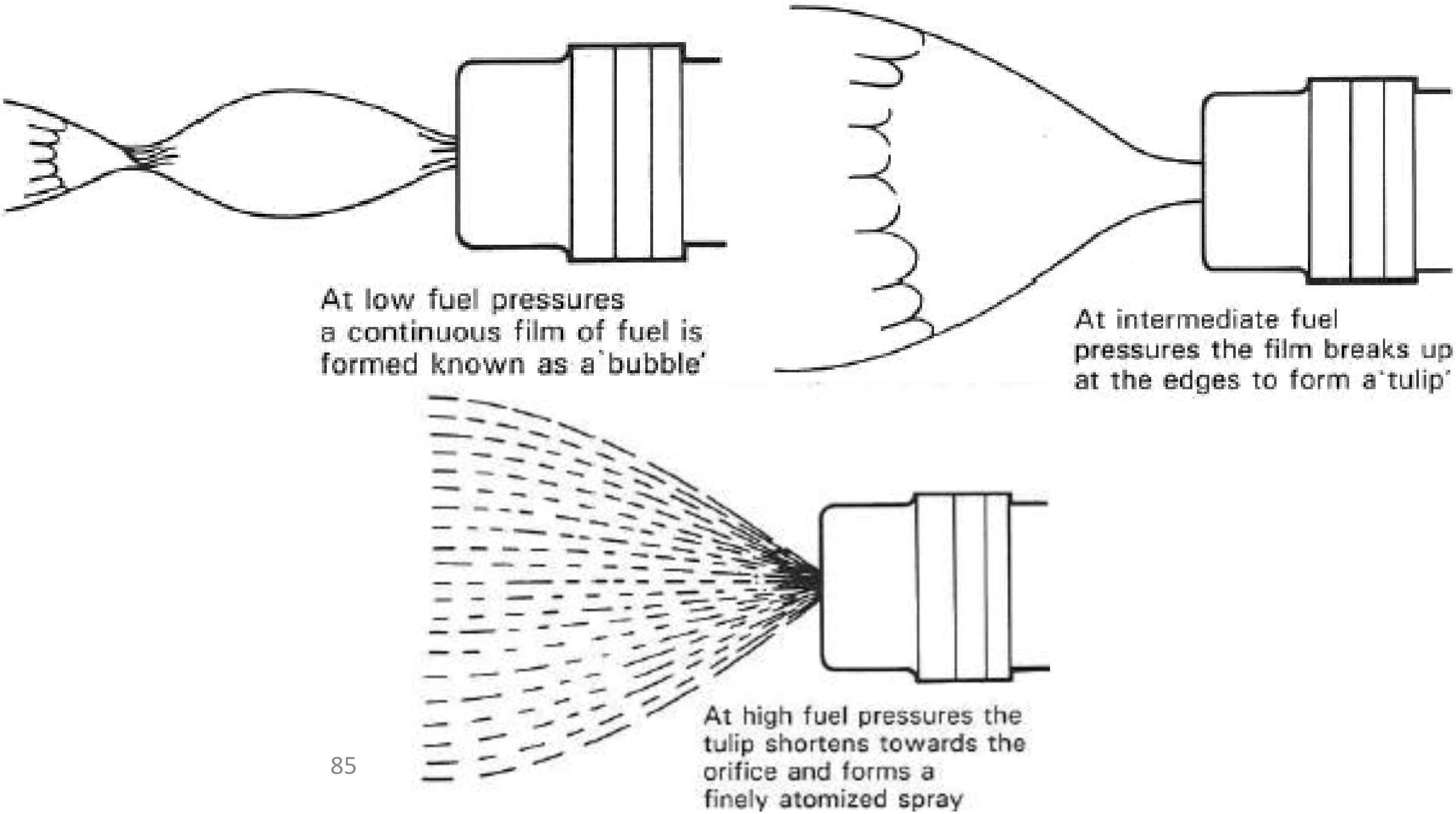
- ➢ Air speed in the last stage of compressor is around 150m/s. But combustion chamber flame tube requires flow speed in the range 30~45m/s.
- ➢ Divergent geometry at the snout reduce speed quickly.



1. The Turbojet Engine

➢ The Combustor: Fuel Vaporization

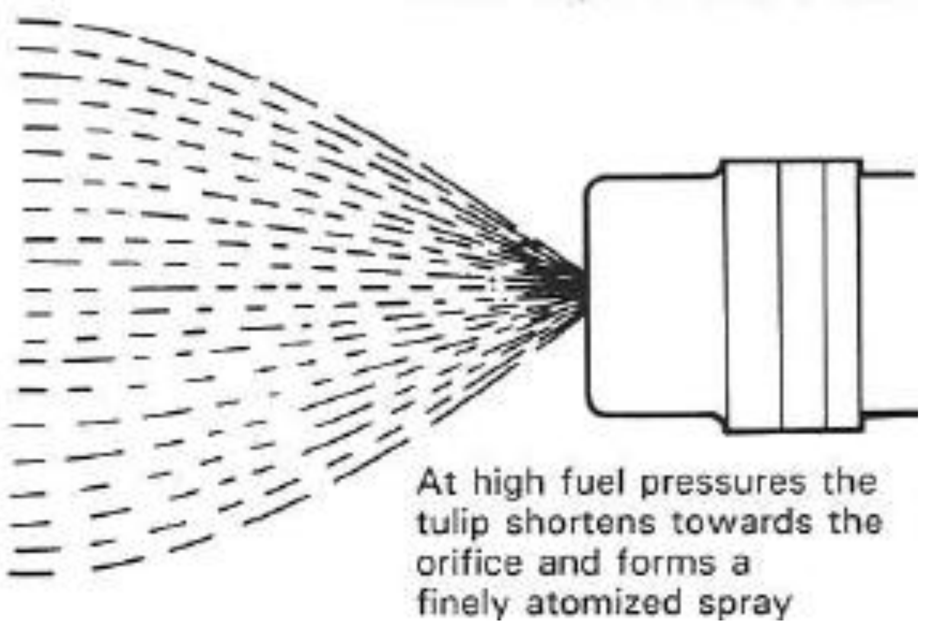
- ➢ Atomization



1. The Turbojet Engine

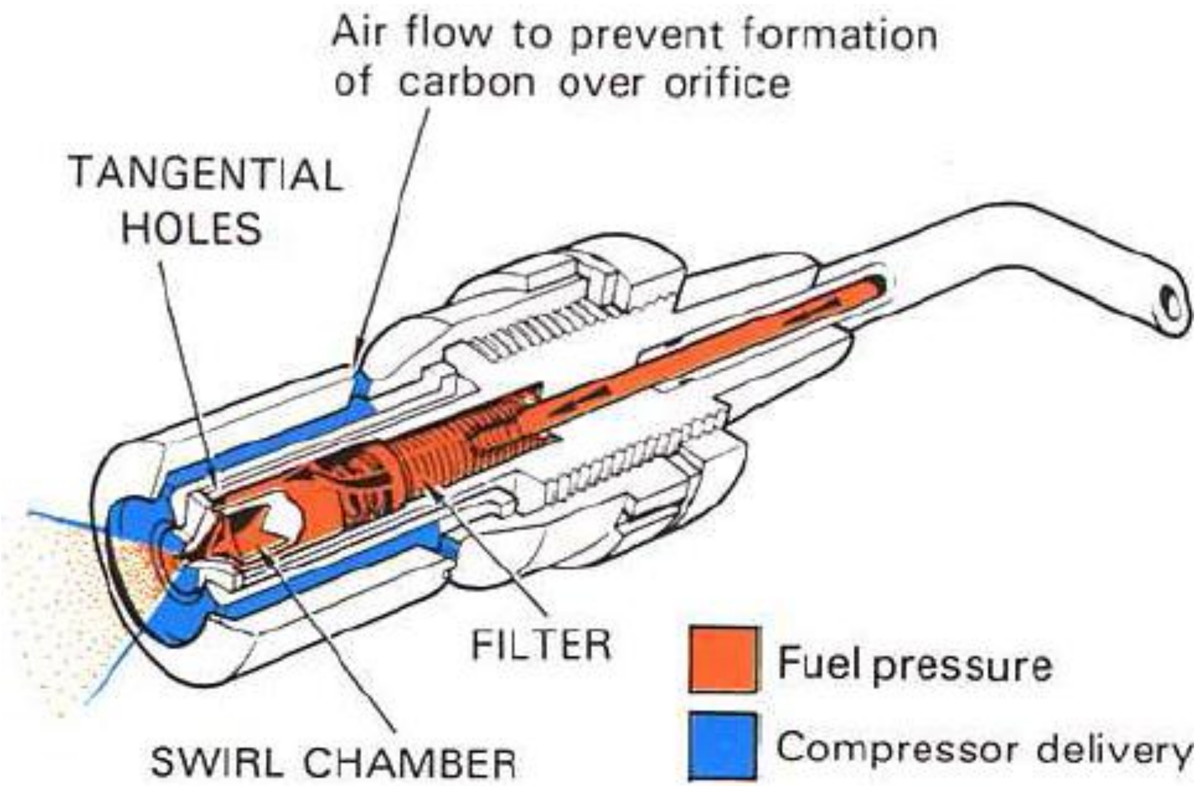
➢ The Combustor: Fuel Vaporization

- ➢ Atomization
  - ➢ to get tiny fuel droplets.
  - ➢ to increase contact surface with air.
  - ➢ to absorb more heat.
  - ➢ to vaporize.



1. The Turbojet Engine

- **The Combustor: Injection**
  - Fuel spray nozzle (Swirl Injector)

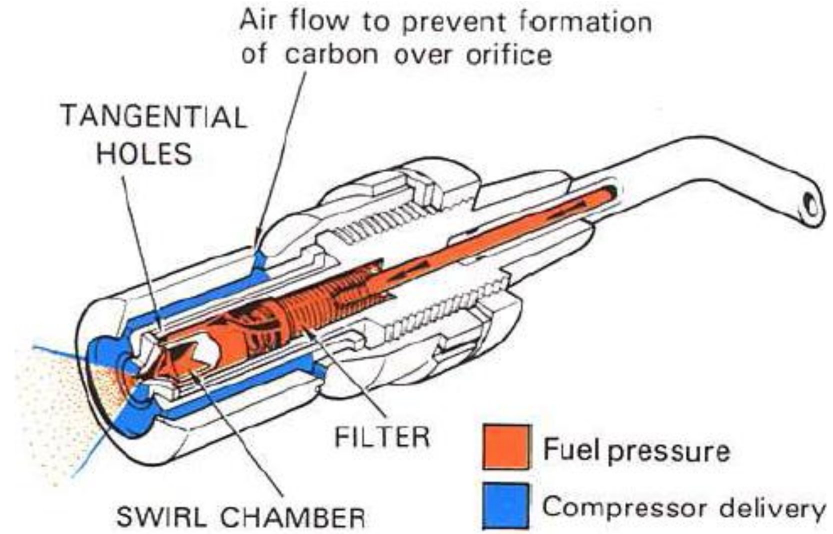


A Simplex fuel spray nozzle.

1. The Turbojet Engine

➢ The Combustor: Injection

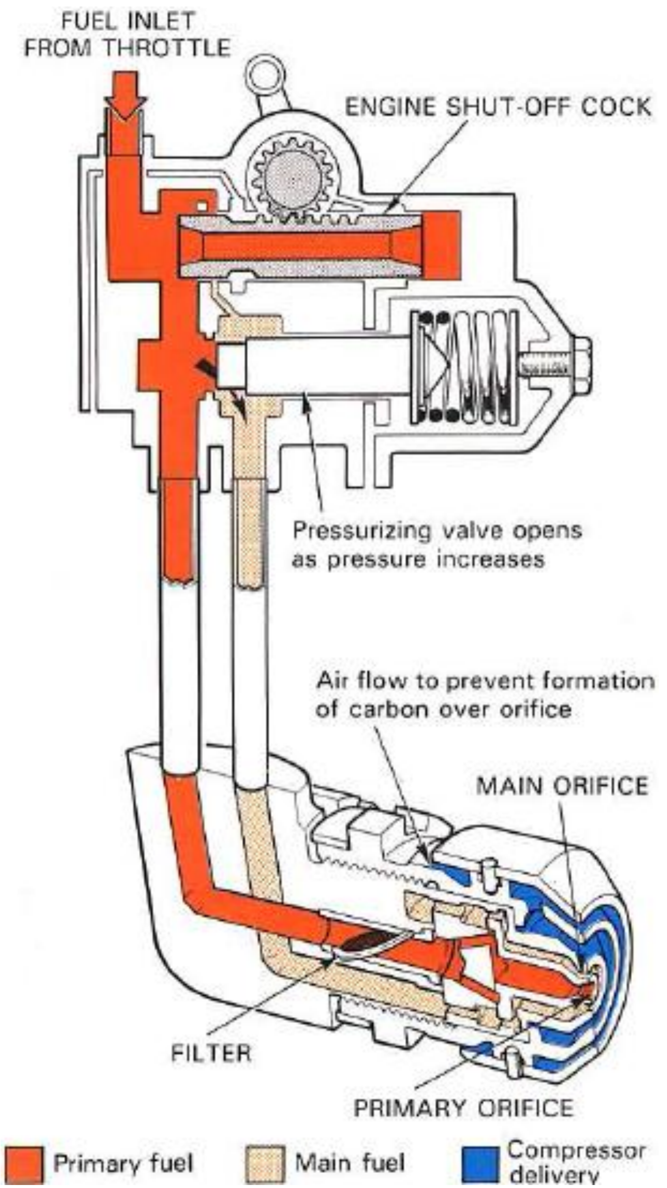
- ➢ Fuel spray nozzle (Swirl Injector)
  - ➢ For a normal fuel pump, output fuel flow rate is proportional to the square root of injection pressure.
  - ➢ An engine may sometimes require lesser fuel, for example 1/10 (idle) of max-power fuel. Under this condition the pump pressure is 1/100 of that at max-power.
  - ➢ Under low pressure injection conditions, vaporization is bad.



1. The Turbojet Engine

- **The Combustor: Injection**
  - Fuel spray nozzle (Swirl Injector)

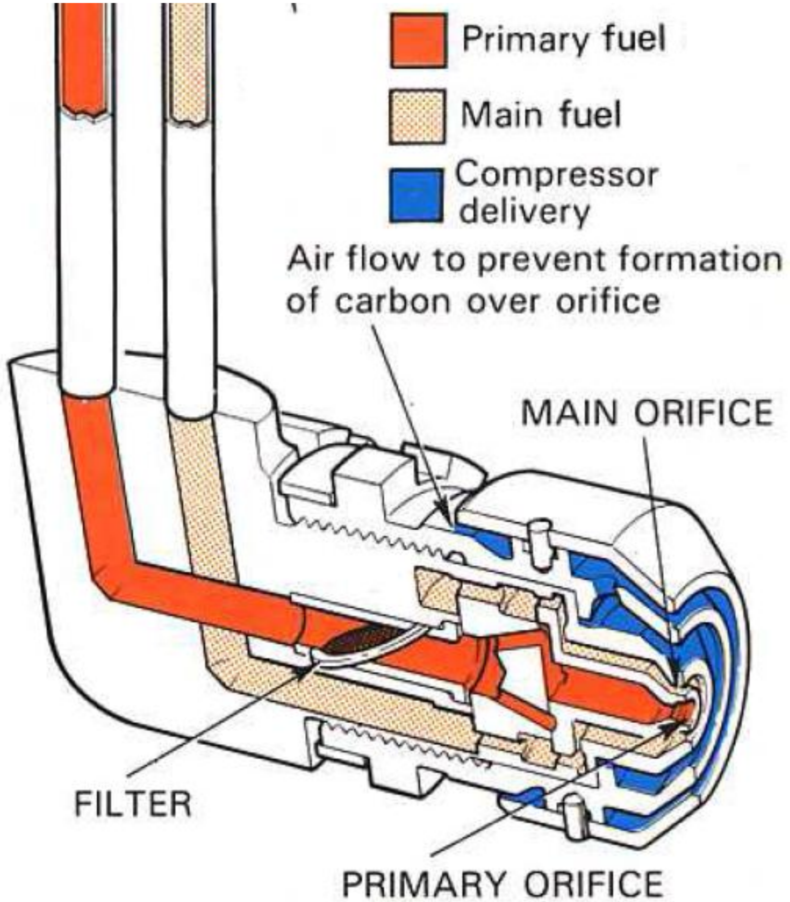
A <u>Duple</u> fuel spray nozzle and pressurizing valve.



1. The Turbojet Engine

➢ The Combustor: Injection

➢ Fuel spray nozzle (Swirl Injector)



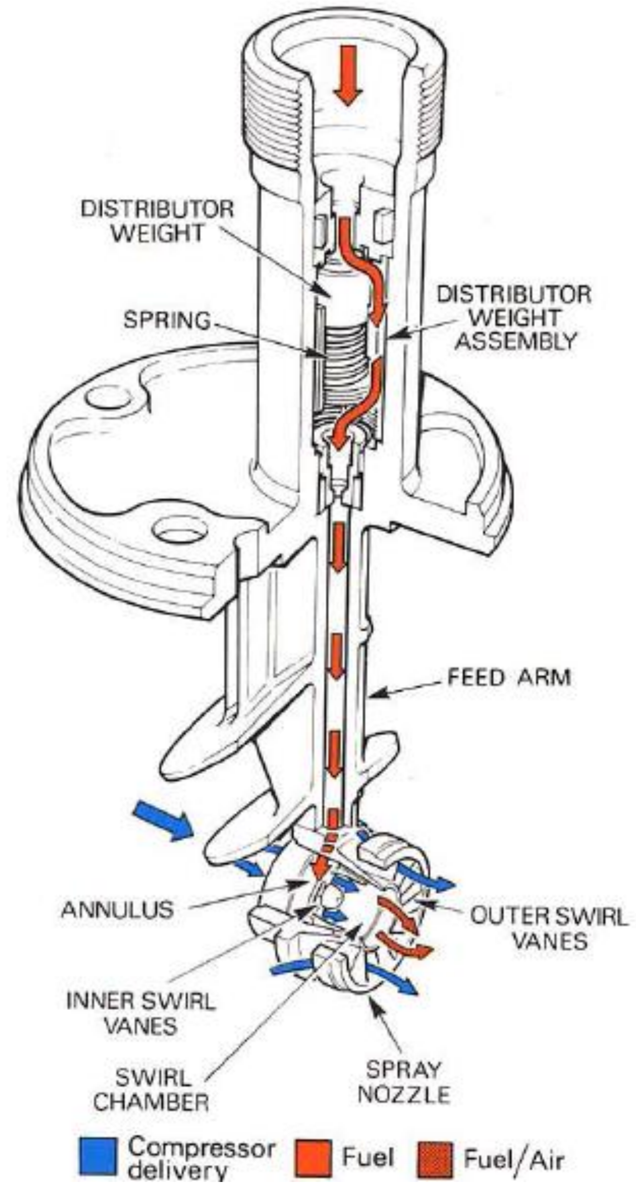
➢ Duplex can supply fuel in large amounts through 2 fuel flow channels.

A <u>Duple</u> fuel spray nozzle.

1. The Turbojet Engine

➢ The Combustor: Injection

- ➢ Fuel spray nozzle (Swirl Injector)

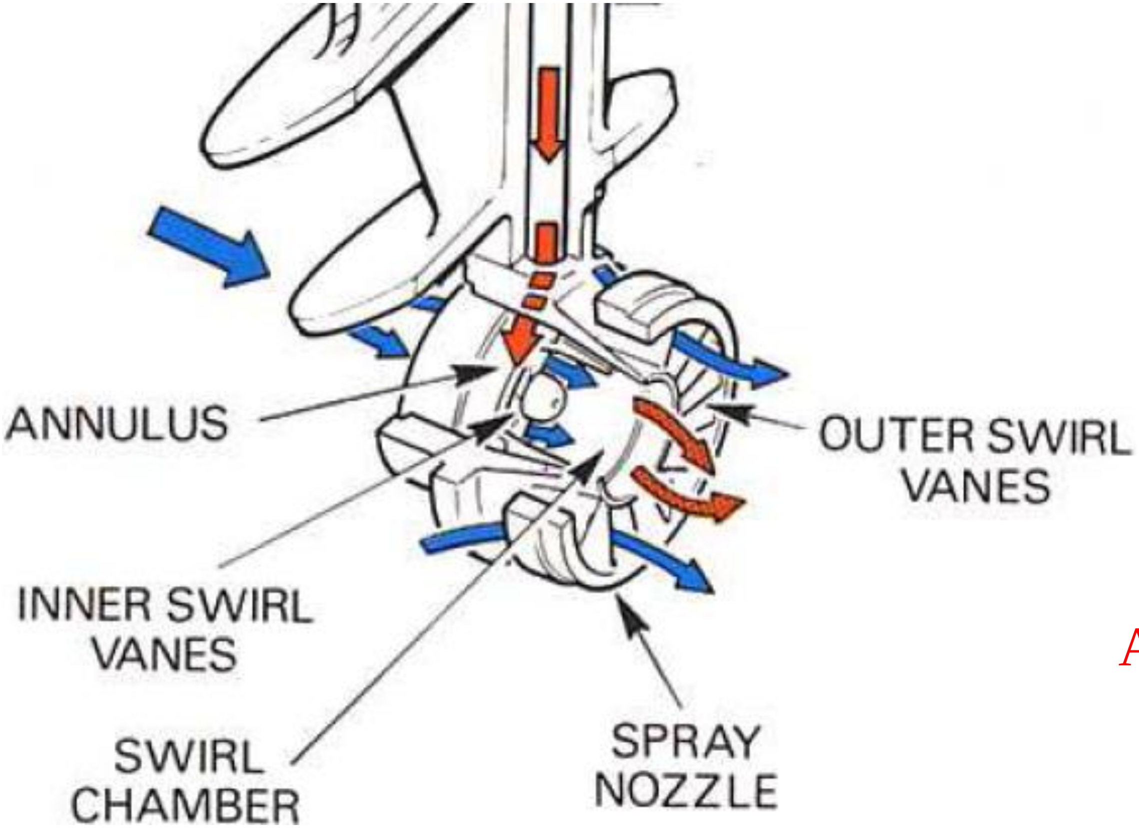


- ➢ Duplex can supply fuel in large amounts through 2 fuel flow channels.

Airspray nozzle.

1. The Turbojet Engine

- **The Combustor: Injection**
  - Fuel spray nozzle (Swirl Injector)

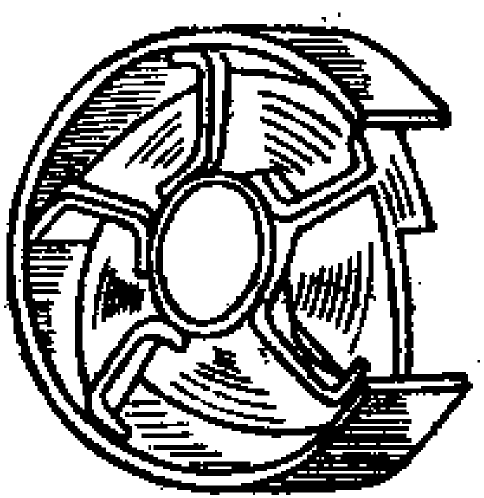


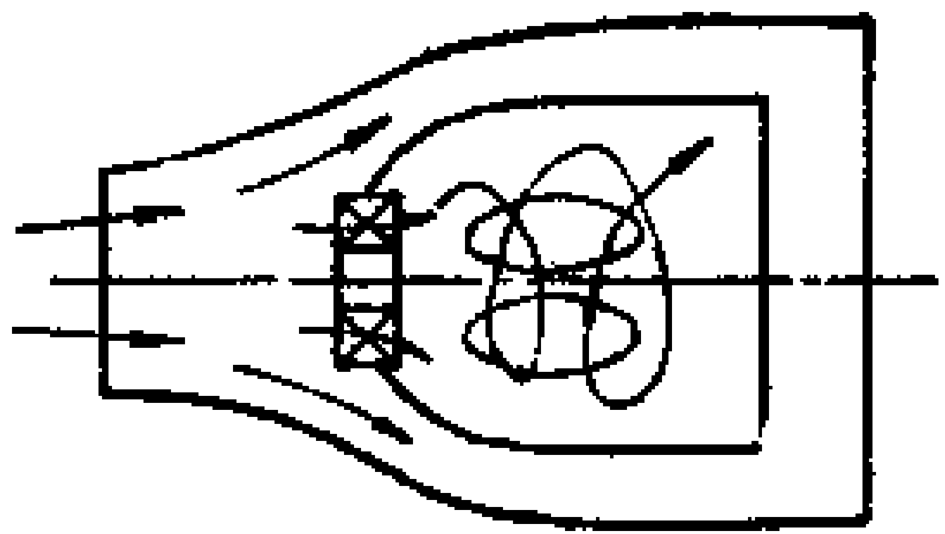
Airspray nozzle.

1. The Turbojet Engine

➢ The Combustor: Flame Stabilization

- ➢ In the head of flame tube, swirl vanes are installed to provide necessary swirl to the entering air flow.
- ➢ Due to viscosity, a low pressure region is formed in the center of the tube which results in the air to flow back from downstream. As a result, a vortex is formed in the flame tube.

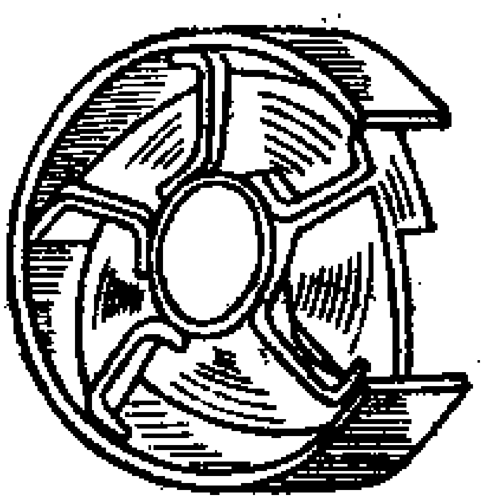


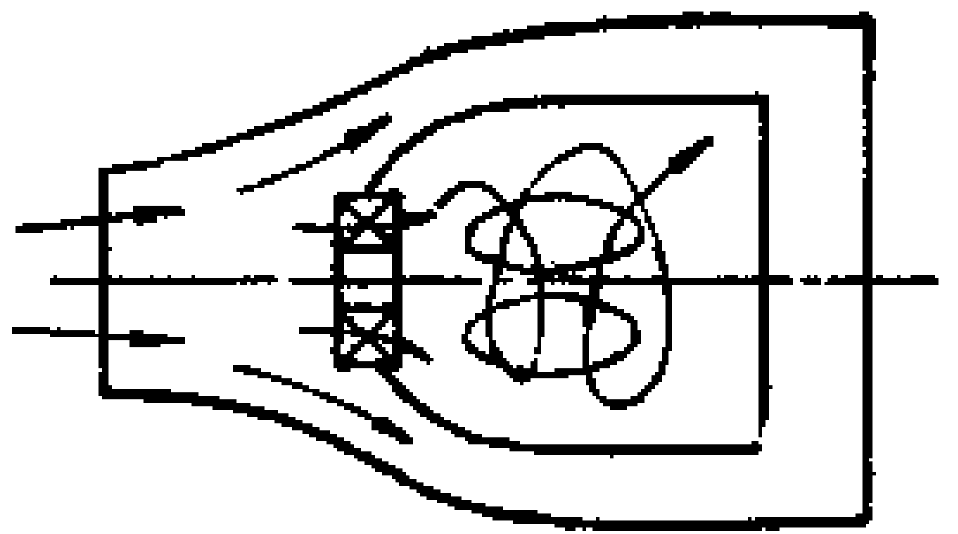


1. The Turbojet Engine

➢ The Combustor: Flame Stabilization

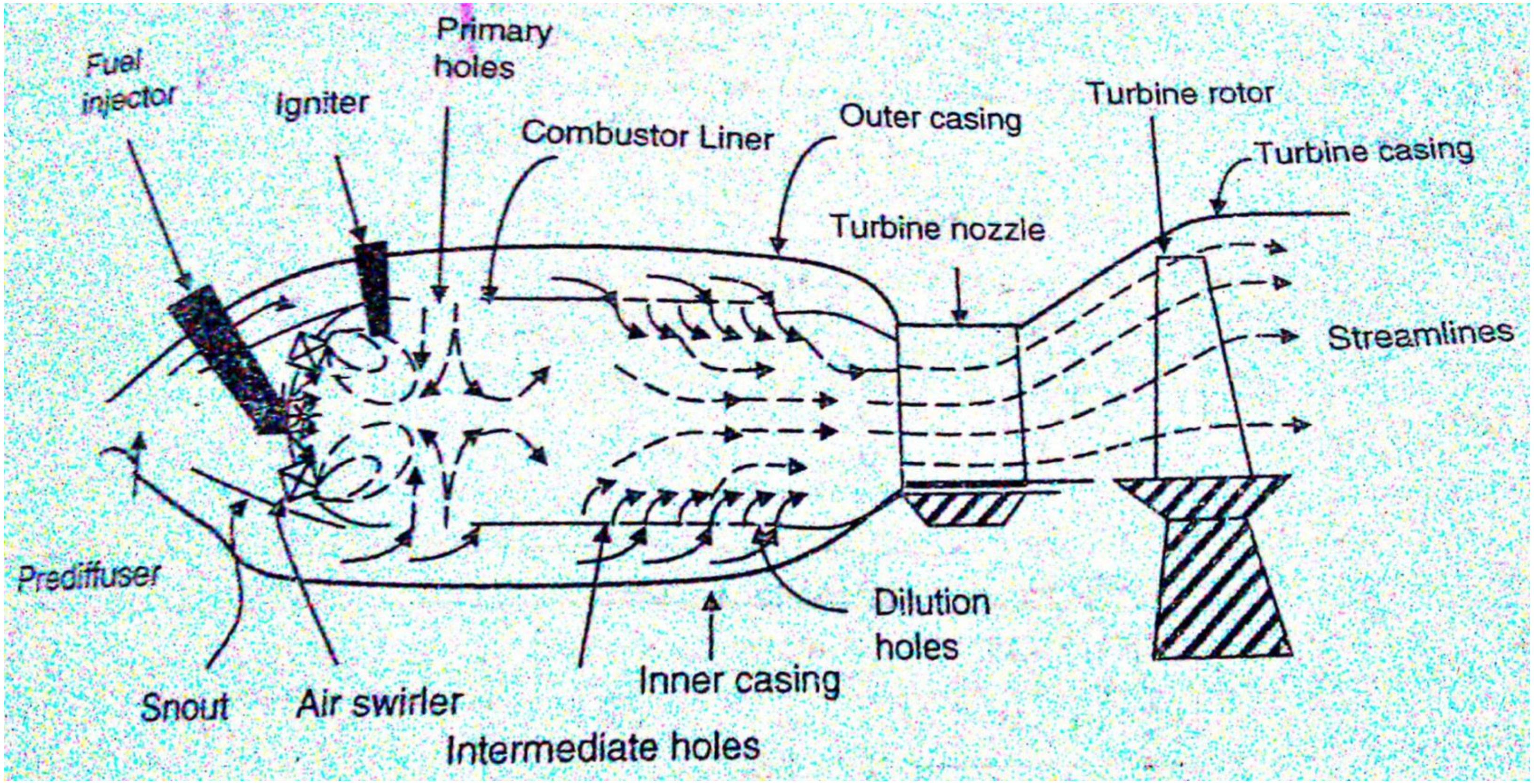
- ➢ In this vortex, temperature is high (good for vaporization) because air comes from the downstream, and the flow speed is low so that it gets easier to burn the mixture.
- ➢ There exists a line in which flow speed is equal to flame propagation speed so that the flame is held in the flame tube.
- ➢ Incoming mixture is thus ignited by the previous flame.





1. The Turbojet Engine

➢ The Combustor: Basic Components

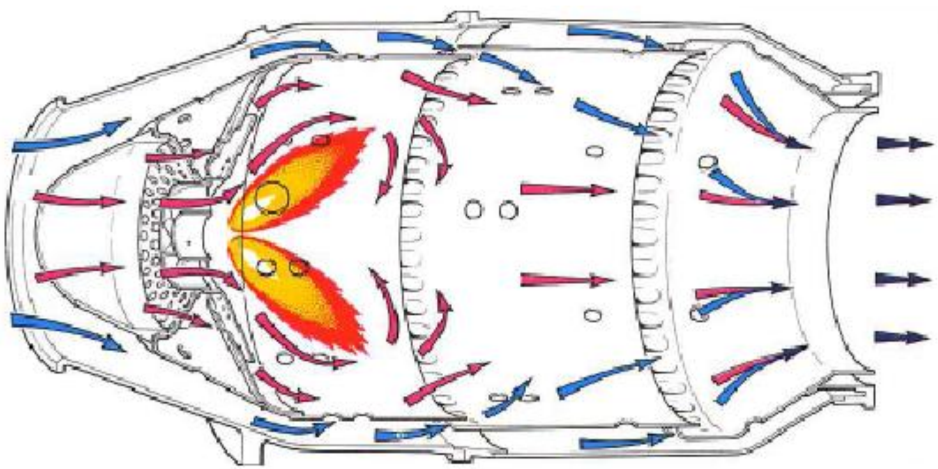


Components of a conventional combustor
and the first turbine stage.

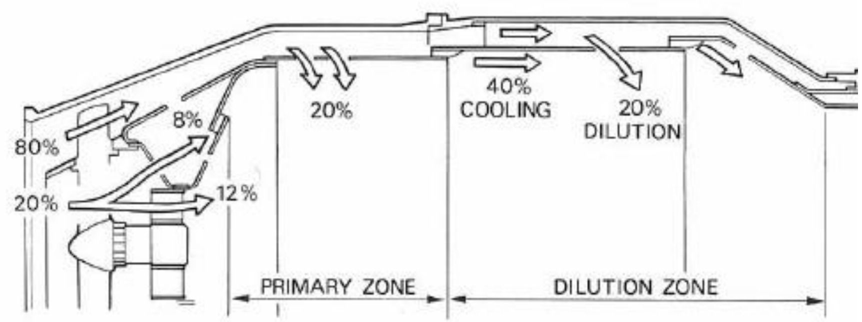
1. The Turbojet Engine

➢ The Combustor: Combustion

- ➢ Fresh air comes from the snout, and fuel is injected from spray nozzle. They are mixed and flamed. When the gas arrives at the outlet of the combustion chamber, it should be burnt completely.



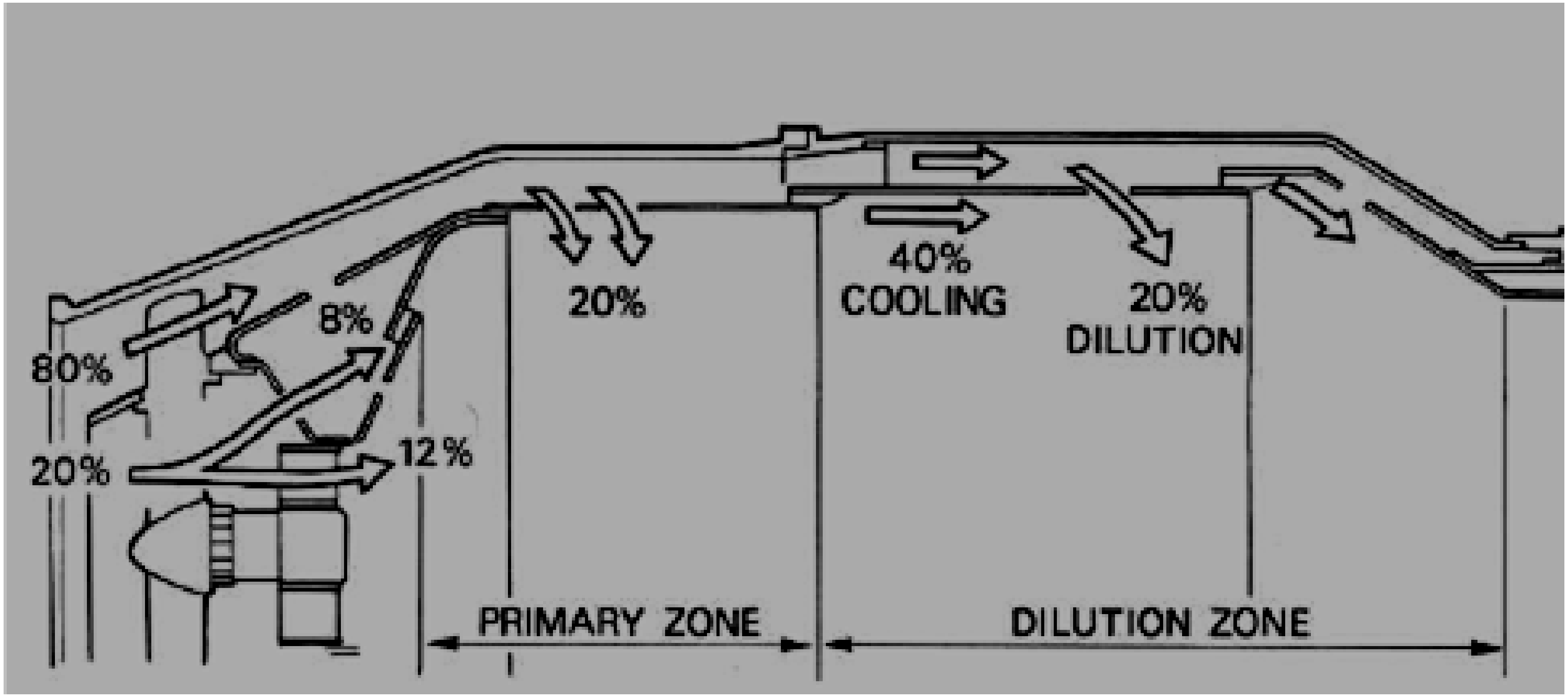
Flame stabilizing and general airflow pattern



Apportioning the airflow

1. The Turbojet Engine

➢ The Combustor: Combustion

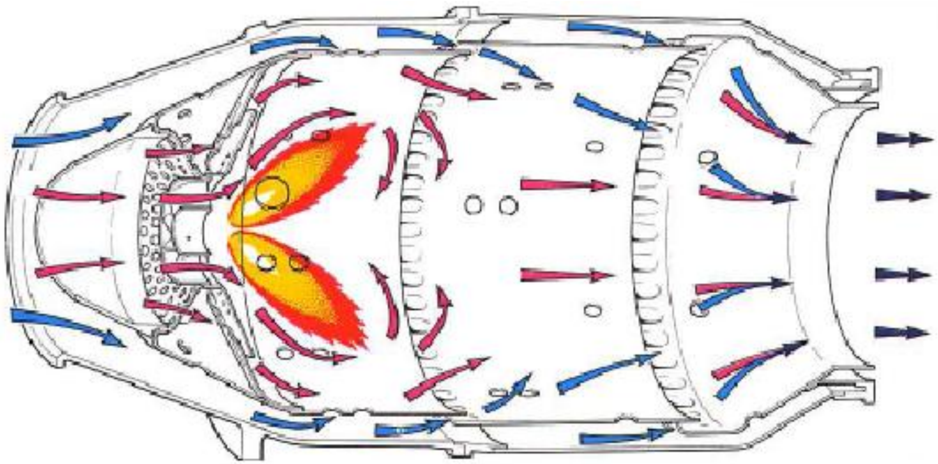


Apportioning the airflow.

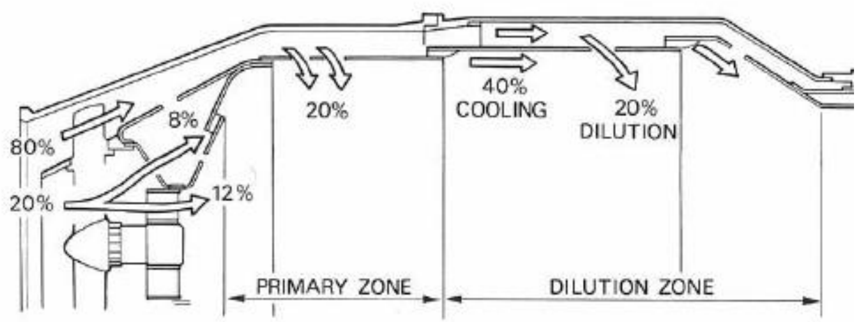
1. The Turbojet Engine

➢ The Combustor: Combustion

- There are two combustion zones:
  - **Primary zone**, where most fuel is burnt.
  - **Dilution zone**, where burning continues and rest air dilutes and cools.



Flame stabilizing and general airflow pattern



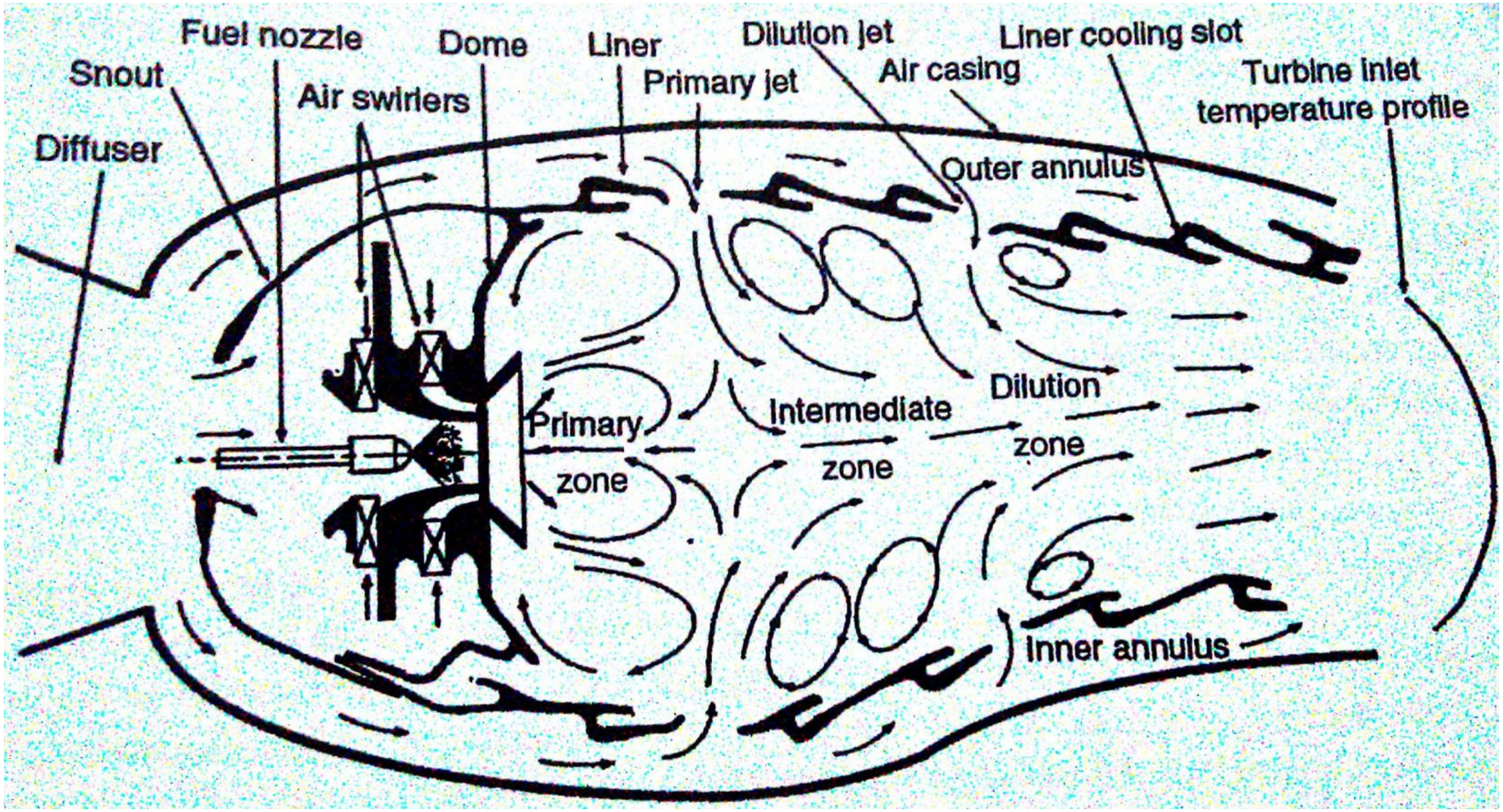
Apportioning the airflow

1. The Turbojet Engine

- **The Combustor: Combustion**
  - In **dilution zone**, most of the fuel is already burnt.
  - The main function in this zone is dilution by secondary flow to reduce temperature. The rest of fuel continues to burn in this region.
  - In **primary zone**, temperature can reach > 2000K. To protect the flame tube, cooling is necessary.
  - Position and dimension of holes depend on temperature field on the flame tube walls and at the combustor exit.

1. The Turbojet Engine

➢ The Combustor: Combustion



Representative flow pattern in an annular combustor with double air swirler.

1. The Turbojet Engine

➢ The Combustor: Combustion Efficiency Considerations

- ➢ Air coefficient, α
  - ➢ α at design condition, highest efficiency
  - ➢ **$\boldsymbol{\alpha}$** ↓□ : air not sufficient, flame becomes longer, primary zone longer, burning not complete, even flame-out by rich fuel.
  - ➢ **$\boldsymbol{\alpha}$**□ ↑ : pump pressure lower, vaporization worse, bigger fuel droplets, primary zone longer, even flame-out by weak fuel.
- ➢ Inlet pressure, p_3
  - ➢ If p_3 ↑, air density ↑, which improves mixture and flame propagation speed.
  - ➢ So, combustion efficiency increases when p_3 ↑, but when it attains a certain value, there will be no significant influence on the efficiency.

1. The Turbojet Engine

- **The Combustor: Combustion Efficiency Considerations**
  - Inlet temperature, T_3
    - If $T_3 \uparrow$, it accelerates exchange of energy and mass between air and fuel drops.
    - But, when T_3 reaches a certain value, no more significant influence exists.
  - Inlet velocity, v_3
    - If $v_3 \uparrow$, stay-time of fuel in combustion chamber is shorter; so, the combustion efficiency decreases.

1. The Turbojet Engine

- **The Combustor: Combustion Efficiency Considerations**
  - In summary of above points, we introduces a dimensionless parameter , θ.

$$\theta = \frac{p_2^{1.75} e^{T_2 / 300}}{q_m}$$

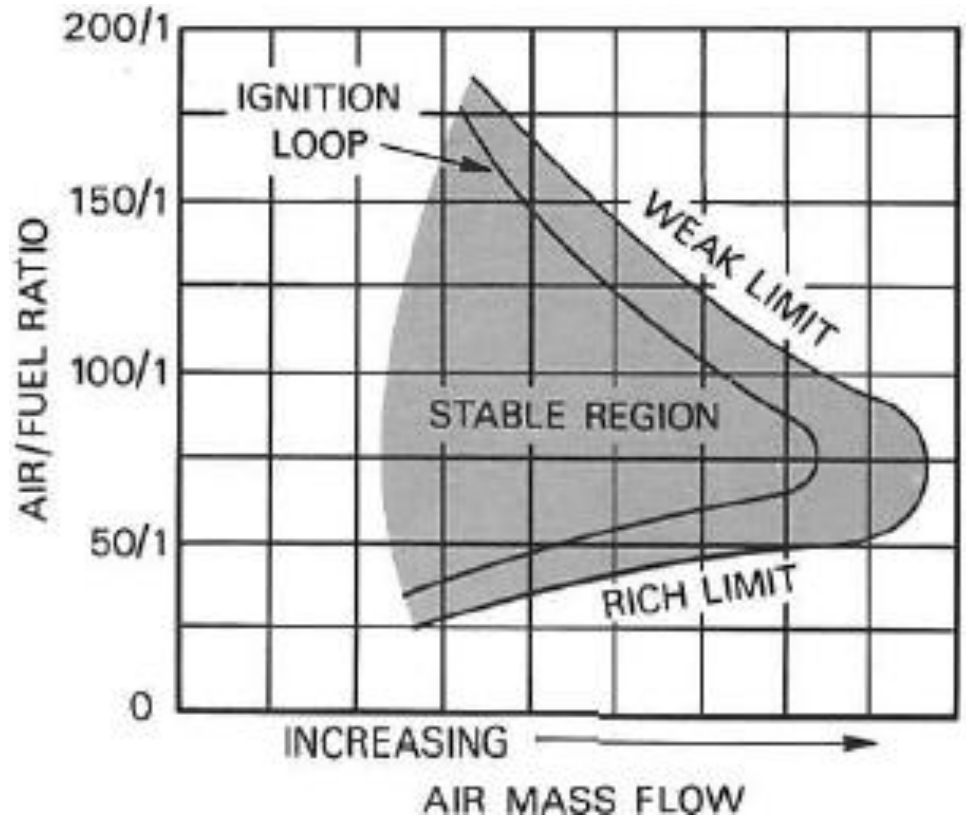
to obtain a generic characteristics function for a given combustion chamber:

$$\eta_b = f(\theta)$$

1. The Turbojet Engine

- **The Combustor: Combustion Stability Considerations**
  - Air coefficient, α, when too large or too small may cause flame-out. The first condition is called a **weak fuel flame-out**, while the second one is called a **rich fuel flame-out**.

Combustion stability limits.



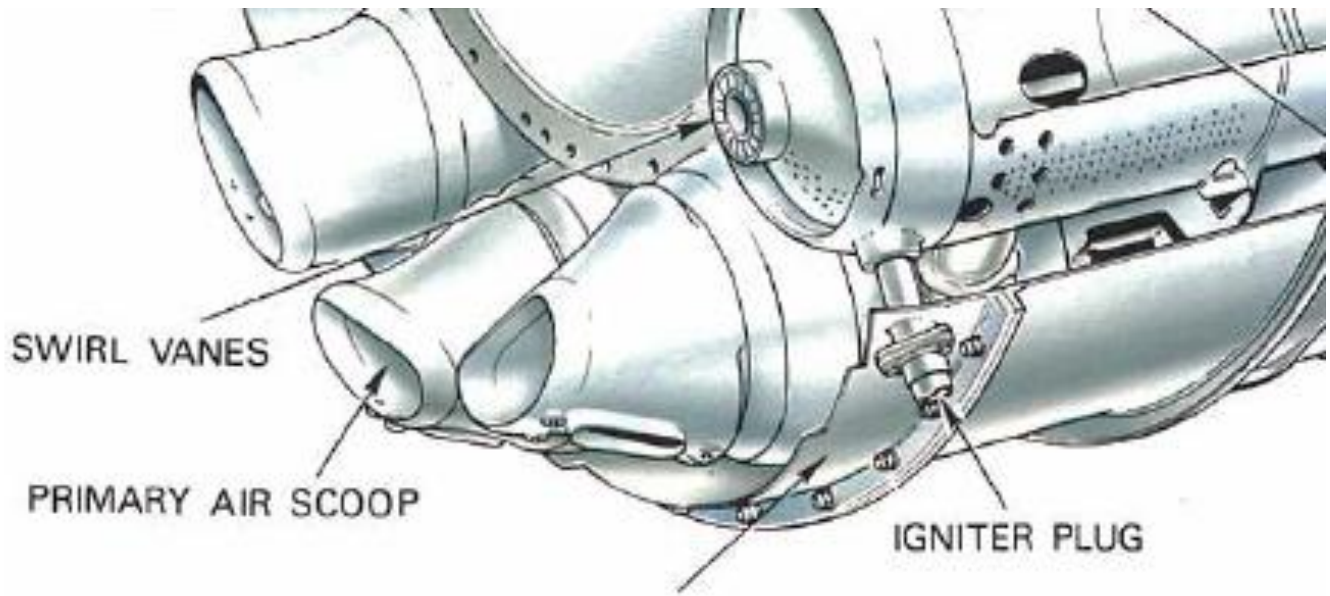
1. The Turbojet Engine

- **The Combustor: Combustion Stability Considerations**
  - When v_3 is too big, flame can not be held since at high v_2 , stable zone is close to optimal point, i.e. $\alpha = 1$ only in primary zone.
  - Normally, for a combustion chamber, when **$\boldsymbol{\alpha}$ = 2.5~3.5, $\boldsymbol{\alpha}$ = 1 in primary zone**.
  - When v_3 is too low, it is also difficult to hold the flame since at small fuel flow rates fuel vaporization is also poor.

  - Relation between air-coefficient and stoichiometry?

1. The Turbojet Engine

- **The Combustor: Total Pressure Loss Considerations**
  - Causes:
    - Air flowing through the air scoop.
    - Air passing through holes and gaps (friction).
    - Vortexes and mixing of hot and cold air.



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➢ The Combustor: Total Pressure Loss Considerations

- The primary causes of total pressure loss in the combustor are the wall friction, turbulent mixing and chemical reaction at finite Mach number.

$$\sigma_b = \frac{p_{t4}}{p_{t3}}$$

- The approximate expression for σ_b in terms of the average Mach number of the gas in the burner is given as,

$$\sigma_b = 1 - \varepsilon \frac{\gamma}{2} M_b^2 \qquad 1 \prec \varepsilon \prec 2$$

- The equation points out the merits of slow combustion in a conventional burner.

1. The Turbojet Engine

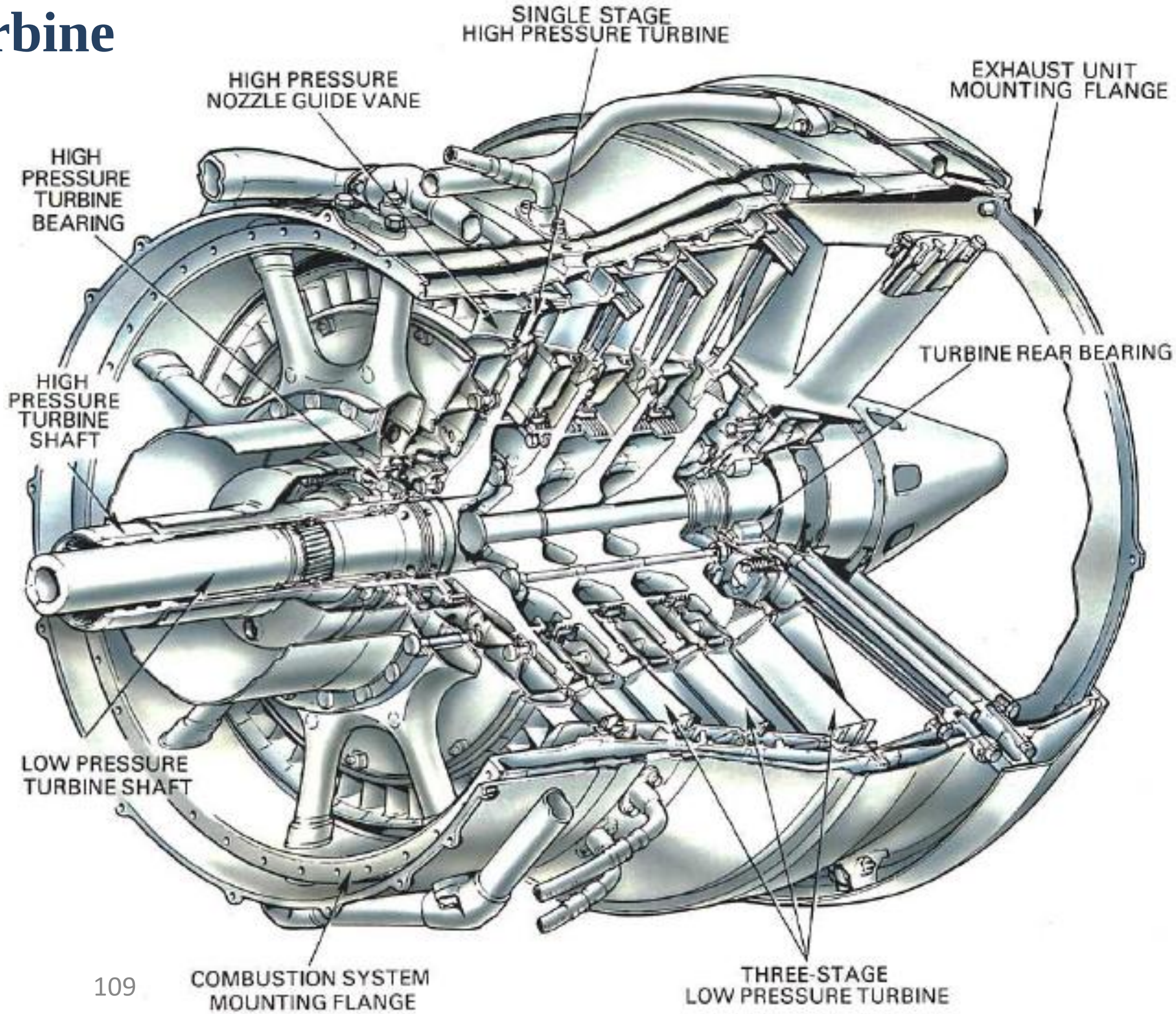
➢ The Combustor

- For the purpose of cycle analysis, a combustor flow is analyzed only at its inlet and outlet. Thus, the details of combustion processes such a vaporization, atomization, mixing, chemical reaction, and dilution are not considered in the cycle analysis phase.
- Energy balance equation about the combustor is given as,

$$\dot{m}_0 h_{t3} + \dot{m}_f Q_R n_b = \left(\dot{m}_a + \dot{m}_f\right) h_{t4} = \dot{m}_0 \left(1 + f\right) h_{t4}$$

1. The Turbojet Engine

➢ The Turbine



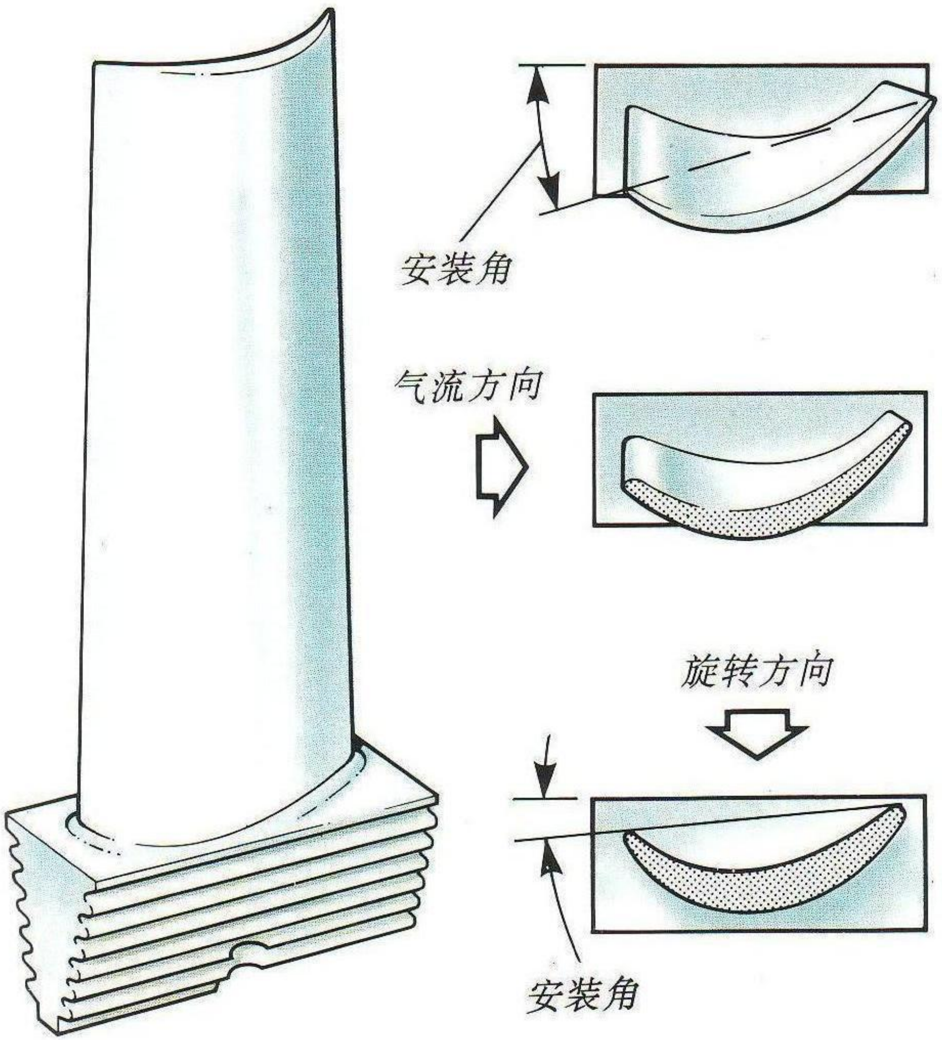
1. The Turbojet Engine

- **The Turbine**
  - Turbine powers compressor and accessories in turbo-engine.
  - Both turbine and compressor are turbomachine. They are similar in fundamental theory. However, in functionalities, they are different.
  - Compressor changes mechanical energy to pressure potential energy and kinetic energy. Therefore, turbine changes gas enthalpy to mechanical work.
  - One blade can generates 10T of centrifugal force.
  - They work under high temperature conditions, ~1700 K.
  - Made from nickel based alloys.
  - Attachment- Fir tree fixing.

1. The Turbojet Engine

- **The Turbine**

Fir-Tree Fixing.



1. The Turbojet Engine

- **The Turbine**
  - Fundamental equations

Energy Equation $$W_{out} = h_4 - h_5 + \frac{v_4^2 - v_5^2}{2} = h_{t4} - h_{t5}$$

Assumptions:

- Fixed coordinate system.
- Neglecting heat exchange.

1. The Turbojet Engine

- **The Turbine**
  - Fundamental equations

Bernoulli's equation

$$W_{out} = \int_4^5 \frac{dp}{\rho} + \frac{v_5^2 - v_4^2}{2} + W_f$$

Assumption:

- Fixed coordinate system

W_f : flow losses (work amount deducted from the net work output of the turbine).

Polytropic expansion work

$$\int_4^5 \frac{dp}{\rho} = \frac{n}{n-1} R(T_5 - T_4)$$

1. The Turbojet Engine

- **The Turbine**
  - Fundamental equations

For actual turbine

$$W_{nT} = -\int_4^5 \frac{dp}{\rho} = \frac{n}{n-1} R' T_4 \left(1 - \frac{1}{\left(\frac{p_4}{p_5} \right)^{\frac{n-1}{n}}} \right)$$

For isentropic turbine

$$W_{iT} = \frac{\gamma'}{\gamma' - 1} R' T_4 \left(1 - \frac{1}{\left(\frac{p_4}{p_5} \right)^{\frac{\gamma' - 1}{\gamma'}}} \right)$$

1. The Turbojet Engine

- **The Turbine**
  - Fundamental equations

For actual turbine

$$W_{nT} + \frac{v_4^2 - v_5^2}{2} = W_{out} + W_f$$

Thus, the expansion of hot gages in the turbine and change in kinetic energy generate mechanical work and overcome flow losses.

For isentropic turbine

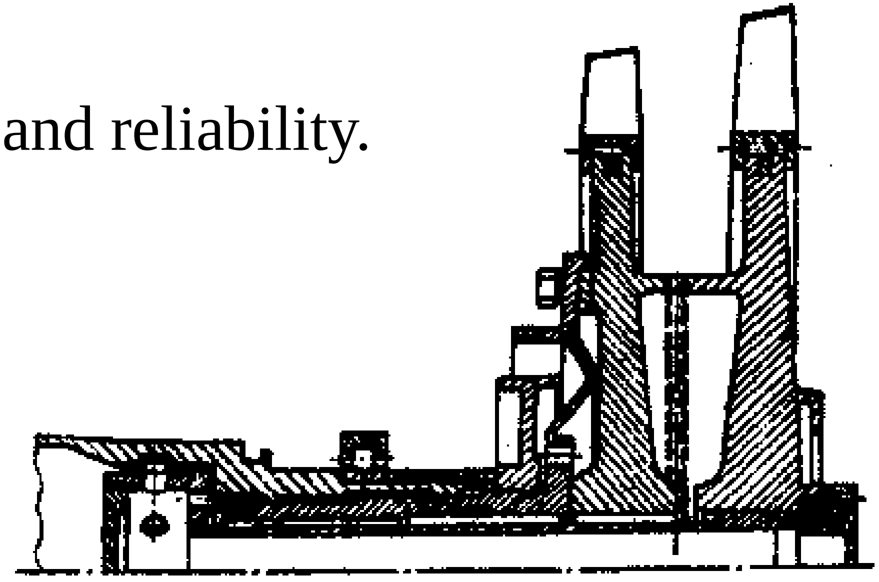
$$W_{iT} + \frac{v_4^2 - v_5^2}{2} = W_{out}$$

1. The Turbojet Engine

➢ The Turbine

➢ Rotor

- ➢ Construction consists of blades, disks and shaft(s).
- ➢ High rotational speed.
- ➢ High temperature operation.
- ➢ Corrosion resistance.
- ➢ High strength, stiffness and reliability.

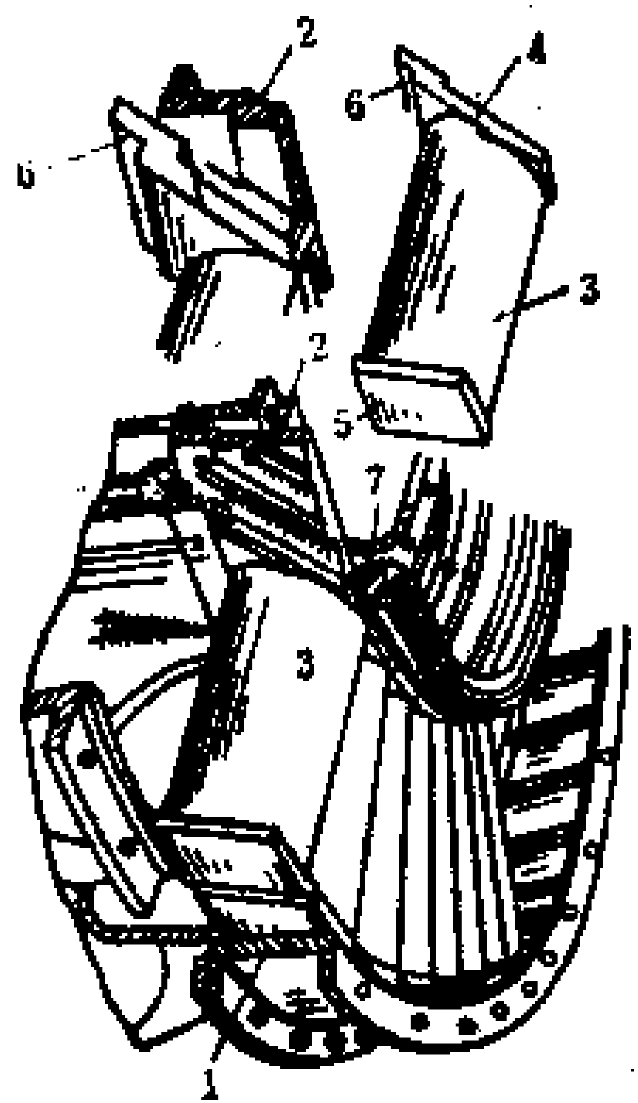


1. The Turbojet Engine

➢ The Turbine

➢ Stator

- Consists of guide vanes and casings.
- Sometimes, bolts pass through some vanes radially to connect the internal and external casings so that the forces on the bearings are transferred to outside.

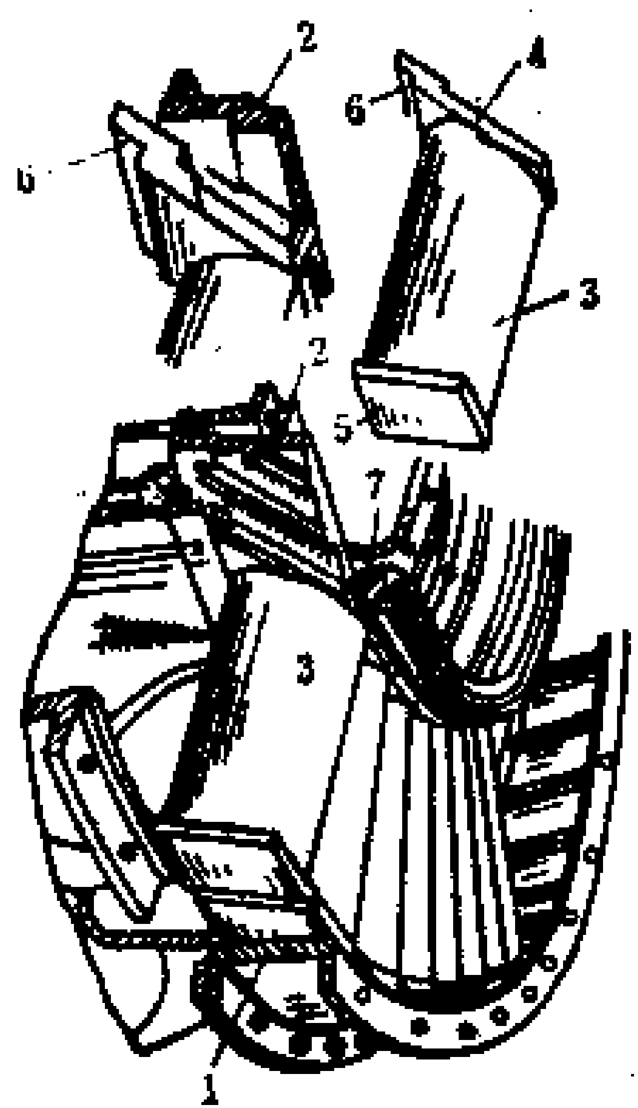


1. The Turbojet Engine

➢ The Turbine

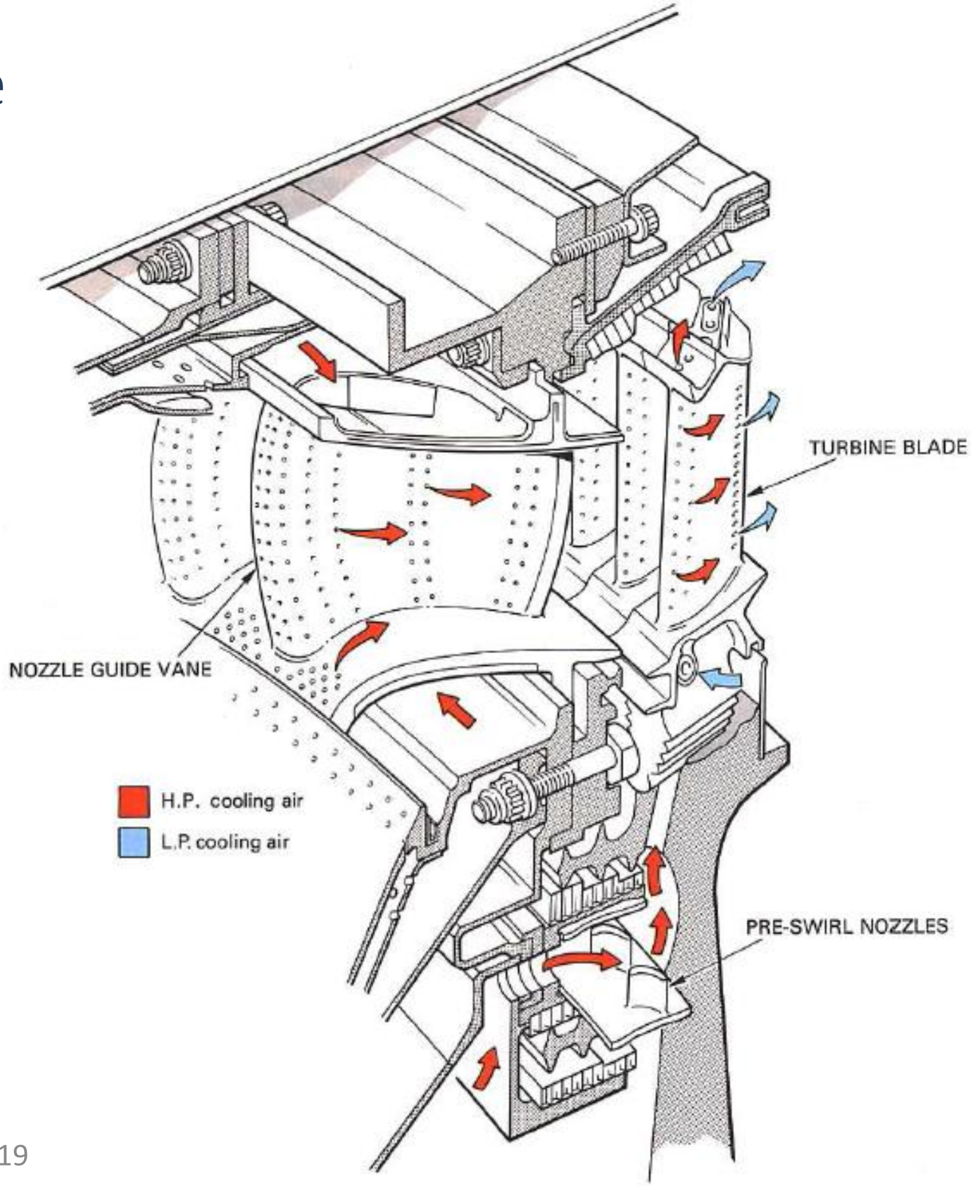
➢ Stator

- ➢ Area of the outlet of the first stage vane has a great influence on engine's performance and A_{throat} , i.e. the area of the throat of the engine controlling mass flow.
- ➢ It can be adjusted with vane's installation angle.



1. The Turbojet Engine

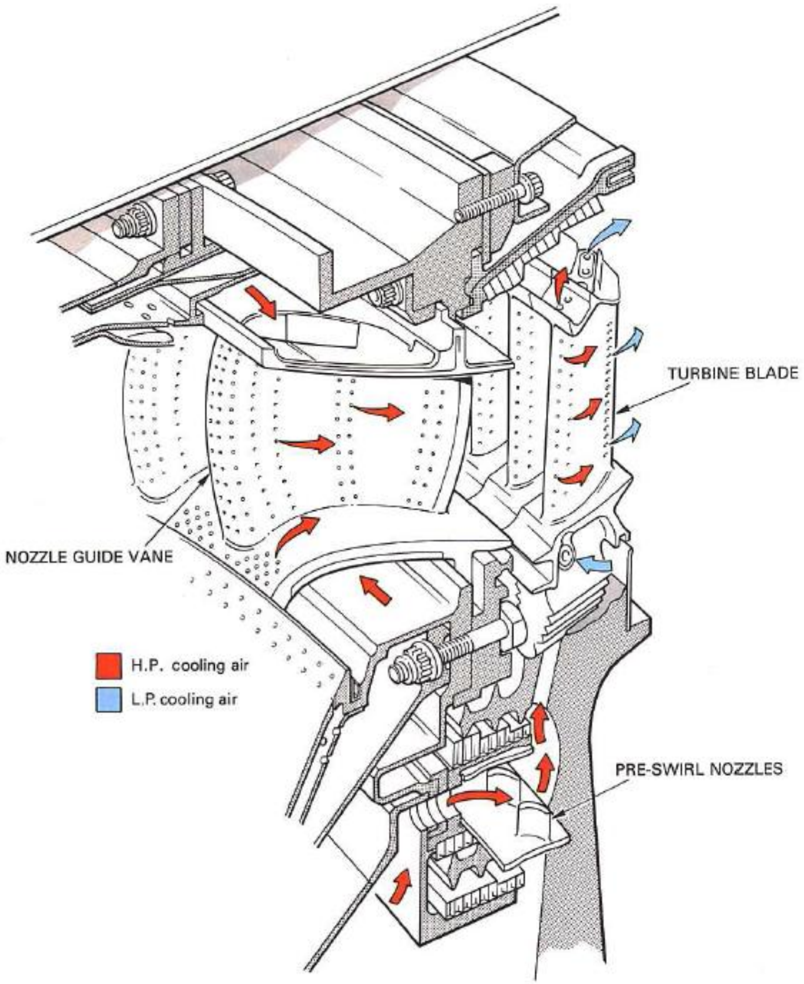
- **The Turbine**
  - **Cooling**



1. The Turbojet Engine

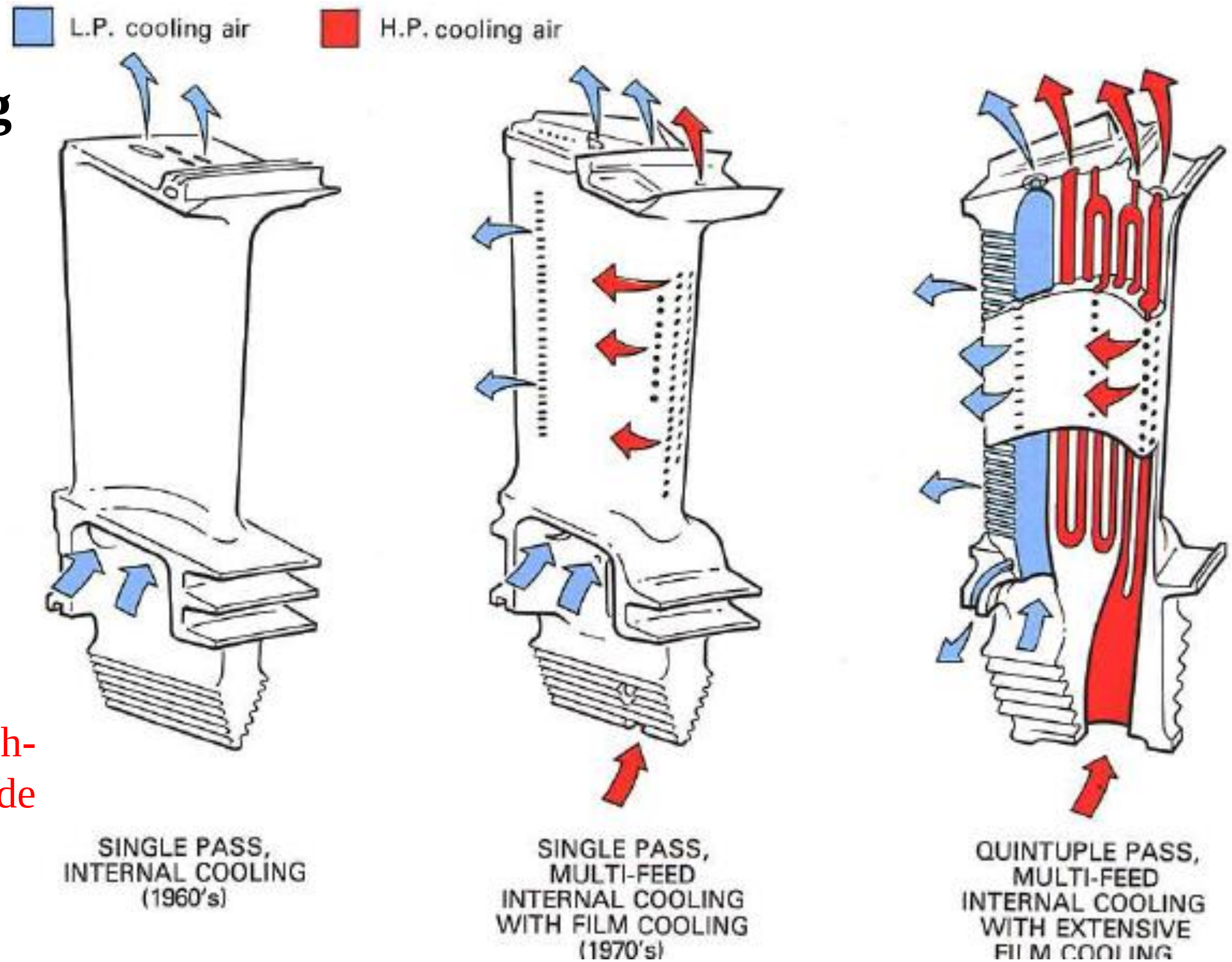
- **The Turbine**

- **Cooling**
  - Higher T_{t4} is better for performance.
  - It is limited by the turbine blade material thermal stress capability.



1. The Turbojet Engine

- **The Turbine**
  - **Cooling**

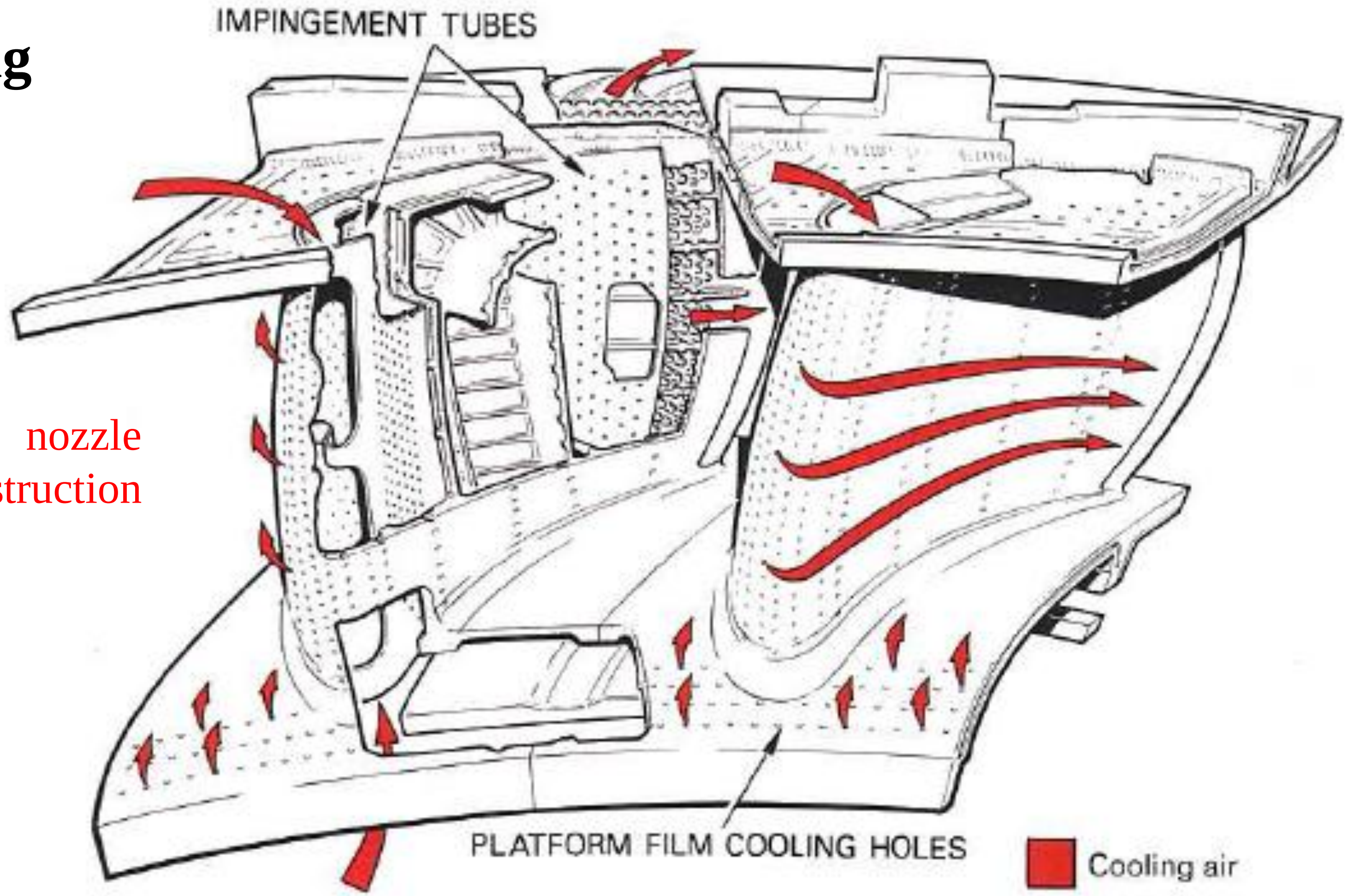


Development of high-pressure turbine blade cooling.

1. The Turbojet Engine

➢ The Turbine

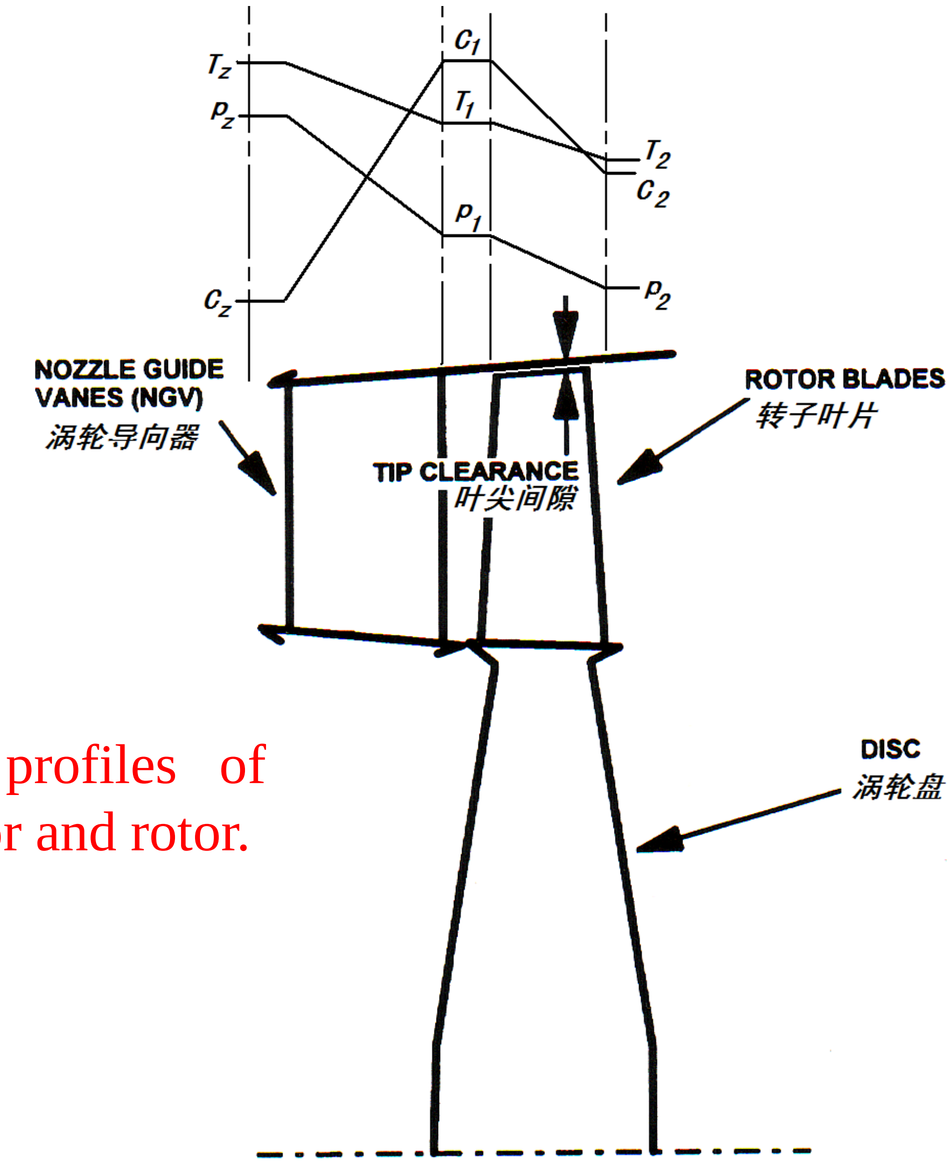
➢Cooling



High-pressure nozzle guide vane construction and cooling.

1. The Turbojet Engine

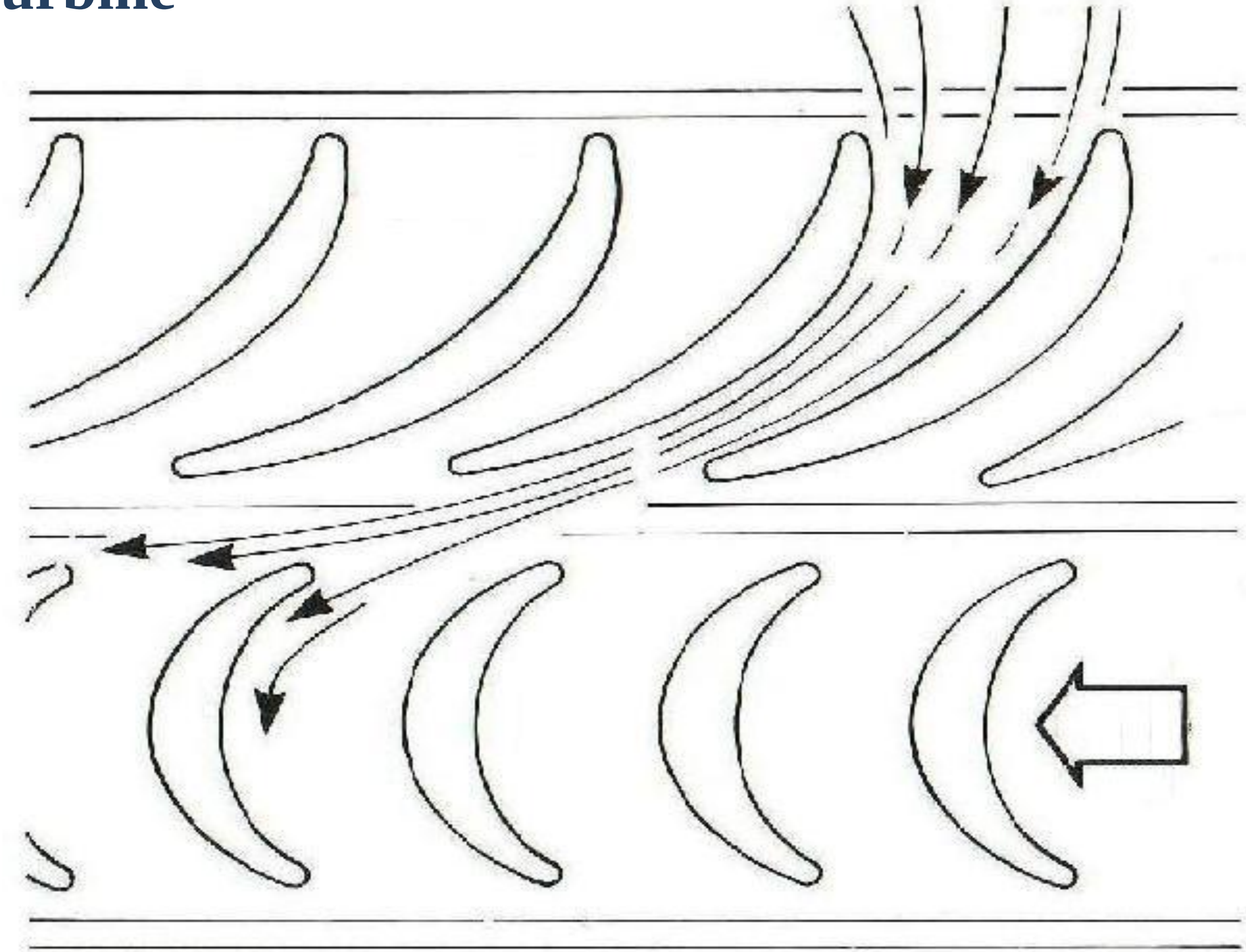
➢ The Turbine



Turbine construction and profiles of flow properties over the stator and rotor.

1. The Turbojet Engine

➢ The Turbine



Flow pattern in turbines.

1. The Turbojet Engine

➢ The Nozzle

1. The Turbojet Engine

➢ The Nozzle

- The ratio of actual kinetic energy at the nozzle to the ideal kinetic energy that emerges from an isentropic expansion in the nozzle is defined as the **nozzle adiabatic (or isentropic) efficiency**.

$$n_n = \frac{h_{t7} - h_9}{h_{t7} - h_{9s}} = \frac{\frac{V_9^{\,2}}{2}}{\frac{V_{9s}^{\,2}}{2}} = \frac{\frac{V_9^{\,2}}{2}}{\left[\frac{V_9^{\,2}}{2}\right]_{ideal}}$$

- Actual exhaust gases has a higher temperature than the exhaust gases emerging from an isentropic nozzle.

1. The Turbojet Engine

➢ The Nozzle

- Nozzle total pressure recovery:

$$\pi_n = \frac{p_{t9}}{p_{t7}}$$

- Nozzle Pressure Ratio (NPR):

$$NPR = \frac{p_{t7}}{p_0}$$

- Critical nozzle pressure ratio (minimum NPR that chokes the flow):

$$p_{t8} = p_8 \left\{1 + \frac{\gamma - 1}{2} M_8{}^2 \right\}^{\frac{\gamma}{\gamma-1}} = p_0 \left\{\frac{\gamma + 1}{2}\right\}^{\frac{\gamma}{\gamma-1}}$$

1. The Turbojet Engine

➢ The Nozzle

- Thus the two important figures of merit for an adiabatic nozzle are π_n & n_n .
- They are interrelated by the following expression:

$$n_n = \frac{\left\{NPR\left(\dfrac{p_0}{p_9}\right)\right\}^{\frac{\gamma}{\gamma-1}} - \pi_n^{-\frac{\gamma}{\gamma-1}}}{\left\{NPR\left(\dfrac{p_0}{p_9}\right)\right\}^{\frac{\gamma}{\gamma-1}} - 1}$$

or,

$$n_n = \frac{\{NPR\}^{\frac{\gamma}{\gamma-1}} - \pi_n^{-\frac{\gamma}{\gamma-1}}}{\{NPR\}^{\frac{\gamma}{\gamma-1}} - 1}$$

For

$(p_0 = p_9)$