9. Engine Component Operation:

Exhaust System

Classification

- Propelling Nozzles (exhaust nozzle, nozzle)
- Exhaust Diffusers

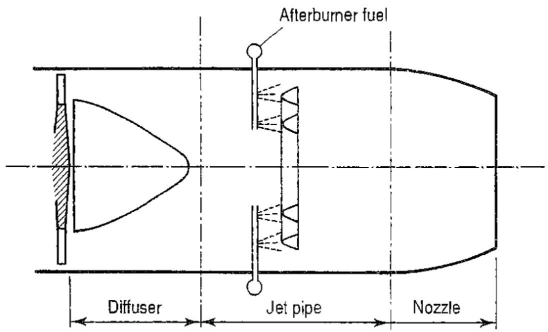
Propelling Nozzles

Purpose

The propelling nozzle serves as a back-pressure control for the engine and an acceleration device converting gas thermal energy into kinetic energy. A secondary function of the nozzle is providing required thrust reversing and/or thrust vectoring. The nozzle design can also reduce the infrared signature of the engine.

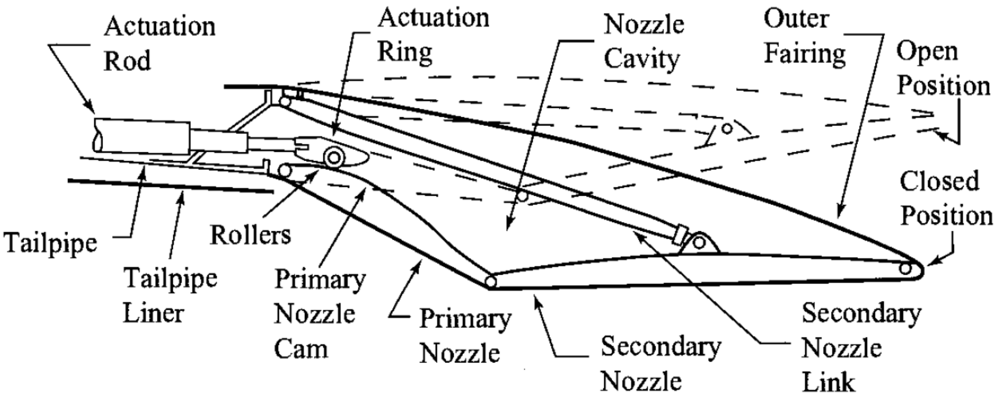
Nozzles can be:

- Convergent Exhaust (subsonic);
- Supersonic.

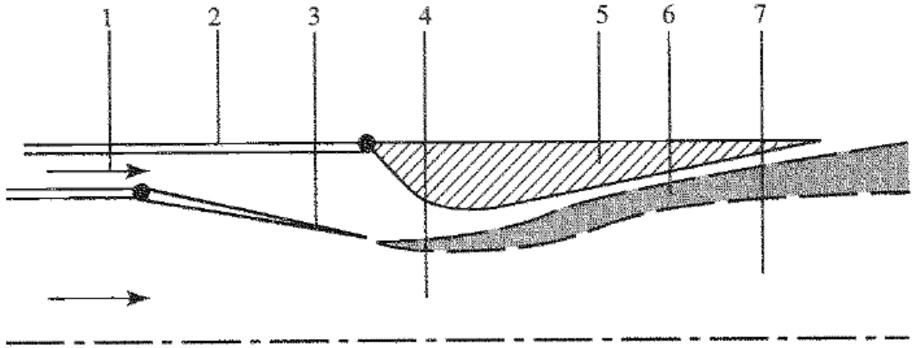


Supersonic Nozzles are divided on:

- Convergent-Divergent Nozzles;



- Ejector Nozzles;



(1) secondary flow;

(2) outer case engine;

(3) movable primary nozzle;

(4) primary flow;

(5) movable secondary nozzle;

(6) mixing layer between primary and secondary streams;

(7) supersonic primary flow.

Modern Exhaust Systems can provide the deflection of the output jet stream that creates forces and moments enabling complete directional control of the aircraft flight path without the implementation of the conventional aerodynamic flight controls.

Exhaust Diffusers serve to reduce the pressure at the turbine exit and thereby increase power of turboshaft engines.

Operational parameters

M_{f} - flight Mach number.

λ_9 - critical velocity ratio at the discharge station.

π_{n} - actual nozzle (or exhaust diffuser) pressure ratio.

π_{n} is the ratio of total pressure at the nozzle inlet to static pressure at the nozzle exit:

$$\pi_{\mathrm{n}}=\frac{p_7^*}{p_9}=\frac{1}{\pi\left(\lambda_{9s}\right)}.$$

$\pi_{n.c}$ - available nozzle (or exhaust diffuser) pressure ratio - pressure ratio referred to complete expansion.

$\pi_{n.c}$ is the ratio of total pressure at the inlet of the nozzle to ambient (static) pressure :

$$\pi_{n.c} = \frac{p_7^*}{p_0}.$$

At the convergent nozzle complete expansion to ambient pressure can be obtained at available pressure ratio equal or less then critical pressure ratio $\pi_{n.c} \le \pi_{cr}$,

where

$$\pi_{cr} = \left(\frac{k+1}{2}\right)^{\frac{k}{k-1}} = \frac{1}{\pi(\lambda=1)}.$$

If $k = k_{cg} = 1{,}33$, $\pi_{cr} = 1{,}85$.

Thus, convergent nozzle implements following operating modes:

- sub-critical: $\pi_{n.c} < \pi_{cr} \Rightarrow \pi_n = \pi_{n.c}$, $p_9 = p_0$ и $\lambda_9 < 1$;

- critical: $\pi_{n.c} = \pi_{cr} \Rightarrow \pi_n = \pi_{cr} = \pi_{n.c}$, $p_9 = p_0$ и $\lambda_9 = 1$;

- over-critical: $\pi_{n.c} > \pi_{cr} \Rightarrow \pi_n = \pi_{cr}$, $p_9 > p_0$ и $\lambda_9 = 1 \Rightarrow$ underexpansion.

For convergent-divergent nozzles relation between $\pi_{n.c}$ and π_n also defines operating mode.

If $\pi_n = \pi_{n.c}$, then $p_9 = p_0$ - complete expansion.

If $\pi_n < \pi_{n.c}$, then $p_9 > p_0$ - underexpansion.

If $\pi_n > \pi_{n.c}$, then $p_9 < p_0$ - overexpansion.

Efficiency parameters

φ_n - velocity coefficient.

φ_n is the ratio of the actual exit velocity c_9 to the ideal exit velocity c_{9s} corresponding to complete isentropic expansion $p_9 = p_0$

$$\varphi_n = \frac{c_9}{c_{9s}}$$

Velocity coefficient represents the effect of frictional loss in the boundary layer of the nozzle.

$\varphi_n = 0{,}97 \ldots 0{,}995$ - for turbojet and turbofan engines;

$\varphi_n = 0{,}90 \ldots 0{,}97$ - for turboprop and turboshaft engines.

σ_n - nozzle (or exhaust diffuser) total pressure loss factor.

Nozzle total pressure loss factor is equal to the ratio of the total pressure at the discharge to the total pressure at the inlet of the nozzle:

$$\sigma_n = \frac{p_9^*}{p_7^*} .$$

Total pressure loss factor is commonly used as efficiency parameter for exhaust diffuser of turboshaft engines:

$$\sigma_d = 0{,}98 \dots 0{,}99 .$$

Total pressure loss factor and velocity coefficient are interrelated.

r_{n} - gross thrust coefficient.

The gross thrust coefficient r_{n} is defined as the ratio of the actual gross thrust P_{n} to the ideal gross thrust $P_{\mathrm{n}s}$ at equal mass flow rate:

$$r_{\mathrm{n}} = \frac{P_{\mathrm{n}}}{P_{\mathrm{n}s}} .$$

Ideal gross thrust $P_{\mathrm{n}s}$ is a dynamic momentum at the nozzle exit corresponding to complete isentropic expansion ($\varphi_{\mathrm{n}} = 1$, $p_9 = p_0$):

$$P_{\mathrm{n}s} = G_9 \cdot c_{9s} .$$

Actual gross thrust P_{n} is a sum of actual dynamic momentum and static component of engine thrust:

$$P_{\mathrm{n}} = G_9 \cdot c_9 + F_9 \left(p_9 - p_0 \right) .$$

μ_n - throughput capacity factor.

μ_n is the ratio of actual mass flow rate of the working fluid through the nozzle throat to the ideal mass flow rate under the same conditions:

$$\mu_n = \frac{G_8}{G_{8.ideal}} .$$

A_n - throughput capacity.

A_n allows to estimate amount of mass flow rate passing through the nozzle under specified conditions at the inlet

$$A_n = \frac{G_7 \cdot \sqrt{R \cdot T_7^*}}{p_7^*} .$$

$\mu_n q(\lambda_8) F_8$ - throughput capacity.

$$\mu_n q(\lambda_8) F_8 = \frac{G_7 \cdot \sqrt{T_7^*}}{m \cdot p_7^*}.$$

$$\mu_n q(\lambda_8) F_8 \sim A_n.$$

a_n - relative throughput capacity.

$$a_n = \mu_n q(\lambda_8) = \frac{G_7 \cdot \sqrt{T_7^*}}{m \cdot p_7^* \cdot F_8}.$$

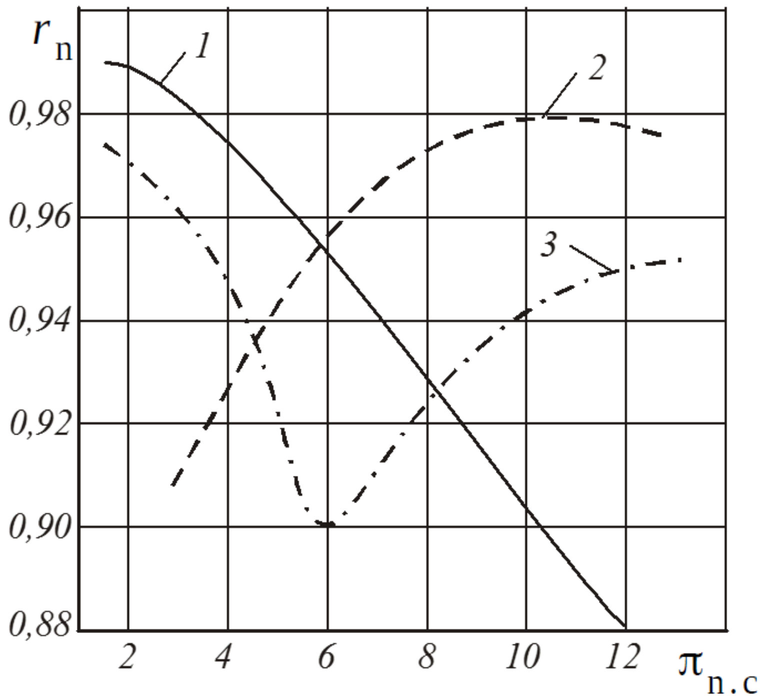
Nozzle thrust map

The variations of the gross thrust coefficient with nozzle pressure ratio are represented for different types of propelling nozzle.

(1) - Convergent Nozzle,

(2) - Convergent-Divergent Nozzle,

(3) - Ejector Nozzle.

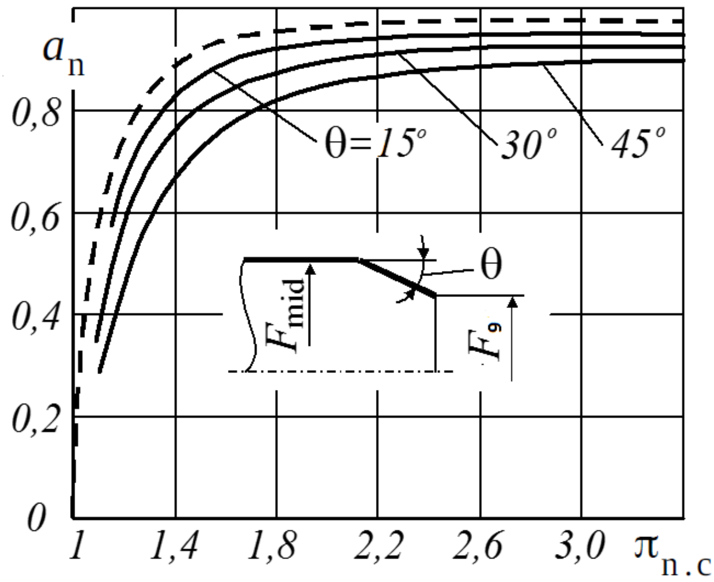


Nozzle discharge map

The variation of the relative throughput capacity a_{n} with nozzle pressure ratio $\pi_{n.c}$ is shown for a conic convergent nozzle.

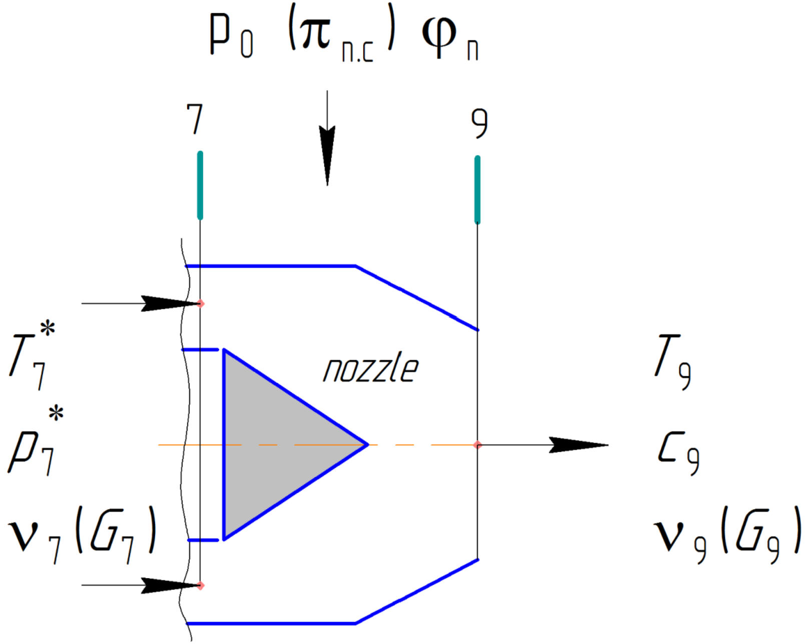
When the nozzle is choked, the discharge coefficient reaches a maximum value.

The value of a_{n} is also a function of the primary nozzle half-angle Θ.



Nozzle Performance Calculation

Calculation Scheme



In the simplified approach parameters are calculated assuming complete expansion.

Available nozzle pressure ratio

$$\pi_{n.c} = \frac{p_7^*}{p_0}.$$

Exit velocity:

$$c_9 = \varphi_n \sqrt{2 \cdot c_{p.cg} \cdot T_7^* \cdot \left(1 - \frac{1}{\pi_{n.c}^{\frac{k_{cg}-1}{k_{cg}}}}\right)}, \ \frac{m}{s}.$$

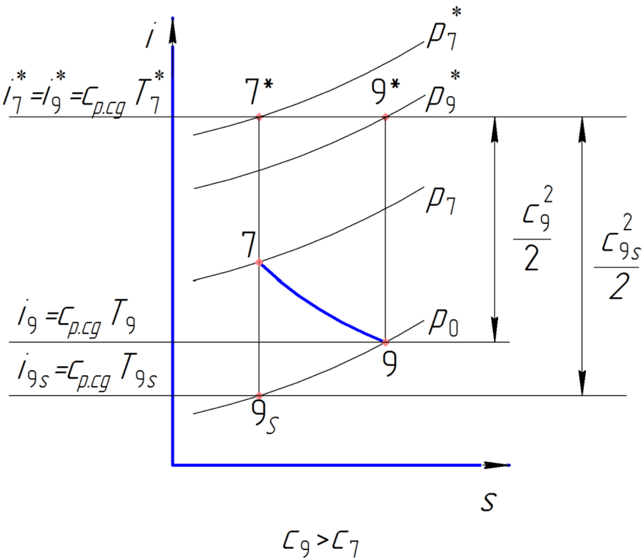
Static temperatureat discharge:

$$T_9 = T_7^* - \frac{c_9^2}{2 \cdot c_{p.cg}}, \ K.$$

Relative mass flow rate at discharge:

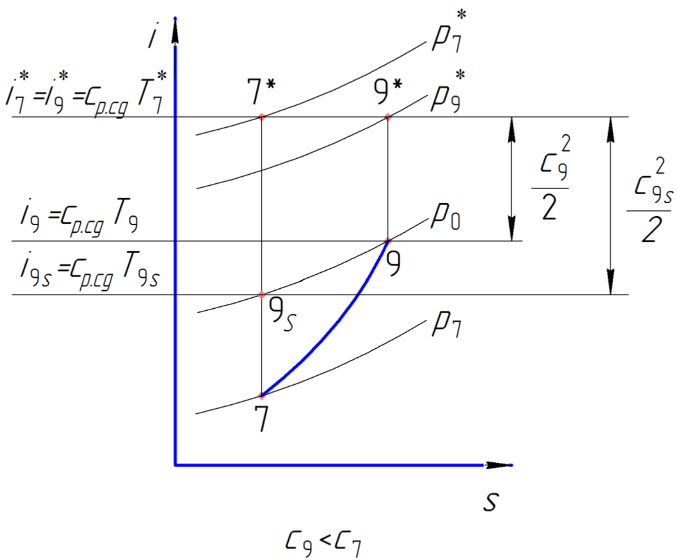
$$\nu_9 = \nu_7.$$

i-s diagram of thermodynamic processes at the exhaust system.



Nozzle

Expansion



Exhaust Diffuser

Compression