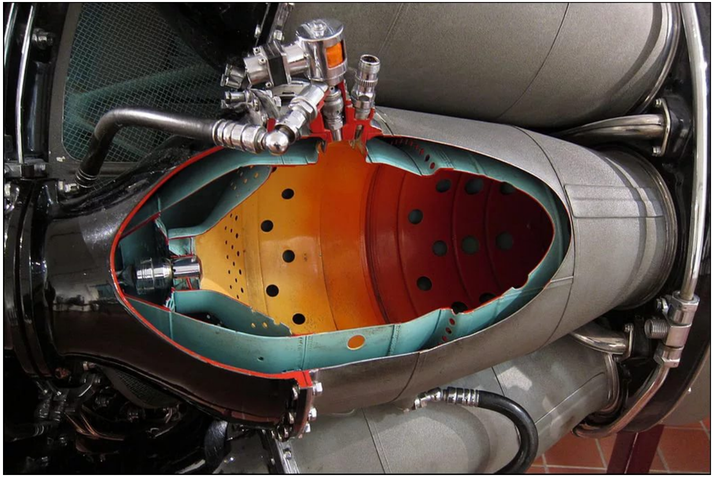
6. Engine Component Operation: Combustion System

Purpose

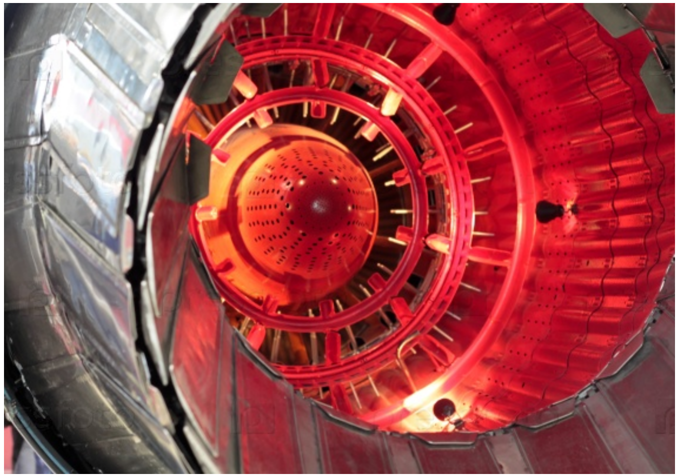
The purpose of the combustion system of aircraft gas turbine engines is to increase the thermal energy of a gas stream by combustion, which is an exothermic chemical reaction between the onboard hydrocarbon fuel and the oxygen in the air stream.

Classification

Combustor (Combustion Chamber, Main Burner)

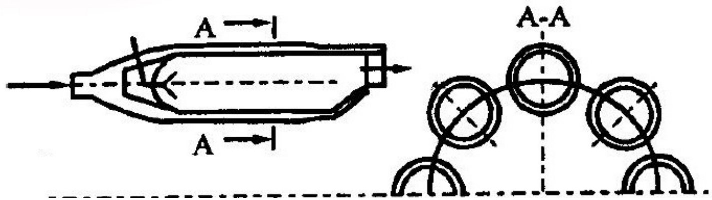


Afterburner (Reheater)



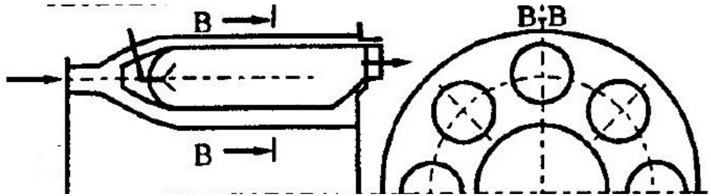
Main burner types

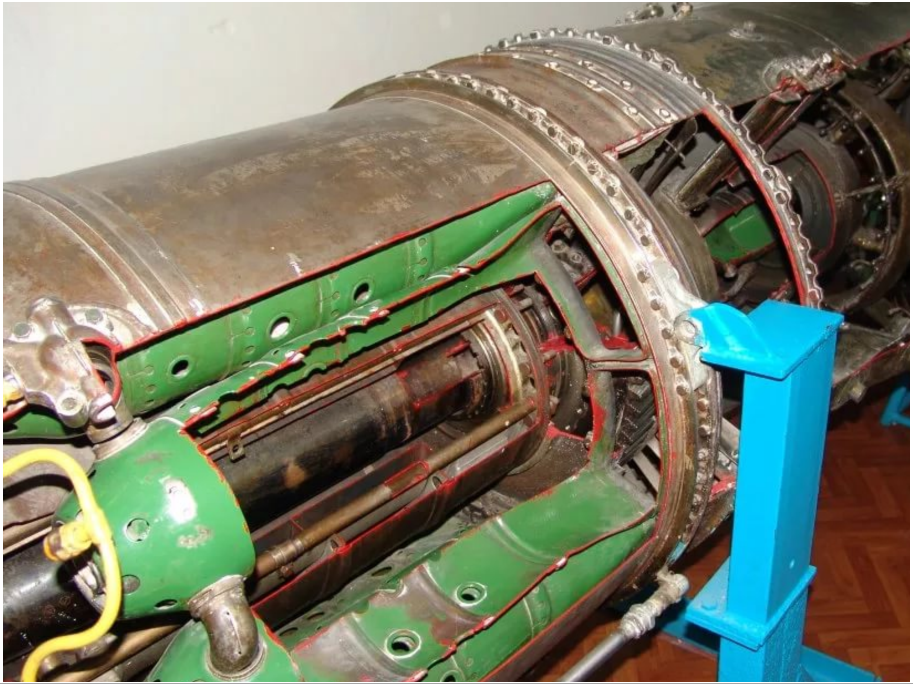
Can



RD-45F

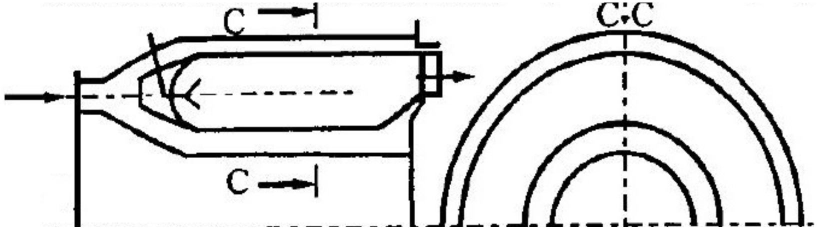
Cannular

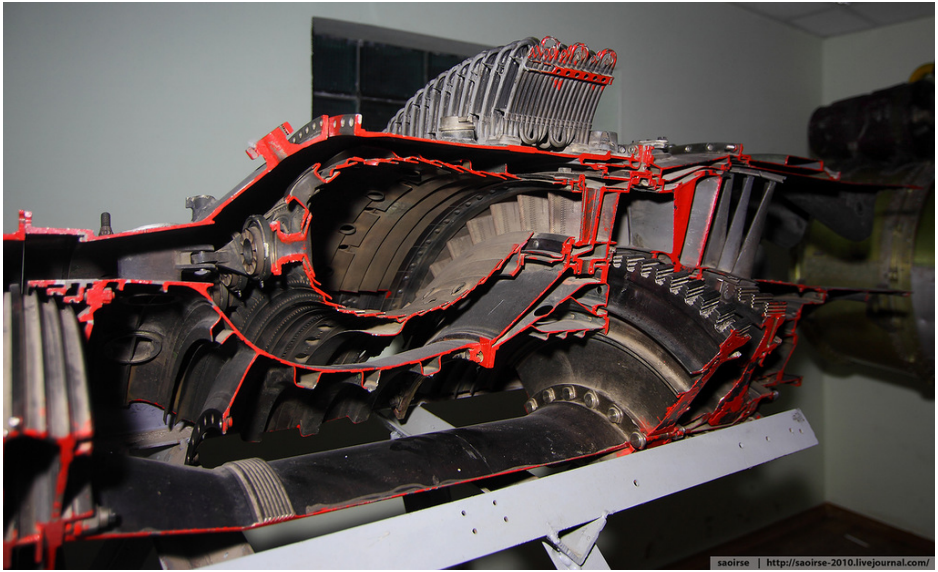




R11F2-300

Annular

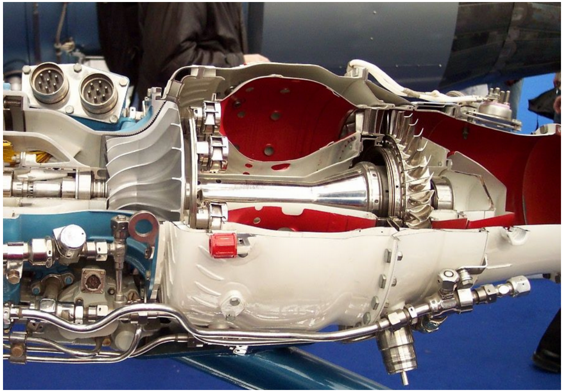




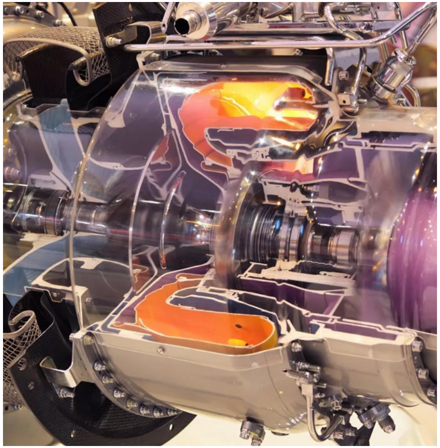
AL-31F

Combustion system configuration may also be classified according to airflow direction through the chamber.

Axial throughflow

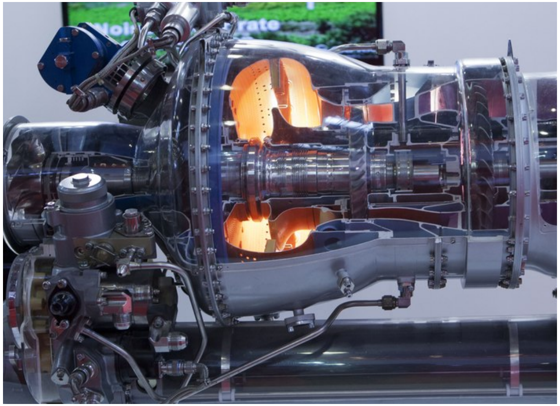


Reverse flow

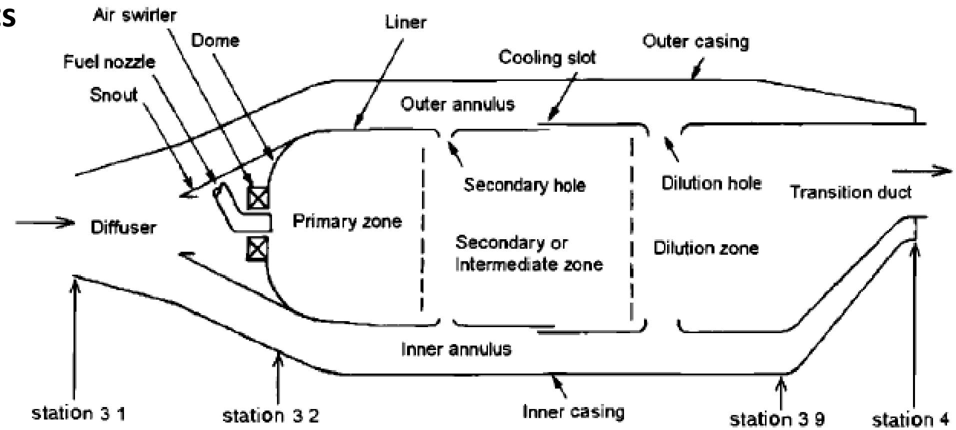


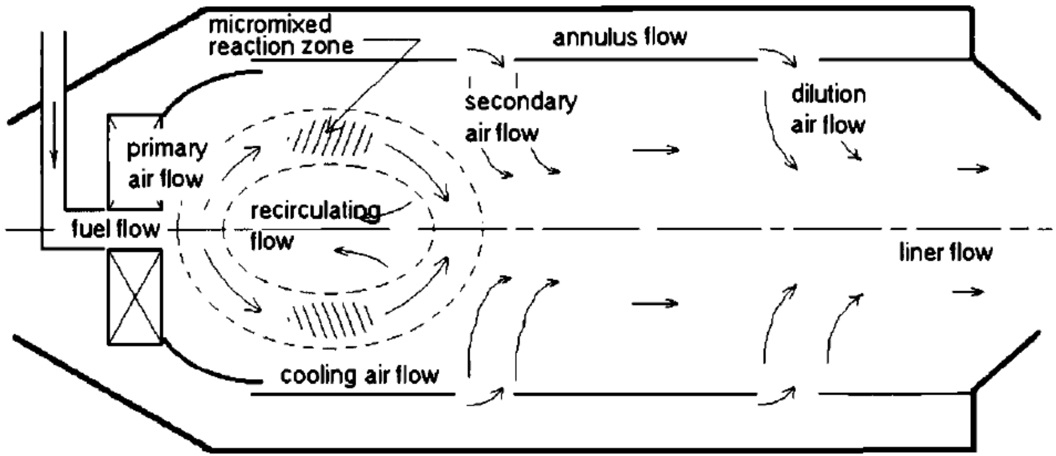
Radial inflow

(or radial outflow)

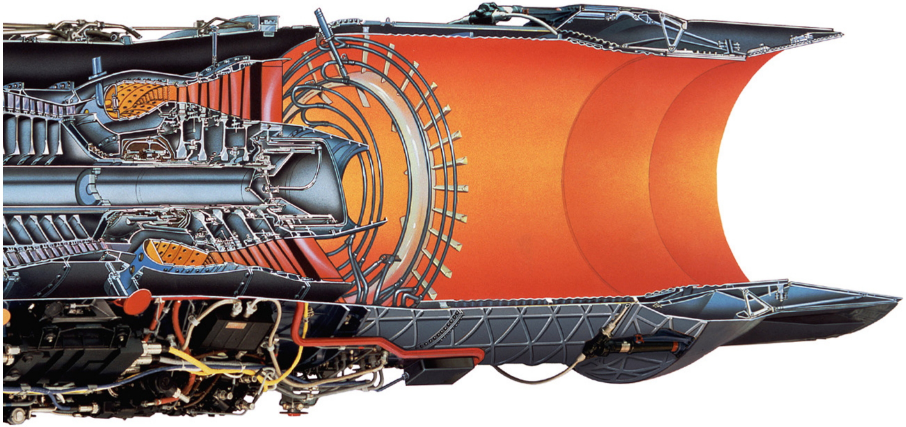


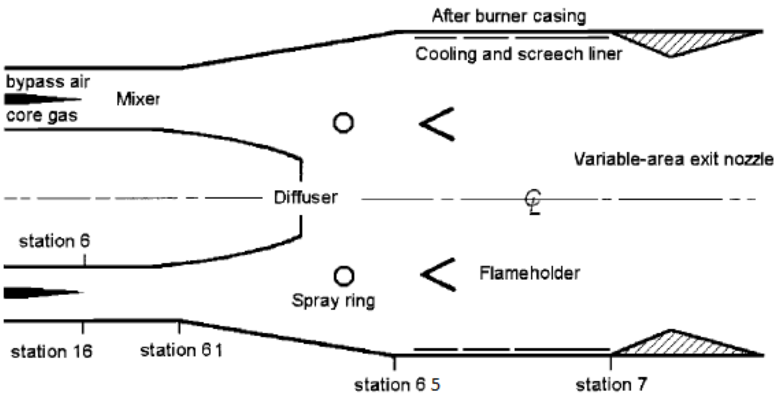
Combustor Components

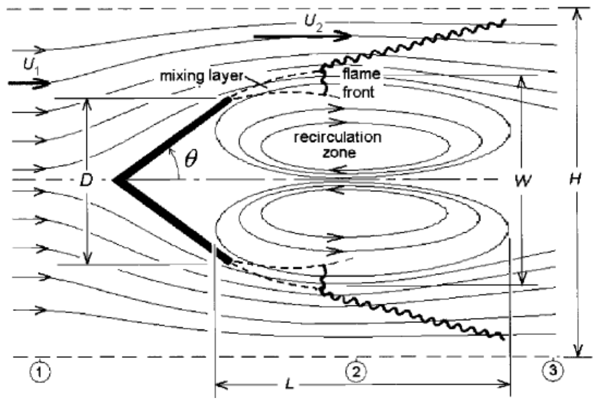




Afterburner







Fuel Properties

Hydrocarbon fuel is commonly used for gas turbine engine.

The fuel is characterized by:

Fuel

- **The Composition** of the fuel can be expressed by chemical formula $C_n H_m$;
- **Heat of Reaction** H_r - the amount of heat energy that is released in the calorimeter by the complete combustion of 1 kg of fuel with subsequent cooling of the combustion products to the initial temperature of fuel and air $T_0 = 293\,\mathrm{K}$;
- **Stochiometric Coefficient** L_0 - the amount of air that is theoretically required for complete combustion of 1 kg of fuel.

For correct comparison of results of thermodynamic calculations it is recommended to use properties of the **standard hydrocarbon fuel**:

- chemical formula: $C_{0,855}H_{0,145}$;
- heat of reaction: $H_r = 42\,915\,\frac{\text{kJ}}{\text{kg}}$;
- stochiometric coefficient: $L_0 = 14{,}78$.

Operational Parameters

α - air excess factor.

The air excess factor is the ratio of the air flow rate passed through the combustor to the air flow rate theoretically required for complete combustion of the fuel

$$\alpha = \frac{G_{31}}{G_f \cdot L_0}.$$

If $\alpha = 1$, the amount of air corresponds to the complete combustion of the fuel, and the air/fuel mixture is called «stochiometric».

If $\alpha < 1$, then mixture is called «rich» (by fuel) and part of the fuel remains unburned.

If $\alpha > 1$, then mixture is called «lean».

Combustion chamber of gas turbine engine operates with $\alpha > 1$.

q_f - relative fuel consumption.

The relative fuel consumption is the ratio of fuel consumption to the air flow rate passed through the combustion chamber

$$q_f = \frac{G_f}{G_{31}} = \frac{1}{\alpha \cdot L_0} .$$

T^*_{31}, p^*_{31} - total temperature and total pressure at the inlet of the combustor.

T^*_4 - combustor exit (total) temperature or turbine inlet (total) temperature.

If fuel composition, air composition and T^*_{31} are given, then T^*_4 defines the value of relative fuel consumption. This relation can be represented by a chart or a table.

Efficiency

σ_b - burner total pressure loss factor.

Combustion chamber total pressure loss factor is equal to the ratio of the total pressure at the discharge to the total pressure at the inlet of combustor:

$$\sigma_b = \frac{p_4^*}{p_{31}^*}\ .$$

η_b - combustion efficiency.

The combustion efficiency is the ratio of the released heat energy $\left(G_{31} \cdot Q_1\right)$ to the potential chemical energy of fuel $\left(G_f \cdot H_r\right)$:

$$\eta_b = \frac{G_{31} \cdot Q_1}{G_f \cdot H_r} = \frac{Q_1}{q_f \cdot H_r} = \frac{Q_1}{Q_0} .$$

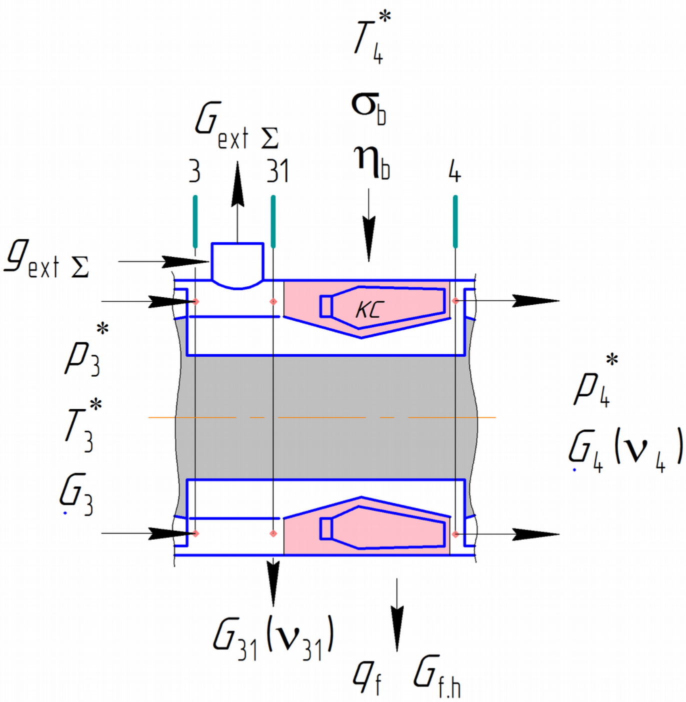
Both variables are expressed as a rate. It can also be described as the ratio of actual temperature rise to the theoretical temperature rise in jet engines.

Modern gas turbine engines are characterized by high combustion efficiency and small total pressure losses.

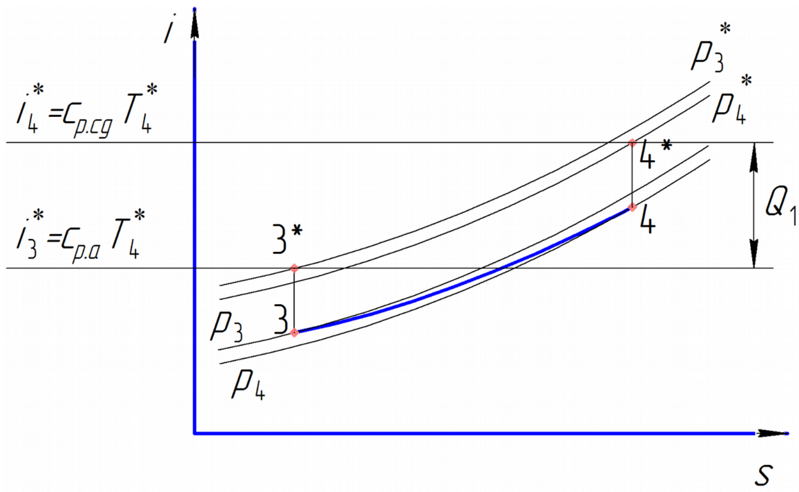
At basic operating modes the combustion efficiency is generally equal to $\eta_b = 0{,}99 \ldots 0{,}995$, and the total pressure loss factor is about $\sigma_b = 0{,}94 \ldots 0{,}96$.

Main Burner operating

Calculation Scheme



i-s diagram



Main Burner Performance Calculation

Relative fuel consumption:

- using chart or table as function of T_3^*, T_4^*;
- simplified formula:

$$q_f = \frac{c_{p.cg} \cdot T_4^* - c_{p.a} \cdot T_3^*}{H_r \cdot \eta_\mathrm{b}} .$$

Total pressure at the exit of the main burner:

$$p_4^* = p_3^* \cdot \sigma_\mathrm{b} , \ \mathrm{kPa} .$$

Relative mass flow rate at the station 31:

$$\nu_{31} = 1 - g_{\mathrm{ext}.\Sigma} = 1 - \sum_i g_{\mathrm{ext}.i} = 1 - \left(\sum_i g_{\mathrm{cooling}.i} + g_\mathrm{cond} + g_\mathrm{bleed} \right) .$$

Relative mass flow rate at the exit of the main burner:

$$\nu_4 = \nu_{31} \cdot (1 + q_f) .$$

Mass flow rate of the extracted air:

$$G_{\text{ext}.i}=G_3\cdot g_{\text{ext}.i}\,,\ \frac{\text{kg}}{\text{s}}\,.$$

Mass flow rate at the station 31:

$$G_{31}=G_3-\sum_i G_{\text{ext}.i}=G_3\cdot\nu_{31}\,,\ \frac{\text{kg}}{\text{s}}\,.$$

Mass flow rate at the exit of the main burner:

$$G_4=G_{31}+G_f=G_3\cdot\nu_4\,,\ \frac{\text{kg}}{\text{s}}\,.$$

Fuel consumption:

$$G_{f.h}=3600\cdot G_f=3600\cdot q_f\cdot G_{31}=3600\cdot q_f\cdot\nu_{31}\cdot G_3\,,\ \frac{\text{kg}}{\text{h}}\,.$$

Afterburner Performance Calculation

The combustion efficiency of afterburner is less than in the main burner and depends on the air excess factor α_{reheat}:

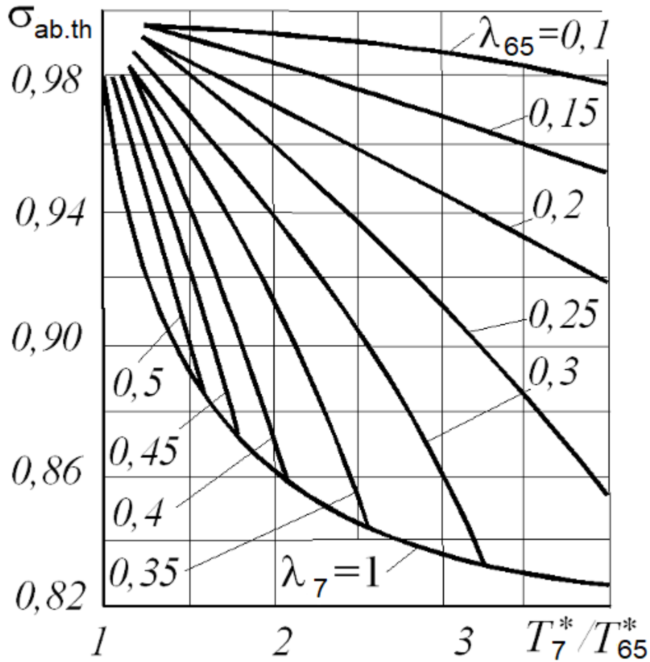
- $\eta_{ab}=0{,}92\ldots0{,}95$, if $\alpha_{ab}>1{,}3$;
- $\eta_{ab}=0{,}85\ldots0{,}92$, if $\alpha_{ab}<1{,}3$.

The total pressure loss factor in the afterburner σ_{ab} is defined by the expression

$$\sigma_{ab}=\sigma_{ab.h}\cdot\sigma_{ab.th}.$$

The coefficient $\sigma_{ab.h}$ takes into account hydraulic losses in the afterburner. Usually, $\sigma_{ab.h}=0{,}94\ldots0{,}97$.

The factor $\sigma_{ab.th}$ takes into account specific losses caused by heating of a moving gas stream. It depends on the flow velocity at the inlet to the cylindrical part of the afterburner λ_{65} ($\lambda_{65}=0{,}18...0{,}25$) and the heating ratio T_7^*/T_{65}^*.



The afterburner relative fuel consumption can be estimated by the approximate formula:

$$q_{f.ab}=\frac{G_{f.ab}}{G_{65}}=\frac{c_{p.cg}\left(T_7^*-T_{65}^*\right)}{H_r\cdot\eta_{ab}}.$$