ANALYSIS OF THERMODYNAMIC CYCLE INFLUENCE OF TURBOFAN MIXER ENGINE ON ITS PERFORMANCE

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Abstract

The turbofan engines are widely used as propulsion of the contemporary airplanes. In the military application the turbofan mixer engines are used. Although the turbofan mixer engines are applied for a long time, the information about exact analysis of their thermodynamic cycle and performance are still incomplete.

The thermodynamic cycle of the turbofan mixer engine is presented and discussed in this paper. Based on it the cycle parameters selection is discussed. Then the optimization of turbofan mixer engine cycle is presented. Final results present the influence of chosen engine cycle parameters on the engine performance. The results are analyzed and discussed. On the basis of them the conclusions are formulated. It is not such an easy process to choose for the turbofan mixer engine thermodynamic parameters. It is connected with the fulfilment of two important rules. The equalization of total pressure of mixer inflow stream for mixer efficient work is the first of it. The other rule is connected with engine cycle optimization. As it is shown it is not possible to choose engine parameters to reconcile the demands of specific thrust maximization and specific fuel consumption minimization. The engine thermodynamics parameters selection process is the search of the compromise between these two demand fulfilments, very often including engine mass analysis.

Keywords: *aircraft engines, turbojet engines, modelling of turbojet engines, turbojet engine characteristics*

1. Introduction

The turbofan mixed stream engines are frequently used as propulsion of the contemporary multipurpose military aircrafts. It is caused by the facts, that these engines connect the positive features of the turbojet and turbofan engines [6]. They have a small bypass ratio. For that reason they have high specific thrust, very close to the turbojet engine. On the other hand the air flow through external duct gives lower fuel consumption in comparison with a turbojet engine. The stream mixing in the engine causes a few percent higher thrust than the similar classical turbofan engine.

Research on such engine has been done for a long time, but the published information is not complete. The presented engine models are basic without any important topics necessary for real engine calculation.

The turbofan engines have been investigated in our Department for a few years. The main effort has been done to modelling of engines performance. The model verification has been done by comparison model simulation data with engine data given by a producer. This action allowed us to notice some important, but not published information about such engines operation, and modelling of them. Some experience of turbofan mixer engines modelling and results of their performance analysis are presented in this paper.

2. Turbofan mixer engine analysis

Typical turbofan mixer engine is shown in Fig. 1. The engine cross-section with the section index is presented in Fig. 2. The characteristic feature of such engine is that stream of air divides

Fig. 1. Turbofan mixer engine

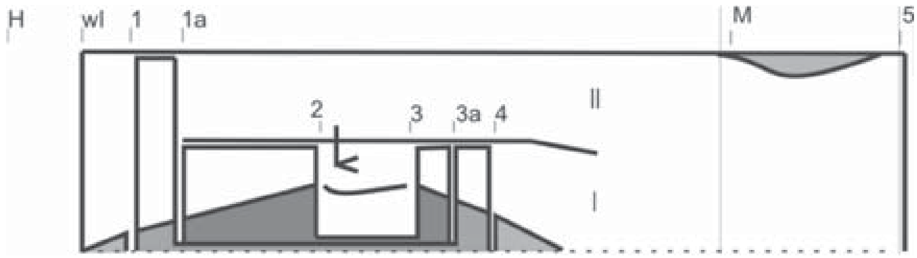

Fig. 2. Turbofan mixer engine cross-section

into external and internal flow in section "1a" after the fan. Steams of bout ducts join in the mixer (section I and II). The stream outflow is by nozzle common for both streams.

One of the conditions of proper engine work is connected with mixer inflow streams pressure. It will be very good if inflow streams pressure is similar [2, 4, 5]. The mixer characteristics presented in the Fig. 3 shows that the maximum efficiency of mixing process occurs when the total pressure of mixer inflow streams is equal. For that reason the engine components should be selected to fulfill this condition. It is done by proper choice of fan and compressor pressure ratio, bypass ratio and turbine inlet temperature.

Other aspects of engine components selection is optimization of thermodynamic engine cycle [1, 5, 6]. It is important to chose engine cycle parameters to reconcile opposing requirements connecting with maximization of thrust and minimization of fuel consumption. As it is known for classical engine characteristics the maximum thrust occurs for more and more lower overall engine pressure ratio than specific fuel consumption (see Fig. 4). The proper choice of engine cycle thermodynamic parameters follows the engine operation requirements [7]. For more powerful engines the engine overall pressure ratio is lower, but the engines are more fuel consumed. For fuel saved engines the overall pressure ratio is higher, but their maximum thrust is lower.

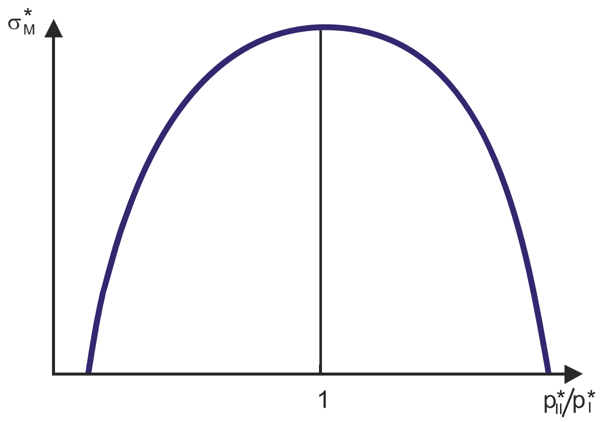

Fig. 3. Mixing flow losses σ_M vs. pressure ratio of external and internal duct [3]

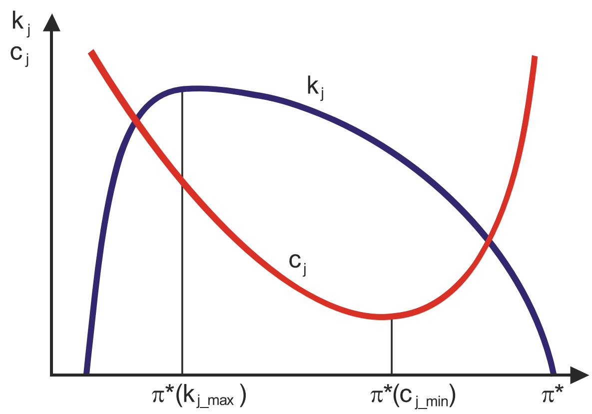

Fig. 4. Specific thrust k_j and specific fuel consumption c_j vs. overall engine pressure ratio π^* for selected turbine inlet total temperature

3. Turbofan mixer engine cycle analysis

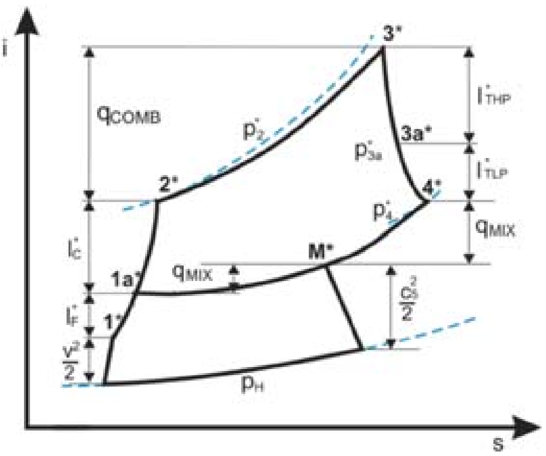

Fig. 5. Enthalpy-entropy (i-s) diagram of turbofan mixer engine, l – specific work, q – specific heat, v – speed of flight, c_5 – gas speed in nozzle outlet

The turbofan mixer engine cycle is presented in Fig. 5 as an enthalpy-entropy diagram. It is consist of lines: from point H to 1a* corresponding the inlet and the fan compression process, line 1a*-2* corresponds the compressor compression process, line 2*-3* corresponds combustion processes, line 3*-4* corresponds the turbines decompression process, lines 1a*-M and 4*-M* correspond mixing processes, line M*-5 corresponds the nozzle expansion process and closed line 5-H corresponds engine heat off. The mixing process determinates the nozzle work and it is depend on the mixer inflow stream thermodynamic parameters (p,T) and mixer geometry. Mixer work analysis shows that the pressure after mixing process could be calculated as [5]:

$$p_M^* = \sigma_M^* p_{M\_aver}^* , \tag{1}$$

where:

σ_M^* - total pressure losses in mixing process,

$p_{M\_aver}^*$ - average total pressure of mixer inflow.

Both of those parameters depend on external and internal flow pressure and the mixer geometry. Total pressure losses of mixing process is given as the mixer operation characteristic chart [5]. Its higher value is when total pressures of streams inflow to the mixer are equal (see Fig. 3). The average total pressure of mixer inflow, could be calculated as [5]:

$$p_{M\_aver}^* = \frac{p_I^* A_I + p_{II}^* A_{II}}{A_I + A_{II}} , \tag{2}$$

where:

p_I^*, p_{II}^* - total pressure of mixer inflow from the internal and external duct,

A_I, A_{II} - frontal mixer area of the internal and external duct.

When total pressures of mixer inflow streams are equal, the average total pressure of mixer inflow is the same. When total pressures of mixer inflow streams are different the value of the average total pressure is between their bout pressure values.

Temperature of stream after mixing is calculated from energy balance equation as:

$$(\bar{c}_{M-I})_p \, \dot{m}_I \left(T_I^* - T_M^*\right) = (\bar{c}_{II-M})_p \, \dot{m}_{II} \left(T_M^* - T_{II}^*\right), \tag{3}$$

where:

$(\bar{c}_{M-I})_p$ - average heat value of constant pressure,

$\dot{m}_I, \dot{m}_{II}$ - mass flow rate of mixer inflow from internal and external duct,

T_I^*, T_{II}^*, T_M^* - total temperature of flow in the entry and exit of mixer.

The gas speed in nozzle outlet is determined by gas temperature after mixing process and the pressure ratio of mixed gas pressure and ambient pressure. It could by presented as:

$$c_5 = \sqrt{c_p T_M^* \left(1 - \frac{p_H}{\sigma_M p_M^*}\right)}, \tag{4}$$

where:

c_p - average heat value of constant pressure,

σ_m - total pressure losses in the nozzle,

p_H - ambient pressure.

Gas speed of outlet nozzle influences the thrust and specific thrust of engine. Engine thrust is:

$$K = \dot{m}_5 c_5 - \dot{m} v, \tag{5}$$

and its specific thrust is:

$$k_j = \frac{\dot{m}_5}{\dot{m}} c_5 - v. \tag{6}$$

Generally higher engine outlet gas speed causes higher thrust, for that reason the maximization of engine thrust is replaced with maximization of engine outlet speed. It corresponds to maximization of engine work.

Another analyzed parameter is specific fuel consumption. It is:

$$c_j = \frac{\dot{m}_{fuel}}{K} = \frac{\dot{m}_{fuel}}{\dot{m} \cdot k_j}, \tag{7}$$

where $\dot{m}_{fuel}$ fuel mass flow.

It could be determined from engine cycle analysis as:

$$c_j = \frac{2q_{COMB}}{c_5^2 - v^2}, \tag{8}$$

where $2q_{COMB}$ - specific heat of combustion process.

4. Engine parameters selection for pressure compensation of mixer inflow streams

As it was mentioned, it is more important for turbofan mixer engine efficient work, that pressures of mixer inflow streams are equal. It needs the proper choice of engine cycle parameters. The analysis of engine component gives us a possibility to write pressure balance equation of external and internal duct, as follow:

$$\sigma_{EXT\_DUCT} = \frac{\pi_S^* \sigma_{COMB} \sigma_{INT\_DUCT}}{\pi_{TWC}^* \pi_{TNC}^*}, \tag{9}$$

where

σ^* - total pressure losses of the combuster and internal and external ducts,

π^* - a compressor, and the high low pressure turbine pressure ratio.

The high and low turbines pressure ratio is a function of total inlet temperature T_3^* and compressor and fun pressure ratio. To determine the turbine pressure drop the energy balance of compressor, fan and turbines are used. After all equations rearrangement it is received the pressure of mixer inflow streams as a function of such parameters:

$$\frac{p_{II}^*}{p_I^*} = f\left(\mu, \pi_F^*, \pi_S^*, T_3^*\right) \approx 1, \tag{10}$$

where μ - bypass engine ratio.

This equation has 4 unknowns, but only 3 of them are independent unknowns. So during the engine thermodynamic parameters selection process, it is possible to choose 3 parameters, and the last parameter should be calculated. Examples of mixer engine analysis are presented below.

First task it is looking for a fan pressure ratio π_F^*, for given other engine cycle parameters to receive equal value of the mixer inflow streams presser. The research is done for bypass ratio $\mu = 0.5$ and $\mu = 1$, the turbine inlet temperature $T_3^* = 1500$ and 1700 K, and range of compressor pressure ratio π_C^* from 5 to 25. The results are presented in Fig. 6.

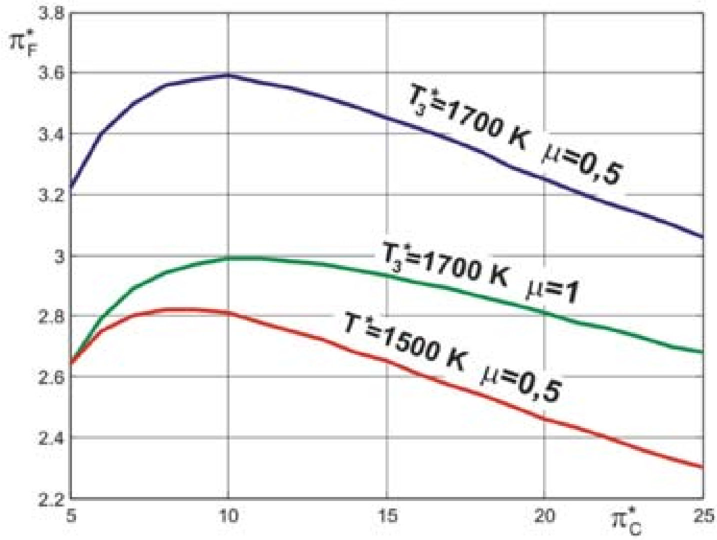

Fig. 6. Fan pressure ratio vs. compressor pressure ratio for mixer inflow streams total pressure compensation

It is obvious that, the fan pressure ratio value changes with all parameters of the engine thermodynamic cycle. Its value significantly depends on the turbine inlet temperature and the bypass engine ratio. For lower turbine inlet temperature T_3^* fan pressure ratio should be lower, and for higher temperature T_3^*, fan pressure ratio should be higher. The increase of bypass ratio causes the lowering of the fan pressure ratio. The compressor pressure ratio influences the fan pressure ratio too. The increase of compressor pressure ratio causes the growth of fan pressure value firstly, and then the lowering of it. Of course, efficiencies of engine components processes influence on the analyzed parameter too [2-4], but it isn't presented in this paper.

The fan pressure ratio similar but other than the data presented in the chart will cause the engine will be working, but its efficiency will be lower [5]. The significant difference between the chosen fan pressure and results presented in the chart bring that the engine will not be able to operate. The difference of pressure of mixer inflow stream will be so significant, and it will produce opposite direction flow in the duct of lower pressure.

A similar analysis could be done for the given fan and compressor pressure ratio and turbine inlet temperature, while bypass ratio should be evaluated. The data of calculation for $\pi_F^* = 3$, and $\pi_F^* = 3.5$, $T_3^* = 1500$ and 1700 K and range of compressor pressure ratio $\pi_C^* = 5$-15 are presented in Fig. 7. The results confirm significant change of engine bypass ratio, while other engine parameters change. It is seen for too low turbine inlet temperature and too high fan pressure ratio that it is not possible to chose engine bypass ratio to confirm the condition of mixer efficient work. Data for $T_3^* = 1500$ show the bypass engine ratio should be 0 for the compressor pressure ratio $\pi_C^* = 18$ and higher. That means, it should be turbojet engine instead of the bypass engine.

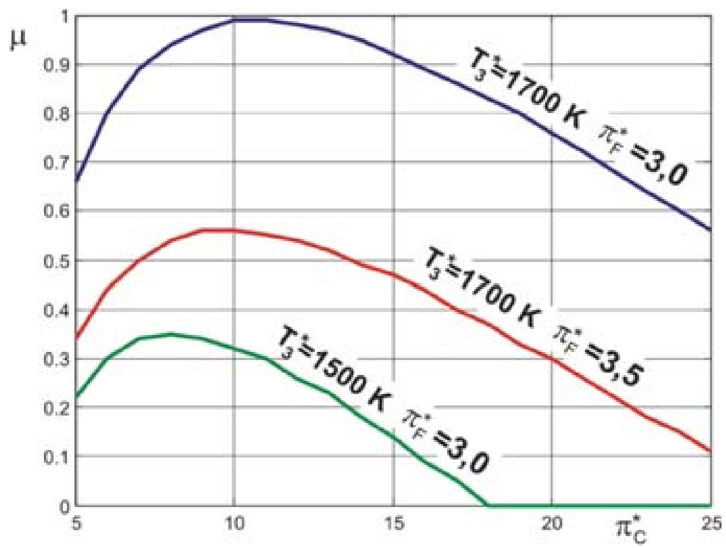

Fig. 7. Engine bypass ratio vs. compressor pressure ratio for mixer inflow streams total pressure compensation

5. Turbofan mixer engine cycle optimization

The selection of turbofan mixer engine parameters for total pressure of mixer inflow streams equalize is not an enough condition for efficient engine work. As it was mentioned earlier, for efficient engine work it is required to chose engine parameters for balancing the difference between maximum engine thrust and minimum specific fuel consumption [1, 5]. It was presented in Fig 4, that for the given turbine inlet temperature change of overall engine pressure ratio causes a significant change of the specific thrust and the specific fuel consumption, and optimal values of both parameters occur for various engine pressure ratios.

The task of the turbofan mixer engine cycle optimization is usually formulated as: engine parameters selection for given turbine inlet temperature and specified operation conditions [1, 6, 7]. Turbine inlet temperature is given, because its increase improves engine performances. For that reason it is advisable to put its value as high as possible [1, 6]. The limit of maximum turbine inlet temperature is material properties [5, 6]. Other engine parameters influence unambiguously its operation parameters, and its proper selection is important for engine performance.

The results of turbofan mixer engine specific thrust and specific fuel consumption vs. compressor pressure ratio for the given turbine inlet temperature and bypass ratio is presented in Fig. 8. The fan pressure ratio was calculated to fulfill the condition of the total pressure of mixer inflow streams equalizing. It is seen that the maximum thrust is obtained for compressor pressure ratio about $\pi_C^* = 6\text{-}8$, this gives the overall pressure ratio ($\pi_{overall}^* = \pi_F^* \cdot \pi_C^*$) about 18-19 for $T_3^* = 1500\,\mathrm{K}$, and about 20-21 for $T_3^* = 1700\,\mathrm{K}$. When the minimum specific fuel consumption is searched then the compressor pressure ratio should be about $\pi_C^* = 70$ for $T_3^* = 1500\,\mathrm{K}$, and above $\pi_C^* > 100$ for $T_3^* = 1700\,\mathrm{K}$. The difference between compressor pressure ratio for which the specific thrust is the highest and the specific fuel consumption is the lowest is significant. The compromise of pressure ratio choice is connected with engine pressure ratio selection for which the specific fuel consumption is satisfactory and specific thrust is not so small. Other circumstances of pressure ratio selection are connected with engine mass. The compressor of higher compression is heavier, and on the other hand the lower specific thrust causes the increase of an engine radial dimension to increase mass flow rate to compensate specific thrust reduction [1, 5, 6]. The radial dimension increase causes engine mass increase too.

The results of the turbofan mixer engine specific parameters optimization for the given total inlet temperature T_3^* and fan pressure ratio π_F^* are presented in Fig 9. The total pressure of mixer inflow streams was equalized by bypass ratio (see Fig. 7). This way of engine parameters selection

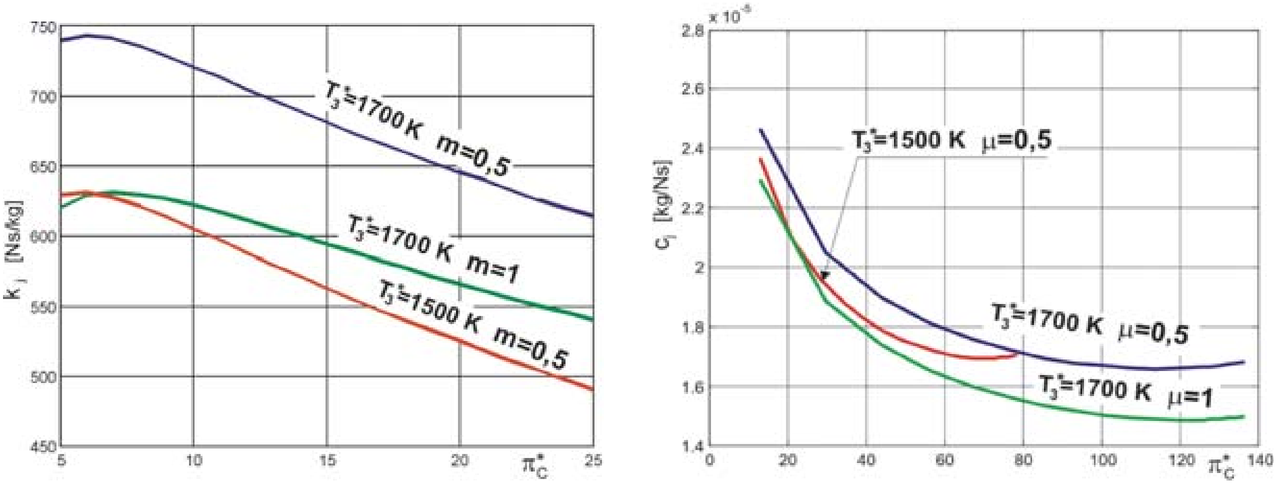

Fig. 8. Turbofan mixer engine specific thrust k_j and specific fuel consumption c_j vs. compressor pressure ratio for given turbine inlet temperature and bypass ratio

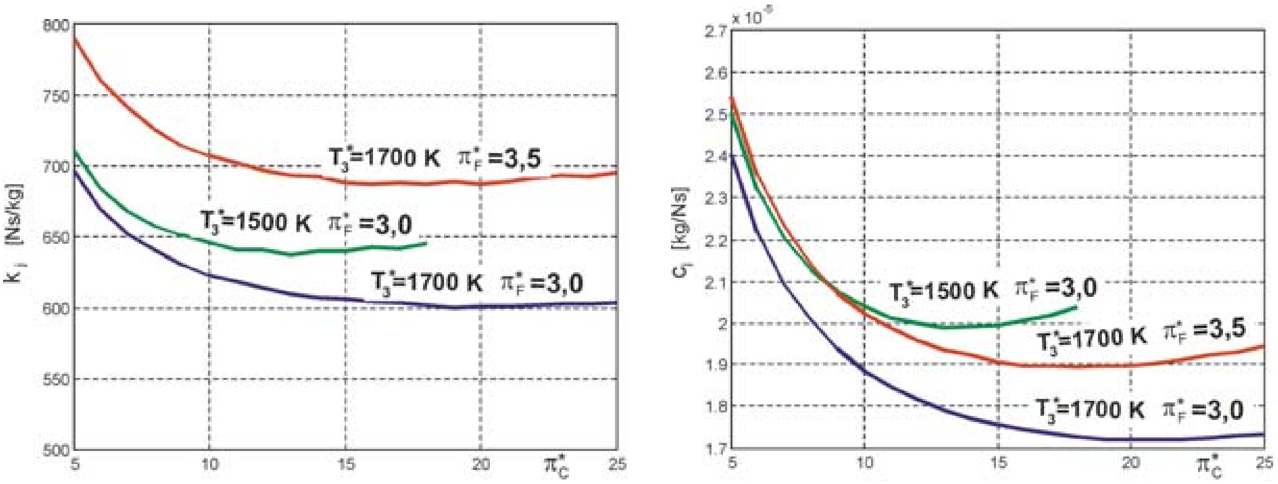

Fig. 9. Turbofan mixer engine specific thrust k_j and specific fuel consumption c_j vs. compressor pressure ratio for given turbine inlet temperature and fan pressure ratio

gives a possibility to find compressor pressure ratio when specific fuel consumption is the lowest. But this is a point when the specific thrust is the lowest too. It is interesting that minimum of specific fuel consumption does not exist in the point, when bypass ratio is the highest. For example, characteristic in Fig. 7 show that for the engine of $T_3^* = 1500\,\mathrm{K}$ and $\pi_F^* = 3$, maximum bypass ratio $\mu = 0.35$ occurs for $\pi_C^* = 8$, but minimum specific fuel consumption occurs for $\pi_C^* = 13$, when $\mu = 0.24$. This shows that turbofan mixer engine parameters dependence on bypass ratio is not similar to the classical turbofan engine, where bypass increase causes lowering of specific fuel consumption.

6. Conclusions

It is not such an easy process to choose for the turbofan mixer engine thermodynamic parameters. It is connected with the fulfilment of two important rules. The equalization of total pressure of mixer inflow stream for mixer efficient work is the first of it. The other rule is connected with engine cycle optimization. As it is shown it is not possible to choose engine parameters to reconcile the demands of specific thrust maximization and specific fuel consumption minimization. The engine thermodynamics parameters selection process is the search of the compromise between these two demand fulfilments, very often including engine mass analysis.

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