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# ANALYSIS OF TURBOFAN ENGINE DESIGN MODIFICATION TO ADD INTER-TURBINE COMBUSTOR

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***Abstract***

*An inter turbine combustion is one of modern direction of turbofan engine cycle modification. It is possible to reduce gas temperature in high-pressure turbine inlet section and reduce $NO_X$ emission by an additional combustor placed between high and low pressure turbines. The analysis of engine cycle modification and its performance are a scope of many scientific investigations, but it is not any work about engine dimension change due to cycle modification. By these way problems of two combustor engine components and dimensions, change with comparison to conventional turbofan engine is a goal of this work.*

*The structure of a turbofan engine with inter turbine combustor is shown and results of evaluation temperature and pressure in specified engine cut sections are presented and discussed. Then the gas density is calculated and by mass continuity equation application, the specified cross section areas are determined. The results of two-combustor turbofan engine are compared with conventional high bypass turbofan engine. The comparison of engines parameters allow to predict how engine components should be modified in two-combustor turbofan when the base of modification is classic turbofan engine. The analyse contain determination of compressor and turbine stage numbers, prediction of areas of cross section and diameters in specified engine sections and overall engine axial dimensions. The results are used to formulate conclusion about the turbofan engine structure modification by additional combustor implementation between turbines.*

***Keywords:*** *jet engine, turbofan engine, turbofan engine design, airplane engine development, inter turbine combustor turbofan*

## 1. Introduction

Over the years gas turbine engines have improved significantly from pure turbojets to the current high bypass turbofan engines. Engine development motivation was done to make them more powerful, lighter and lower fuel consumed. Today aero engines are still developed, but the requirements for new engines introduced to the market growth of new mainly environmental criteria.

Modern engines should be less fuel consumed, but more important is that they should generate less noise and pollution emission. The environment protection and restrictive norms are mine factors influence on engine development. By this way, few ways of engine modifications could be observed. Main of them concentrates on combustion improvement. Some effort is done to modify the main combustor of the engine to make combustion process more efficient and to minimize the pollutions [5]. For example, two zones combustor are investigated and applied to the real engine. By this way it is possible to optimize combustion process and reduce emission in vide range of engine work.

Another works study engine cycle modification to improve engine overall efficiency and reduce its emission. They concentrate on the engine with inter-stage burning. Results presented in [8, 9] show the higher efficiency of such engine than classical turbojet or turbofan. As a reason of such result is the fact that the cycle of inter turbine burning engine is close to the Carnot cycle which is most efficient of engine cycles. The problem is to use turbine blade roves as a classical turbine and additionally as a combustor.

Some other engine cycle modification it is implementation of additional combustor between high and low pressure turbines [3, 4, 6, 7]. This modification allows reducing high-pressure turbine inlet temperature, and by this way to reduce NOx engine emission. By sufficient turbine inlet temperature, decreasing it is possible to eliminate internal blade turbine cooling [3]. By this way, the turbine efficiency grows and the air extraction from compressor for turbine cooling is eliminated. All of this allows increasing overall engine efficiency while maximum engine gas temperature is reduced.

In this paper, the classical high bypass engine modification by additional combustor located between turbines is analysed and discussed. Modified engine is designed with both turbine inlet temperature not exceed 1300 K. By these way turbine blades, internal cooling could be eliminated. The fan pressure ratio and low compressor pressure ratio will be taken from modified turbofan engine. High-pressure compressor pressure ratio will be designed to optimize engine cycle as it is presented in work [4]. The high and low-pressure turbine modification will be evaluated. Finally, the conception of the turbofan engine with additional combustor will be presented.

## 2. Two combustors engine vs. classical turbofan engine

The comparison of classical turbofan engine and turbofan two combustor engine schemes is presented in Fig. 1. A two-combustor turbofan engine has an additional combustor located between high and low pressure turbine (see Fig. 1). This combustor is called inter turbine burner (ITB). The other elements of such engine are similar to the classical turbofan engine. It consist of: an inlet, fan, splitter separated stream for external and internal duct, compressors, turbines, combustor occurring in the internal duct and an external and internal duct propelling nozzles.

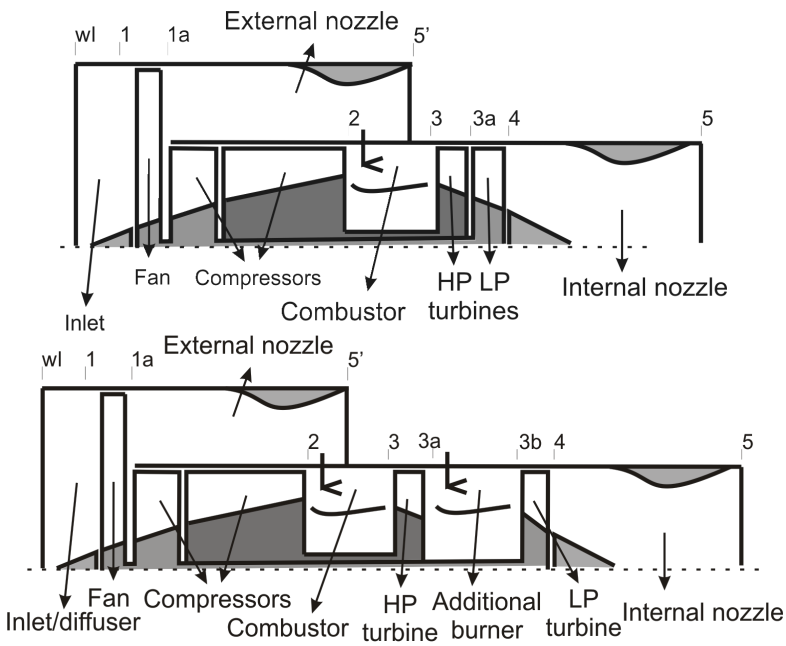


*Fig. 1. Schemes of the classical turbofan engine (up) and turbofan engine with inter-turbine burner (down)*

The mine profit of such engine modification is lowering of the turbine inlet temperature (TIT). In the classical contemporary turbofan, the TIT is about 1700 K [1, 2, 5]. Such turbine inlet temperature level requires advanced turbine disc and blades cooling systems and a lot of air should be extracted from the compressor for turbine cooling [1, 2, 10]. All of this lowers engine effectiveness [1, 2]. TIT decreasing to the level when cooling is not required allows applying simple structure of turbine blades and discs without holes for coolant [1]. This turbine is cheaper for manufacturing, more reliable and durable and increases the time of it safe operation.

Analysed engines achieve compared thrust. Classical turbofan high-pressure turbine inlet temperature is 1600 K. Two combustor turbofan both turbines TIT level is 1300 K. Enthalpy-entropy diagrams for both engines are presented in Fig. 2.

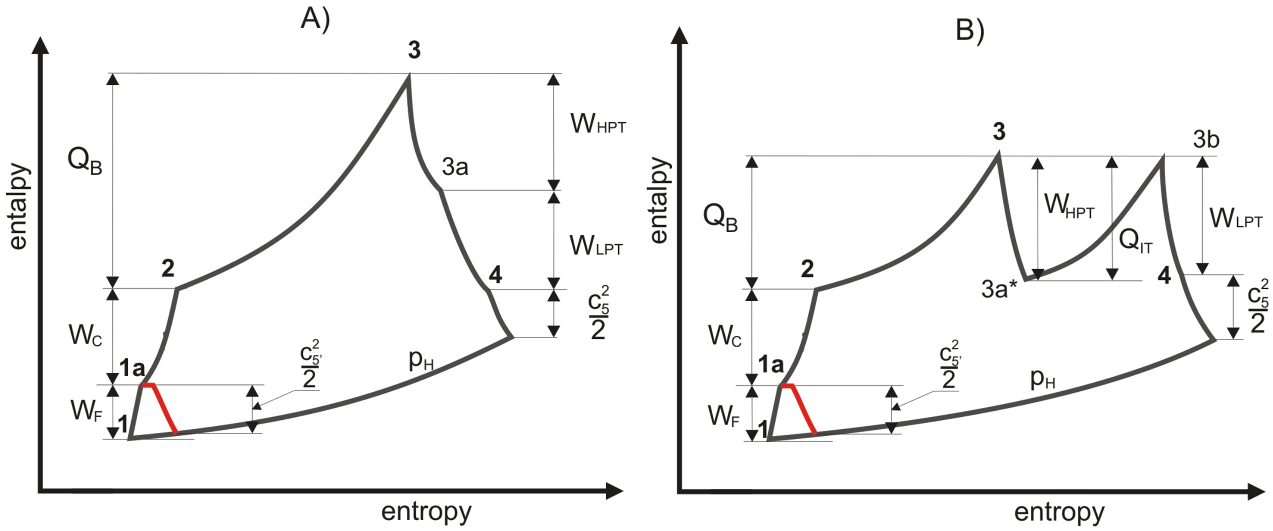


*Fig. 2. Enthalpy-entropy diagram of A) classical turbofan engine, B) turbofan engine with two combustors, indications: W – work, Q – heat, c – gases flow velocity, 1, 2…5 – indications of the engine's cross-section according to Fig. 1*

The difference in work analysis of compared engines comes from one and two combustors. In classical turbofan, heat is added into the engine in one combustor, so total heat added into the engine is equal:

$$Q_t = Q_B. \quad (1)$$

In two-combustor turbofan, heat is added into the engine in two combustors. By this way, total heat added to the engine is equal:

$$Q_t = Q_B + Q_{IT}, \quad (2)$$

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

Similarly, fuel mass consumed by the classical turbofan is the fuel mass supplied to the mine combustor only:

$$\sum m_f = m_{f\_B}. \quad (3)$$

Fuel mass consumed by two-combustor engine is a sum of fuel flow in main and additional burners:

$$\sum m_f = m_{f\_B} + m_{f\_IT}. \quad (4)$$

The relation between heat and fuel flow for main combustor is:

$$Q_B = \frac{m_{f\_B}}{m_I}\, h\, \eta_B = C_p(T_3 - T_2) \quad (5)$$

and for additional combustor is:

$$Q_{IT} = \frac{m_{f\_IT}}{m_I}\, h\, \eta_{IT} = \left(1 + \frac{m_{f\_B}}{m_I}\right) C_p (T_{3b} - T_{3a}), \qquad (6)$$

where:

$m_f, m_I$ – fuel mass flow, air core engine mass flow,

H – fuel heat value,

$\eta_B, \eta_{IT}$ – mine combustor efficiency, inter turbine combustor efficiency,

$C_p$ – specific heat value,

Next equations are valid for both engines:

The engine thrust is calculated as:

$$F = m_5 c_5 + m_I \alpha\, c_{5'} - m_I (1 + \alpha) V. \qquad (7)$$

Specific thrust is calculated as:

$$F_S = \left(\frac{m_5}{m_I} c_5 + \alpha\, c_{5'} - (1 + \alpha) V\right) / (1 + \alpha). \qquad (8)$$

Specific fuel consumption is evaluated as:

$$S_f = \sum m_f / F, \qquad (9)$$

where:

$F$ – thrust,

$F_S$ – specific thrust,

$m_5$ – fumes mass flow of internal duct exit,

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

$\alpha$ – bypass ratio,

V – flight speed.

## 3. Numerical model and simplification of engine internal processes

Engine is represented by numerical model consisted of functional blocks described main engine components. Block structure of the two-combustor engine is presented in Fig. 3. All components are connected by functional and structural relationship as in the real engine.

Numerical model was prepared in Matlab. Functional blocks of the engine components include typical numerical description of the flow-thermal processes occurring in them. The additional combustor is modelled as the main combustor, but worse working conditions are described by lower burning efficiency. In this work, additional combustor efficiency was assumed 0.965, while the main combustor efficiency was assumed 0.985 [11].

Globally engine work conditions are represented by characteristic parameters like pressure ratio of fan and compressors and temperature ratio of combustors. Other important factors, which determine engine performance, are engine losses, which are characterized by coefficients described real processes derogation from ideal processes. On that basis fan, compressor and turbine process imperfection is characterized by polytropic efficiency. The pressure losses coefficient is applied for inlet, propelling nozzles, combustors and other ducts.

In analyse of classical turbofan engine the data of GE90-85B was applied. This engine's bypass ratio is 8.4, fan pressure ratio is 1.58, low-pressure compressor pressure ratio is 1.1 and overall pressure ratio of the engine is 40.4. Internal processes were characterised as in work [11].

The data of two-combustor turbofan was assumed by optimisation of engine cycle to achieve maximum specific thrust and minimum specific fuel consumption, as it was presented in [4]. The assumption was done the thrust and specific thrust of bout engine should be on the same level. TIT of both turbines in the two-combustor engine was assumed 1300 K. The comparison of both engine mine parameters is presented in Tab. 1.

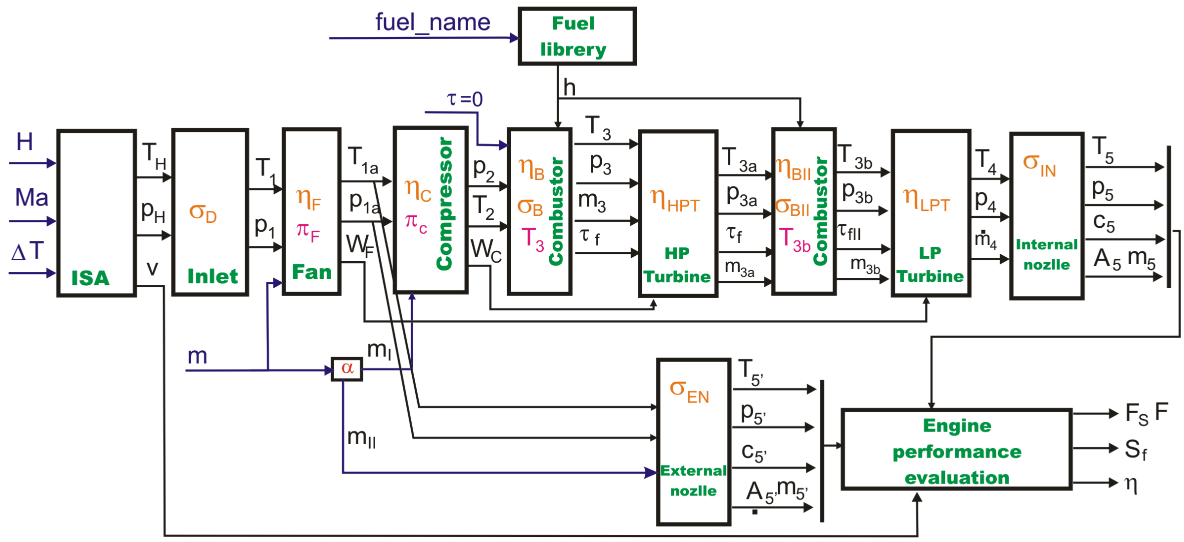


*Fig. 3. Blocs structure of double combustor turbofan engine model*

*Tab. 1. Comparison of basic parameters determined for the two combustor engine and data for the GE90-85B engine [11] for take-off condition*

| | Two-combustor engine | GE90-85B engine |
|---|---|---|
| Total pressure ratio | 26.2 | 40,4 |
| Fan pressure ratio | 1.58 | 1.58 |
| Low pressure compressor ratio | 1.1 | 1.1 |
| Bypass ratio | 8.4 | 8.4 |
| Air mass flow [kg/s] | 1350 | 1350 |
| Thrust [kN] | 379.4 | 375.3 |
| Specific thrust [Ns/kg] | 281 | 278.1 |
| Specific fuel consumption [kg/daN/h] | 0.341 | 0.285 |
| Fuel consumption [kg/s] | 3.60 | 2.99 |

The determined values show that the two-combustor engine has a similar thrust, but it has a higher specific fuel consumption. This unfavourable effect can be caused by two reasons. Firstly, too low coefficients of the processes in the additional combustor were assumed. This has a significant influence on the increase of the specific fuel consumption, which can be deducted on the basis of the research presented in work [6]. Secondly, the increase of the turbine performance due to elimination of cooling processes was not taken into account. These issues will be analysed in the next time.

## 4. Two-combustor turbofan engine gas path modification

The turbofan engine modification for inter turbine burner application was studied. Basses structure of engine was taken from GE-90 description [11]. The engine overall length is 4775 mm, an inlet and a fan diameter are 3124 mm The scheme of GE 90 gas path is presented in fig 4a. Main components modification is analysed by comparison to GE 90 engine.

For cross-areas evaluation of specified engine cut sections, the continuity equation was applied:

$$A_i = \frac{m_i}{\rho_i \cdot c_1}, \tag{10}$$

where

A – cross section area,

m – mass flow of gas,

ρ – gas density,
c – normal velocity of gas flow,
i – index of cut section

Engine radial and axial dimensions were determined based on the scaled engine scheme presented in fig 4 and the results of engine thermal-flow parameters study. Based on GE 90 data the single stage mean pressure ratio of compressor and turbines were determined as:

$$\pi_{st} = \sqrt[n]{\pi}, \tag{11}$$

where:
$\pi$ – pressure ratio of engine component,
n – amount of stages,
$\pi_{st}$ – single stage mean pressure ratio.

By this way, the number of compressors and turbines stages of the modified two-combustor turbofan was determined. The results are presented in Tab. 2. The fan, low-pressure compressor, external duct are the same for both engines so the data of such elements are not presented in the table.

*Tab. 2. GE 90 and two combustor turbofan gas-flow parameters and radial dimensions summary*

| Parameter | GE 90 | Two combustor turbofan |
|---|---|---|
| HPC PR/ P2[kPa]/ T2[K] | 23.24/4003.9/867 | 15.07/2588.7/776 |
| HPC mean stage PR/ stage numbers | 1.37/10 | 1.37/8+1.215 |
| External/internal diameter [m]/area [$m^2$] in section 2 | 0.748/0.650/0.108 | 0.748/0.646/0.111 |
| P3[kPa]/T3[K] | 3923.8/1600 | 2536.9/1300 |
| External/internal diameter [m]/area [$m^2$] in section 3 | 0.931/0.787/0.185 | 0.931/0.858/0.100 |
| HPT PR/ P3a[kPa]/T3a[K] | 6.2/632.8/1079 | 4.63/547.4/0.298 |
| HPT mean stage PR/ stage numbers | 2.49/2 | 2.15/2 |
| External/internal diameter [m]/area [$m^2$] in section 3a | 0.931/0.787/0.187 | 0.931/0.696/0.298 |
| LPT PR/ P4[kPa]/T4[K] | 5.77/109.6//719 | 3.98/132.1/954 |
| LPT mean stage PR/ stage numbers | 1.34/6 | 1.41/4 |
| External/internal diameter [m]/area [$m^2$] in section 4 | 1.833/1.198/1.51 | 1.833/1.463/0.956 |
| Internal nozzle PR/ gas speed [m/s] / area [$m^2$] | 1.082/161/1.51 | 1.303/361/0.891 |

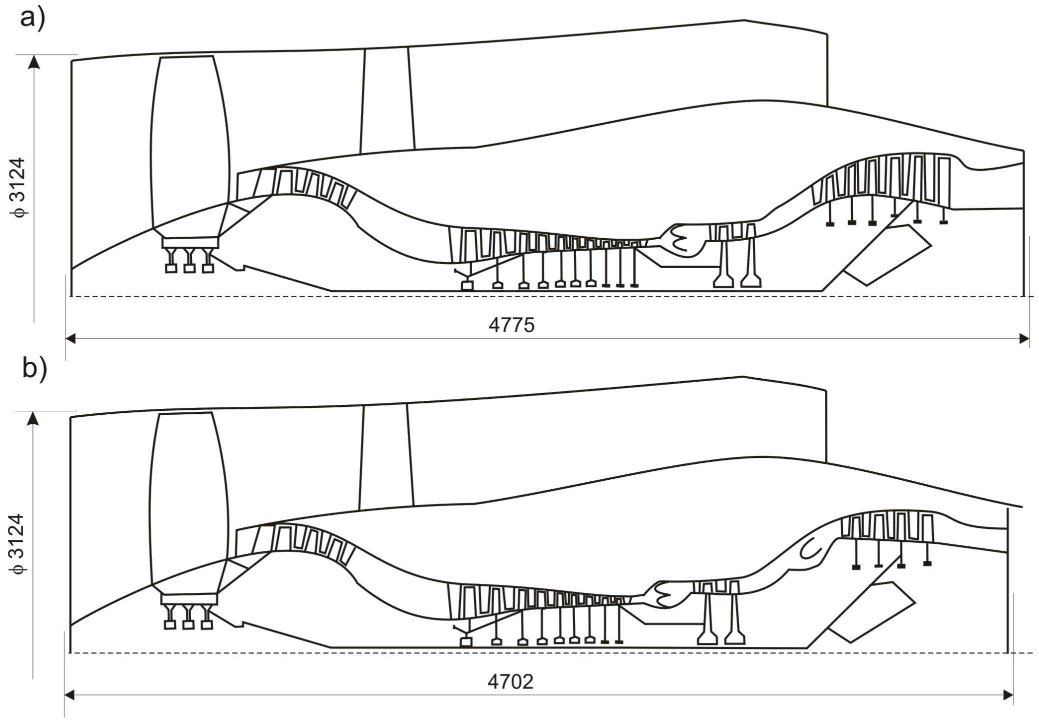


*Fig. 4. Scathes of GE-90 (a) and its modification by inter turbine burner application (b)*

Scheme comparison of two engines is presented in Fig. 4. The results presented in Tab. 2 and in Fig. 4 allow to conclude GE-90 modification for inter turbine combustor application. According to an earlier assumption the fan, low-pressure compressor and external duct are not changed in modified engine. The first modified element is a high-pressure compressor (HPC). Its pressure ratio (PR) has been decreased by last stage elimination and lowering PR of ninth stage. By this way the outlet, area of the HPC increased and slightly decreased axial dimension.

In the combustor exit of modified engine, gas temperature and pressure are significantly lower. The exit area is also lower. Modified engine HPT should has lower pressure drop because power for propelling HPC of lower pressure ratio is lower. By this way, HPT is planned to consist of two less loaded stages and shorter blades. Pressure drop of LPT is lower even that it power the same low-pressure unit (fan and low-pressure compressor (LPC) are the same in both engines). It is caused by higher gas temperature in the LPT inlet.

The space for additional combustor is prepared by elimination of two LPT stages and utilization space between HPT and LPT. By this way it is possible to design and prepare turbofan engine with additional combustor located between turbines with not increase of it overall dimensions. Proposed two-combustor turbofan is shorter of last stage of HPC. It is overall lent is 4702 mm.

## 5. Conclusions

Classical turbofan engine should be modified for inter turbine burner application. In this study was assumed that fan and external duct of based engine are not changed. The cycle optimization shown overall pressure of the two combustor engine should be lower than the classical turbofan. By this way, the high-pressure compressor was modified for decreasing its pressure ratio. Temperature and pressure changes in combustors and turbines influence flowing gas density. By this way cross section area of modified engine components decrease. Turbines should be redesigned for fitting them to lower load. It should be reduced the number of stages of the low-pressure turbine. By this way, it was possible to save space for inter turbine burner without increasing engine overall dimension.

The concept of the engine seems to be more interesting for future investigation and development. The future analysis among other things should concentrate on an additional combustor design. Engine dynamics should by analysed two. It could be expected faster acceleration of modified engine by lower spool inertia and two sources of heating.

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