NOZZLES OF AIR-BREATHING TURBOJETS

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Contents

1. General Features of Flows in Nozzles

Exhaust units of propulsion systems equipped with turbojet engines are designed to convert the thermal and potential energy of gases to the kinetic energy of the propulsive jet, and their designs take account of the input flow configuration and the engine layout in the aircraft. The velocity of the propulsive mass in the exhaust unit increases owing to the pressure drop. Depending on the velocity in the exit cross section, the exhaust units are classified as subsonic and supersonic.

At the present time, the exhaust unit is a complex component of the propulsion system essentially different from simple nozzles of the first jet engines. Since the reactive thrust P generated by a turbojet engine is determined, in terms of its inherent parameters (when the exhaust gas expands freely downstream of the nozzle, $p_{\mathrm{E}} = p_{\mathrm{U}}$), as the difference between the momentum in the intake and exit cross sections, P is always smaller than the thrust generated by the exhaust unit, P_{E}. Moreover, every percentage point of a loss in the exhaust thrust causes a loss of several percents in the total thrust of the propulsion system.

At small pressure drops, tapered nozzles are used. At higher pressure differences, exhaust units are shaped as de-Laval nozzles (Fig. 1).

2. Basic Parameters of Nozzles

The nozzle efficiency is controlled by several parameters. Primarily, this is the ratio between the pressures $p*$, the total pressure at the nozzle intake, and p_{E}, the static pressure in the nozzle exit cross section:

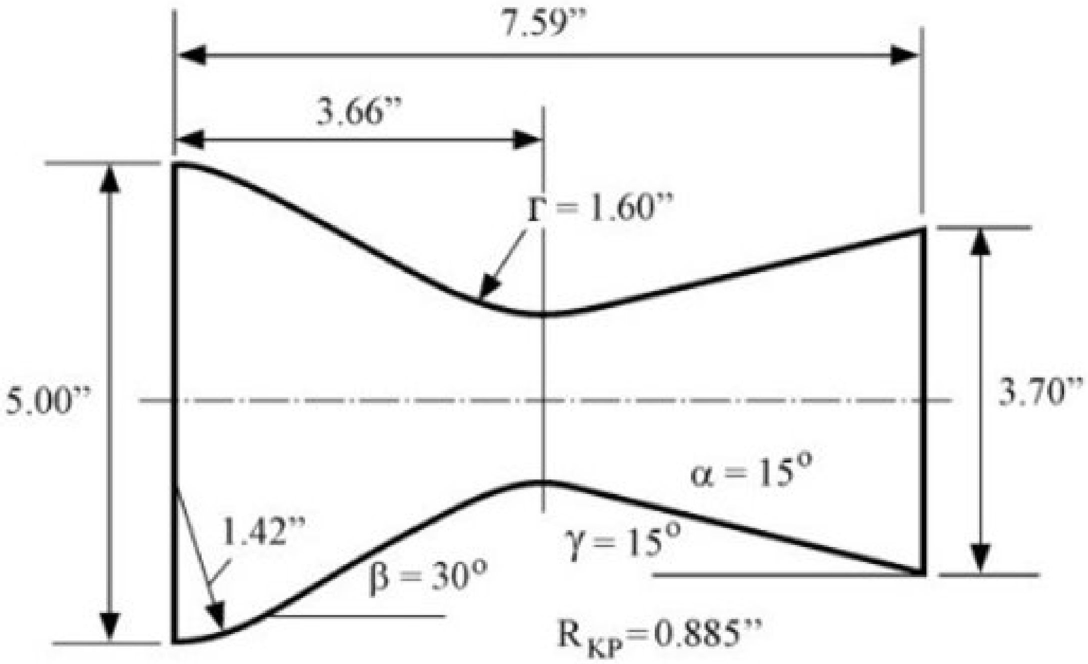

Figure 1. De Laval nozzle (from the book by Bartz)

$$\pi_{\mathrm{E}} = p_{\mathrm{E}} / p^{*}. \tag{2.1}$$

In the nominal regime of nozzle operation, the pressure in the nozzle exit section is assumed to be equal to the ambient pressure, $p_{\mathrm{E}} = p_{\mathrm{U}}$.

The thrust in this case is given by the equation

$$P = G_{\mathrm{air}}\left(w_{\mathrm{E}} - w_{\mathrm{fl}}\right) + G_{\mathrm{f}}\left(w_{\mathrm{E}}\right) + F_{\mathrm{E}}\left(p_{\mathrm{E}} - p_{\mathrm{U}}\right),$$

where G_{air} is the air consumption, G_{f} is the fuel consumption, w_{E} is the gas velocity in the exit section, w_{fl} is the flight velocity, and p_{E} is the static pressure in the exit section.

In this case, the thrust is maximal.

The design jet velocity in the exit section of a tapered nozzle is assumed to be the sound velocity, $\lambda_{\mathrm{des}} = 1$. In accordance with this assumption, $\pi_{\mathrm{E,des}} = 1.85$ (for $\kappa = 1.33$). In supersonic nozzles, the design jet velocity in the exit section is higher than the sound velocity, and in the ideal nozzle it is controlled by the ratio between the areas of the critical cross section and exit cross section:

$$q\left(\lambda_{\mathrm{E,des}}\right) = \frac{F_{\mathrm{cr}}}{F_{\mathrm{E}}} = f\left(\lambda_{\mathrm{E,des}};\kappa\right). \tag{2.2}$$

In such exhaust units $\pi_{\mathrm{E}} = 1.85$ and can be calculated by the equation

$$\pi_{\mathrm{E,des}} = \frac{1}{\pi\left(\lambda_{\mathrm{E,des}}\right)} \tag{2.3}$$

The value of π_{E} at which the jet velocity in the exit section equals the sound velocity is termed its design value.

In calculating the cross sections of an exhaust unit, one should have the consumption factor of the propulsive mass passing through the cross section, which is the ratio between the real propulsive mass flow G_{real} through the exhaust unit and the ideal flow G_{id}:

$$\mu = \frac{G_{\mathrm{real}}}{G_{\mathrm{id}}} \tag{2.4}$$

The ideal flow through the exhaust unit is calculated using the relation

$$G_{\mathrm{id}} = \frac{2}{\kappa+1}\left(\frac{\kappa}{R}\right)^{1/2} \frac{P^*_{\mathrm{n}}}{\sqrt{\mathrm{T}^*_{\mathrm{n}}}} F_{\mathrm{cr}} q(\lambda_{\mathrm{cr}}) \tag{2.5}$$

In the flow-through section of the subsonic nozzle, which is shaped as a cylindrical surface connected to a conical section, the parameter μ depends on the ratio between the cylinder cross section area and the minimal cross section, and the length (or the convergence angle) of the conical section. The feature of the $\mu - \pi_{\mathrm{E,des}}$ dependence is that a stable μ is obtained not at the critical pressure ratio $\pi_{\mathrm{E,cr}}$, but at a slightly higher value $\pi_{\mathrm{E,nom}} = \pi_{\mathrm{stab}}$.

This property is common for all convergent end-pieces, and the difference between these two values is the higher, the sharper the features in the region of the minimal cross section, especially in the presence of sharp edges.

The thrust-generating efficiency of exhaust units can be estimates in terms of the velocity factor φ_{E}, thrust factor $\overline{P}_{\mathrm{E}}$, and relative impulse $\overline{J}_{\mathrm{E}}$.

The velocity factor of the exhaust unit is the ratio of the real velocity in the exit section to a certain characteristic velocity:

$$\varphi_{\mathrm{E}} = w_{\mathrm{E,real}} / w_{\mathrm{char}} \tag{2.6}$$

The real velocity in the exit section of an exhaust unit, $w_{\mathrm{E,real}}$, can be determined by different methods: (a) it can be calculated by the ideal liquid model with subsequent corrections; (b) is can be calculated on the base of the measured velocity field; (c) derived from measurements of the thrust or pressure distribution over the walls. The exit velocities determined by different methods are different, and the most reliable data are derived from thrust measurements.

The incoming flow interacts with the jet of the propulsive mass flowing out of the exhaust unit, as a result, the thrust calculated on the basis of the jet parameters does not equal the propulsion force of the aircraft. In this case, the propulsion force is the effective thrust of the propulsion system. As was noted previously, the interaction between the propulsive mass jet and incoming flow can be taken into account by introducing the drag coefficient of the aft section of the propulsion system:

$$C_x = 2x_{\mathrm{aft}} / \left(\rho_{\mathrm{U}} w_{\mathrm{fl}}{}^2 F_{\mathrm{mid}}\right) \quad (2.7)$$

where the drag of the aft section, X_{aft}, includes the pressure drag, X_{pr}, and viscous drag, X_{vis}. Both these components should be determined with due account of the interaction between the propulsive mass jet and incoming flow. Given the coefficient of external drag, C_X, and the thrust derived from the jet parameters, one obtains the force of external drag X_{aft} and determine the effective thrust of the exhaust unit:

$$P_{\mathrm{E,eff}} = P_{\mathrm{E,real}} - X_{\mathrm{aft}} \quad (2.8)$$

Here $P_{\mathrm{E,nom}}$ is the exhaust unit thrust derived from inherent jet parameters.

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