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PRELIMINARY ANALYSIS OF TWO COMBUSTORS TURBOFAN ENGINE

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Abstract

The problems of turbofan engines development is briefly discussed in the beginning. Next the conception of turbofan engine with two combustors is presented, and an engine thermodynamic cycle is analysed. The proposed engine it is a modification of the contemporary turbofan engine by addition of another combustor. First one is classical combustor located between high pressure compressor and turbine. Second one is located between high pressure turbine and low pressure turbine. This conception allows to lower the high pressure turbine inlet temperature. The second combustor increases energy of gasses inflow the low pressure turbine to the sufficient level for fan drive. The results of numerical analysis are used to show performance of the proposed engine and to present their advantages with compare to the classical turbofan engine construction. Then some other positive aspects of two combustors engine are discussed. It refers to possibilities of pollution emission reduction and overhauling period increasing and engine life time extension. On the other hand some aspects of engine hot elements (turbine) production simplification and cost reduction is analysed. In the next chapter the problems of the proposed engine technical realization are discussed. The summary and conclusions are presented in the last part of article.

Keywords: *jet engine, turbofan engine*

1. Introduction

Turbofan engine has gained popularity in most new aircrafts. It has been done by its specific features which are very important for aviation transport. The most important features are low specific fuel consumption and noise emission and great thrust. They are mainly connected with high bypass ratio of these engines and great amount of air bypassed combustor and turbines.

By this way such engines are more frequently applied in passenger large aircraft flying with subsonic speed. Almost all passenger and cargo air transport uses these types of engines, therefore there are particle attention paid on such engines improvement.

Today realized projects in these engines development are concentrated on lowering fuel consumption and noise and emission reduction. New types of combustors for low prolusion and noise emission are designed, researched and developed [4]. Greatest effort is done to introduce new types of fuel to aviation such as bio-kerosene or hydrogen [1]. Another concept is engine cycle modification. One of them is a concept of additional combustion in turbine and between turbines [5-8]. The main goal of such conception is engine cycle modification for its performance improvement.

In this article the two combustors engine conception with the additional inter-turbines combustor is presented. It is proposition of the engine development by addition of another combustor in the section between high and low pressure turbines. The idea of two combustors turbofan is connected with some aspects, which finally should brink increasing of engine overall efficiency. The possible advantages of such solution could be [8]:

- decreasing of maximum high pressure turbine temperature, and compensation engine energy balance by second combustor,

– increasing of turbine efficiency by lowering ore elimination turbine blade cooling,
– decreasing NOx emission by lowering maximum temperatures in engine.

2. Two combustors engine

Classical turbofan engine consist of fan, compressor, combustor, high and low pressure turbine and two separated propelling nozzles (see Fig. 1). Two combustors turbofan engine has additional combustor between high and low pressure turbine. It is called inter-turbine burner (see Fig. 2).

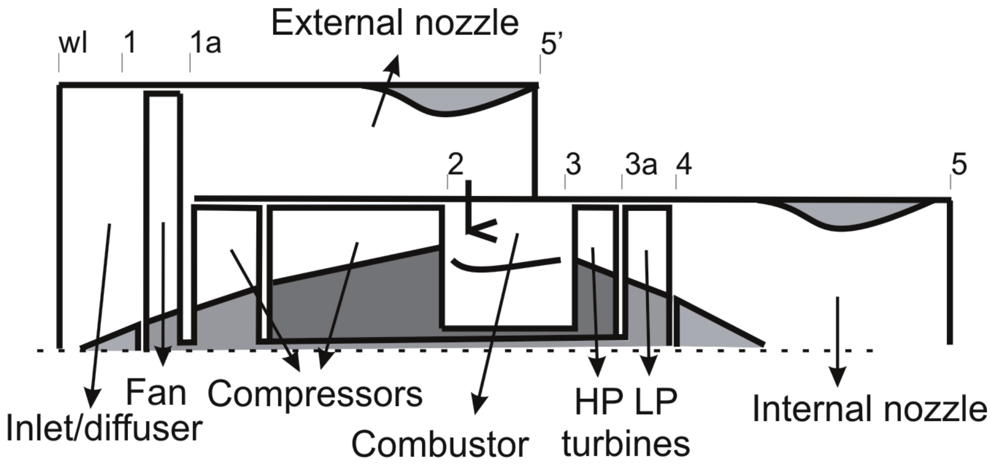

Fig. 1. Classical turbofan engine scheme

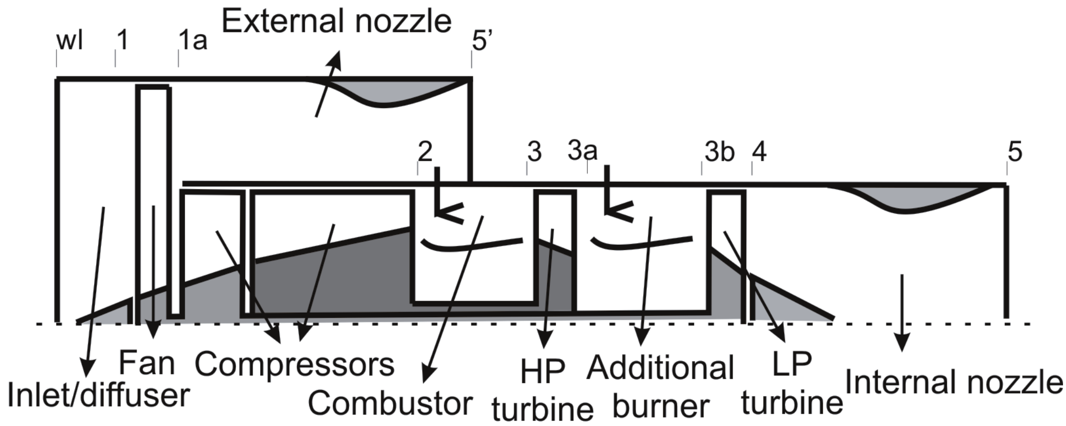

Fig. 2. Turbofan engine with inter-turbine burner scheme

Cycle's comparison of both turbofan engine type is presented in Fig. 3. The heat added in burner Q_B in the classical turbofan engine cycle should be necessary to produce power by high and low pressure turbine for a fan and a compressor drive and to accelerate stream in internal and external duct. For high by-pass turbofan engines (they are low fuel consumed) the low pressure turbine power is large. It is caused by high fan which impact on large mass of air. Therefore heat added in the combustor should be large. So turbine inlet temperature should be very high – above 1700 K.

The engine with inter-turbine burner cycle shown that the heat is added in two combustors. First is heat added in classical combustor, the second one is added in the additional burner between turbines. By this way it is possible to increase engine thrust, when high turbine inlet temperature is applied. Another possible solution is remain thrust at the same level and decrease turbine inlet gas temperature. Some aspects of the second solution is presented later.

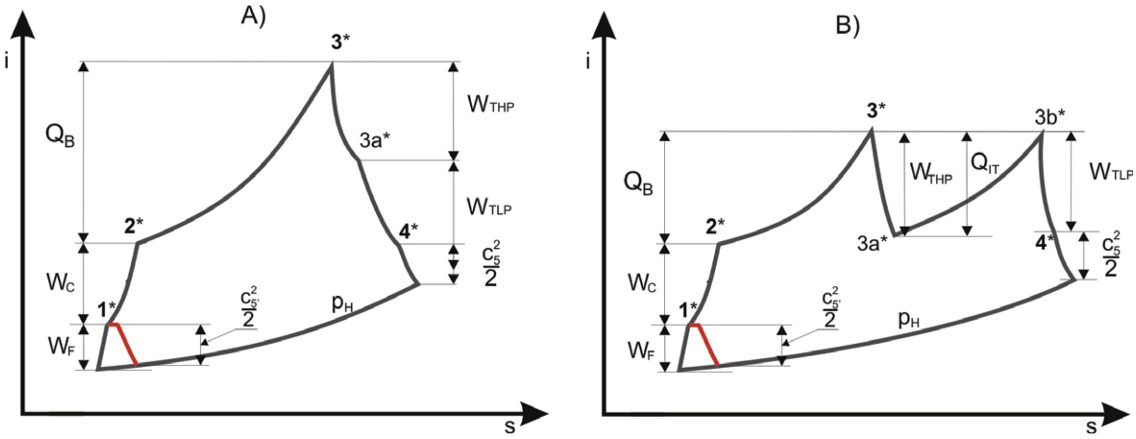

Fig. 3. i-s diagram A) classical turbofan engine, B) turbofan engine with two combustors

The problem of maximum cycle temperature lowering was investigated. The assumption was the maximum cycle temperature does not exceed 1300 K. This temperature is the upper limit of the turbine work without internal turbine cooling system [10]. The advantages of such engine are:

- simple and low cost technology of turbine blades and discs production,
- increase of engine time operation by turbine thermal loading reduction,
- turbine efficiency improvement by elimination process of coolant mixing with main stream in the turbine,
- almost all mass of air inflow into the internal duct is working (there isn't mass bleeding for cooling) and the flow mass share in power production is greater,
- reduction of NO_X emission by cycle maximum temperature reduction.

3. Numerical analyses of two combustor engine

Based on presented chart in Fig. 3B the two combustor turbofan engine numerical model was done. The total heat added to the engine is a sum of heat added in the main burner Q_B and in the burner between turbines Q_{IT}:

$$Q_t = Q_B + Q_{IT}\,, \tag{1}$$

where:
Q – heat added into the engine, indexes: t – total, B – in the main burner, IT – between turbines.

Heat added in individual combustor is calculated as:

$$Q = \frac{m_f}{m_I} \cdot h \cdot \eta_B = C_p \left(T_{B2} - T_{B1}\right), \tag{2}$$

where:
m_f, m_I – fuel mass flow, air core engine mass flow,
h – fuel heat value,
η_B – burner efficiency,
C_p – specific heat
T – total temperature,
B1 – burner inlet,
B2 – burner outlet.

Specific thrust is calculated:

$$T_s = \frac{\frac{m_5}{m_I} c_5 + \alpha \cdot c_{5'} - (1+\alpha) \cdot V}{1+\alpha}, \tag{3}$$

where:

m_5 – fumes mass flow i internal duct exit,

c_5, $c_{5'}$ – velocity of jet stream in internal and external nozzle exit,

α – bypass ratio,

V – flight speed.

Specific fuel consumption is evaluated as:

$$S_f = \frac{T_s}{\frac{m_f}{m_I}(1+\alpha)} . \tag{4}$$

Specific thrust and specific fuel consumption are more important parameters determined engine performance. High specific thrust indicates that engine internal processes are efficient and the engine cycle parameters are properly chosen. The designed engine could has smaller radial dimension and could be lighter. Low specific fuel consumption determines the engine process is efficient and its operational cost connected with fuel consumption is less.

Analysis of classical turbofan engines shows that it isn't possible chose the compressor pressure ratio to meet the requirements for the specific thrust maximization and specific fuel consumption minimization [9]. Compressor pressure ratio for minimum specific fuel consumption is more and more great then pressure ratio for maximum specific thrust. The designer should find a compromise between both parameters during the compressor pressure ratio chose.

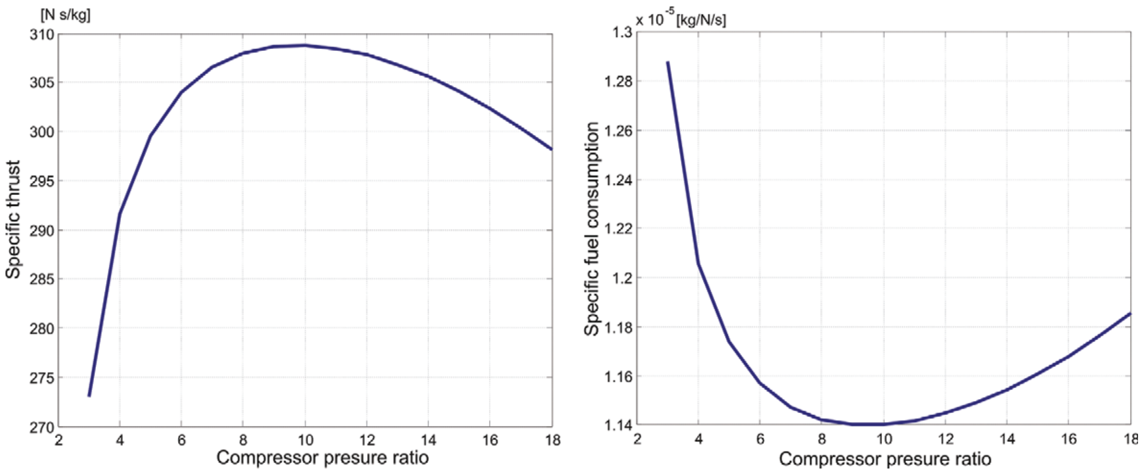

Fig. 4. Specific thrust and specific fuel consumption vs. compressor pressure ratio for two combustors turbofan engine

It is different for two combustors turbofan engine. The chart presented in Fig. 4. shows the results of engine cycle optimization due to the compressor pressure ratio. It is presented that it is possible to find compressor pressure ratio where both parameters specific thrust and specific fuel consumption are optimal. Results calculated for two combustors turbofan show that the best solution is compressor pressure ratio about 10 in this case. Of course the results depend on thermodynamic parameters of engine cycle and for other turbines inlet temperatures, fan pressure ratio and bypass ratio optimal compressor pressure ratio will be different.

3. Two combustor and classical turbofan comparison

Advantages and disadvantages analysis is done by comparison of classical turbofan and two combustors turbofan. For analysis were taken engines about compared cycle parameters. For both engines were assumed the same bypass ratio (α=6), fan pressure ratio (π_F=1.7), low pressure compressor pressure ratio (π_{LP}=1.7), high pressure compressor pressure ratio (π_{HP}=10) and most of the engine components losses indexes. The different was turbine inlet temperatures. For the classical turbofan it was (T_3=1700 K), for two combustors turbofan it was in the main combustor outlet (T_3=1300K) and in the inter turbine combustor outlet (T_{3b}=1300 K). In the classical turbofan were assumed internal turbine cooling system. The numerical model of cooling system calculation were assumed as it was presented in [3], the coolant mass and cooling turbine efficiency drop were assumed as it was presented in [2, 10]. For high pressure turbine inlet temperature 1700 K coolant mass flow core engine mass flow ratio was assumed 0.16 and polytropic efficiency drop was assumed 2 percent compare to uncooled turbine.

The results of engines main parameters calculation are presented in Tab. 1.

Tab. 1. Comparison of chosen parameters which determine performance of classical and two combustors turbofan

Parameter	Symbol	Unit	Classical turbofan	Two combustors turbofan
Specific thrust	T_s	N s/kg	281	309
Specific fuel consumption	S_f	Kg/N/s	$1.1428\ 10^{-5}$	$1.1402\ 10^{-5}$
Heat added in main combustor	Q_B	kJ/kg	1 130.9	597.2
Heat added in additional combustor	Q_{IT}	J/kg	-	431.6
HPT pressure ratio	π_{HP}	-	5.1	4.32
LPT pressure ratio	π_{HP}	-	4.86	4.39
LPT outlet total temperature	T_4*	K	880	950
LPT outlet total pressure	P_4*	kPa	110	142.3
Internal nozzle jet velocity	C_5	m/s	202	402
External nozzle jet velocity	$C_{5'}$	m/s	293	293

Presented results indicate the performances of two combustors turbofan could be better than of the classical turbofan. Specific thrust is about 10 percent higher and specific fuel consumption is slightly lower. To explain this the thermodynamic analysis of internal engine parameters should be done. The assumption of similar fan pressure ratio and by-pass ratio cause the external nozzle work of both engines are the same. It is indicated by external nozzle jet velocity $C_{5'}$.

The differences exist in core engine work parameters. Internal nozzle yet velocity of two combustors turbofan is twice time the classical turbofan nozzle jet velocity. The mine reason of such situation is higher low pressure outlet temperature T_4* and pressure p_4*. This parameters are determined by turbines and combustors work. In classical turbofan high pressure inlet temperature is very high (1700 K). The high energy main stream is possible to produce high power, but turbine material isn't possible work in this temperature and cooling process is required. By this way some air which is compressed is bleeding for turbine cooling. That modify turbine compressor energy balance equations to:

$$m_{air}c_{pc}\left(T_2^* - T_{1b}^*\right) = \left(m_{air} - m_{bl}\right)c_{pt}\left(T_3^* - T_{3a}^*\right) + m_{bl}Q_{col}, \tag{5}$$

were:

m_{air}, m_{bl} – air mass flow, bleeding air mass flow,
c_{pc}, c_{pt} – compressor, turbine specific heat,
T – total temperature in the engine sections i accordance with Fig. 1,
Q_{col} – specific heat transferred to cooling air, which were calculated as:

$$Q_{col} = c_{pc}\left(T_{3a}^* - T_2^*\right). \tag{6}$$

By this way temperature drop in the high pressure turbine is significant. Low pressure turbine inlet temperature is lower than 1300 K. This turbine don't require the cooling system. It was mentioned earlier the cooling turbine efficiency is lower them uncooled turbine one. Therefore the pressure drop of cooling turbine is greater. The high pressure turbine pressure ratio comparison shows the significant difference between this parameters value for both type of engines. So the gas pressure inflow to the low pressure turbine in classical turbofan is lower them in two combustors turbofan.

Another advantage of two combustor engine is possibility to increase low pressure inlet turbine temperature. It was assumed temperature T_3*=1300 K. Higher inlet turbine energy give possibility to produce sufficient work for fan and low pressure compressor drive, with lower temperature and pressure drop. Finally inlet nozzle temperature and pressure is higher and allow to produce greater thrust.

3. Summary

Presented idea of the turbofan engine cycle modification gives possibility to design more efficient (better) propulsion for large subsonic aircrafts. Their specific thrust could be higher and specific fuel consumption lower them classical turbofan. More positive aspect of such engine design is thrust and fuel consumption optima overlap. Therefore it is easy to chose engine pressure ratio to fulfil both mentioned criteria.

The concept looking as more interested for future investigation and development.

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