Investigation of the Efficiency Limits of the Traditional Gas Turbine Engines

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***Abstract*—The article describes the results of investigation of the theoretical limits of the conventional gas turbine engines on the basis of numerical simulation using the computer-aided system "astra". The results of simulation are used to forecast the gas turbine engines' parameters as well as to determine whether the potentialities of the conventional gas turbine engines are exhausted or not. The approaches to increasing the efficiency of propulsion unit and the thermogasdynamic cycle are suggested.**

***Index Terms*—efficiency, gas turbine engine, optimization, math modeling, prognostication**

I. Introduction

According to the analysis of open-access publications [1]-[5], the prospective ways of further improvement of traditional (without heat recovery and water/steam injection) gas turbine engines may be divided into three groups:

- Decreasing the losses of the engine elements and the flow rate of bleeding air;
- Improving the efficiency of thermodynamic cycle of engine;
- Improving the efficiency of the engine as a propulsion unit.

This article describes the results of numerical investigation of the limits in efficiency increasing of these three approaches, with a turbofan engine as an object of study. The numerical investigation was conducted using the computer-aided system of thermogasdynamic analysis ASTRA [6], developed at the Samara State Aerospace University.

II. Decreasing the Losses of the Engine Elements and the Flow Rate of Bleeding Air

The investigation was performed for the cruising mode of flight at the altitude of 11 km and the airspeed of 850 kmph (Mach number of 0.8). Separate flow three-spool turbofan engine with a principal parameters described in the Table I was selected as a baseline engine, characterizing the modern level of engines development.

Specific fuel consumption of the baseline engine (C_{sp}) is 48.5 kilograms of kerosene per kN of thrust per hour. High values of efficiency ratios of the baseline engine show that their further enhancing will entail great difficulties.

TABLE I. Parameters of a Baseline Engine

Parameter	Value
Stagnation pressure loss ratio of air inlet	1,0
Bypass ratio	11
Pressure ratio of the bypass part of the fan	1,54
Efficiency ratio of the bypass part of the fan	0,93
Efficiency ratio of the primary part of the fan	0,91
Efficiency ratio of the medium pressure compressor (MPC)	0,91
Efficiency ratio of the high pressure compressor (HPC)	0,9
Overall pressure ratio of the compressor	56
Stagnation temperature at the turbine inlet	1500 K
Combustion efficiency ratio	0,995
Stagnation pressure loss ratio of combustion chamber	0,955
Relative flow-rate of high pressure turbine (HPT) cooling air	0,08
Efficiency ratio of the HPT	0,925
Relative flow-rate of medium pressure turbine (MPT) cooling air	0,05
Efficiency ratio of the MPT	0,92
Relative flow-rate of low pressure turbine (LPT) cooling air	0,02
Efficiency ratio of the LPT	0,93
Stagnation pressure loss ratio of the bypass ducting	1,0
Velocity retention ratio of the primary nozzle	0,99
Velocity retention ratio of the bypass nozzle	0,99

Table II shows the parameters of six variants of the baseline engine with various levels of elements efficiency and relative flow-rate of the cooling air:

1) Relative flow-rate of the cooling air is two times less;
2) Relative flow-rate of the cooling air is set to zero;
3) Efficiency ratios of the engine elements are increased by 1-2%;
4) Efficiency ratios of the engine elements are set to 1.0;
5) Relative flow-rate of the cooling air is two times less and efficiency ratios of the engine elements are increased by 1-2% simultaneously;
6) Relative flow-rate of the cooling air is set to zero and efficiency ratios of th*e engine elements are set to 1.0 simultaneously.*

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The first, third and fifth variants represent a short-term perspective of the engines' development (5-10 years), the second, fourth and sixth variants represent the extreme performance of the engine elements that would never be achieved, but characterize a long-term perspective.

Table III shows the results of numerical simulation of six variants of the baseline engine and their comparison with efficiency of the baseline engine.

The results lead to the following conclusions.

1) Increasing the efficiency of elements (turbomachinery effectiveness) provide more significant results than decreasing of the cooling air flow-rate for both short-term perspective (5.2% against 2.3%) and the extreme conditions (19% against 3.5%). It should be noted that significant increase in turbomachinery efficiency is hardly probable in a short-term perspective.

2) Uncooled turbines operating at the high temperatures may be suggested as a short-term perspective of gas turbine engine development, as new materials capable of providing long-term operating performance of turbine blades at temperatures of about 2200K are already developed [6, 7]. However, even a complete rejection of the cooling will reduce specific fuel consumption at cruise conditions only by 3.5%.

3) The simultaneous increase in elements performance and decrease in flow-rate of the cooling air would provide the specific fuel consumption enhancement by 6.5 % in a short-term perspective and about 18 % in the extreme conditions

TABLE II. PARAMETERS OF THE TURBOFAN WITH INCREASED EFFICIENCY OF ELEMENTS AND LESS FLOW RATE OF THE COOLING

Parameter	1	2	3	4	5	6
Efficiency ratio of the bypass part of the fan	0,93	0,93	0,94	1	0,94	1
Efficiency ratio of the primary part of the fan	0,91	0,91	0,93	1	0,93	1
Efficiency ratio of the MPC	0,91	0,91	0,93	1	0,93	1
Efficiency ratio of the HPC	0,9	0,9	0,92	1	0,92	1
Combustion efficiency ratio	0,995	0,995	0,995	1	0,995	1
Stagnation pressure loss ratio of combustion chamber	0,955	0,955	0,97	1	0,97	1
Relative flow-rate of HPC cooling air	0,04	0	0,08	0,08	0,04	0
Efficiency ratio of the HPT	0,925	0,925	0,94	1	0,94	1
Relative flow-rate of MPT cooling air	0,025	0	0,05	0,05	0,025	0
Efficiency ratio of the MPT	0,92	0,92	0,94	1	0,94	1
Relative flow-rate of LPT cooling air	0,01	0	0,02	0,02	0,01	0
Efficiency ratio of the LPT	0,93	0,93	0,95	1	0,95	1
Velocity retention ratio of the primary nozzle	0,99	0,99	0,99	1	0,99	1
Velocity retention ratio of the bypass nozzle	0,99	0,99	0,99	1	0,99	1

TABLE III. EFFICIENCY COMPARISON OF THE IMPROVED VARIANTS OF ENGINE WITH A BASELINE ENGINES

Variant	Baseline	1		2		3		4		5		6	
C_{sp}, $\frac{kg}{kN \cdot hr}$	48.47	47.35	-2.3%	46.75	-3.5%	45.97	-5.2%	39.27	-19%	45.26	-6.6%	39.81	-17.9%

III. IMPROVING THE EFFICIENCY OF THERMODYNAMIC CYCLE OF ENGINE

Parameters of the baseline engine remain the same as in the previous section.

Numerical simulation of the engine with gas temperature at the turbine inlet varying from 1500 K to 2500 K and overall pressure ratio ($\pi^*_{c\Sigma}$) varying from 40 to 1200 was fulfilled to examine the potential improvement of the engine cycle. The bypass ratio of all the variants is equal to the value of the baseline engine and the pressure ratio of the bypass part of the fan (characterizing the energy distribution between the primary and secondary flows) is optimized to provide the minimum of specific fuel consumption for each combination of parameters.

Fig. 1 and Table IV show the results of numerical simulation. The pressure ratio of the bypass part of the fan range between 1.4 and 1.85.

Fig. 1 shows that specific fuel consumption has minimum values along both overall pressure ratio (mutual opposite effect of the heat supply decrease and the thermal efficiency increase) and turbine inlet temperature (mutual opposite effect of the elements' losses to heat supply ratio increase and the kinetic energy of jet loss increasing).

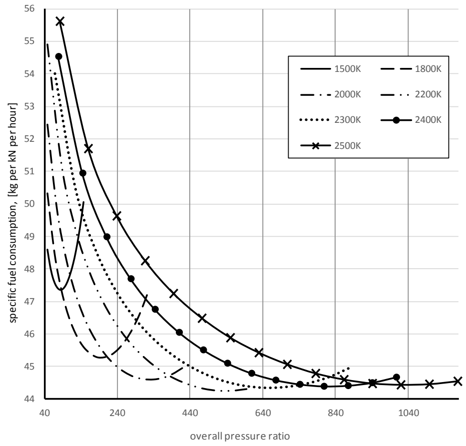

Figure 1. Dependence of turbofan efficiency upon the overall pressure ratio and turbine inlet temperature.

TABLE IV. SPECIFIC FUEL CONSUMPTION OF THE TURBOFAN ENGINE WITH VARIOUS COMBINATIONS OF OVERALL PRESSURE RATIO AND TURBINE INLET TEMPERATURE

T_4^*, K	1500	1500	1800	2000	2200	2300	2400	2500
$\pi_{c\Sigma}^*$	56	84	200	340	530	650	800	1020
C_{sp}, $\frac{kg}{kN \cdot hr}$	48.1	47.35	45.27	44.59	44.24	44.35	44.39	44.42

It should be emphasized that the bypass ratio remained at the same level during the engine thermodynamic cycle examination.

The results lead to the following conclusions.

1) Optimal values of overall pressure ratio and turbine inlet temperature are about 530 and 2200 K respectively (see Table IV). This level of temperature represent a short-tem perspective of engines development, but providing such level of pressure ratio entail great difficulties in terms of both providing high compressor efficiency and its stable operation, and would provide only an 8% of engine efficiency increase.

2) Optimal value of pressure ratio for the baseline engine temperature is about 90 (1.6 times higher) and is possible in a short-tem perspective of engines development, although would provide about a 1.5 % of efficiency increase.

3) Values of specific fuel consumption change slowly around the optimal values of pressure ratio: 1.5 times increased or decreased total pressure ratio leads to less than 1% change in C_{sp}.

IV. IMPROVING THE EFFICIENCY OF THE ENGINE AS A PROPULSION UNIT

Parameters of the baseline engine remain the same as in the previous sections.

Numerical simulation of the wide range of bypass ratio (m) values was fulfilled to examine the potential improvement of the engine cycle. Pressure ratio of the bypass part of the fan (characterizing the energy distribution between the primary and secondary flows) is optimized to provide the minimum of specific fuel consumption for each combination of parameters.

As the thermodynamic cycle substantially influence the optimal values of the investigated parameter, four combinations of total pressure ratio and turbine inlet temperature (see Table V) were examined.

Except for the baseline engine, the total pressure ratios of other combinations were selected in accordance with the results of the previous section:

1) Equal to the baseline engine turbine inlet temperature (but optimal value of $\pi_{c\Sigma}^*$);

2) Turbine inlet temperature of 2000 K (short-term perspective, 5-7 years);

3) Turbine inlet temperature of 2500 K (long-term perspective, 10-15 years).

Fig. 2 shows the results of numerical simulation of the baseline engine, Fig. 3, 4 and 5 - the results of the first, second and third variants respectively.

TABLE V. VARIANTS OF THE THERMODYNAMIC CYCLE PARAMETERS

	baseline	1	2	3
T_4^*, K	1500	1500	2000	2500
$\pi_{c\Sigma}^*$	56	84	340	1020

Table VI shows the comparison of optimal values of bypass ratio for different variants of engine.

TABLE VI. SPECIFIC FUEL CONSUMPTION DECREASE OF THE EXAMINED VARIANTS OF ENGINE IN COMPARISON WITH THE BASELINE ENGINE

T_4^*, K	1500	1500	1500	2000	2500
$\pi_{c\Sigma}^*$	56	56	84	340	1020
m	11	40	35	50	60
C_{sp}, $\frac{kg}{kN \cdot hr}$	48.1	45.21	45.12	40.5	38.43
δC_{sp}	-	-6.0%	-6.2%	-15.8%	-20.1%

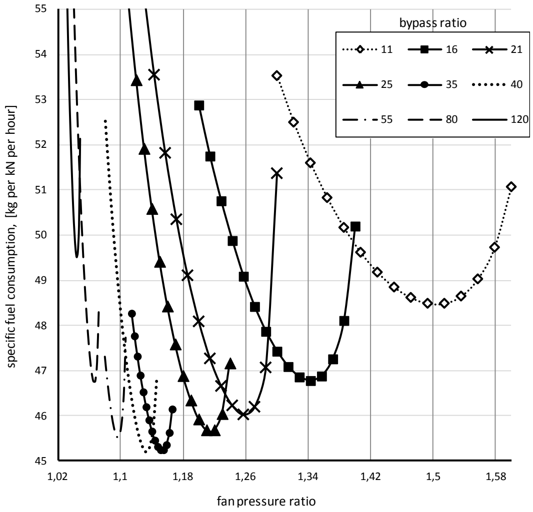

Figure 2. Specific fuel consumption against the bypass ratio and fan pressure ratio (baseline engine).

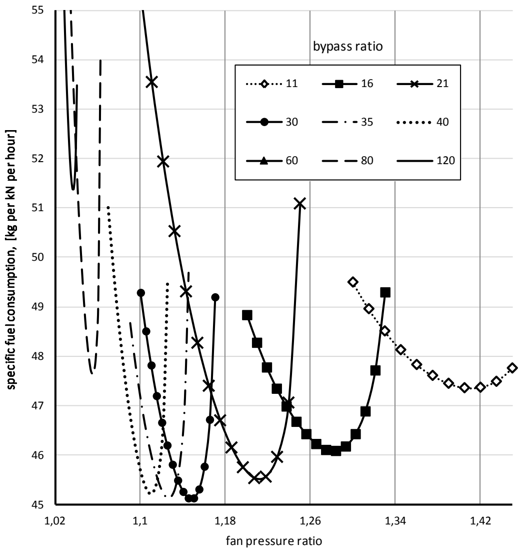

Figure 3. Specific fuel consumption against the bypass ratio and fan pressure ratio (variant 1).

Fig. 2 shows that increasing the bypass ratio from 11 to 40 (with a respective decrease of a fan pressure ratio from 1.54 t o1.14 to provide a uniform energy distribution between the primary and secondary flows) provides the engine efficiency enhancement of 6%.

The results of optimization of the first variant of engine (Fig. 3) show almost the same efficiency level (higher by 6.2%), although the optimal value of bypass ratio is lower (about 35) due to the heat supply decrease because of the total pressure ratio increase.

The optimal values of bypass ratio and fan pressure ratio are 50 and 1.13 respectively for the second variant of the engine (see Fig. 4). These values provide the decrease in specific fuel consumption by 15.8%.

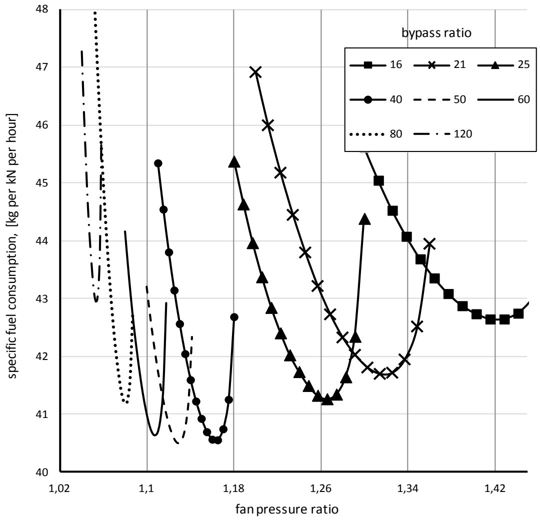

Figure 4. Specific fuel consumption against the bypass ratio and fan pressure ratio (variant 2).

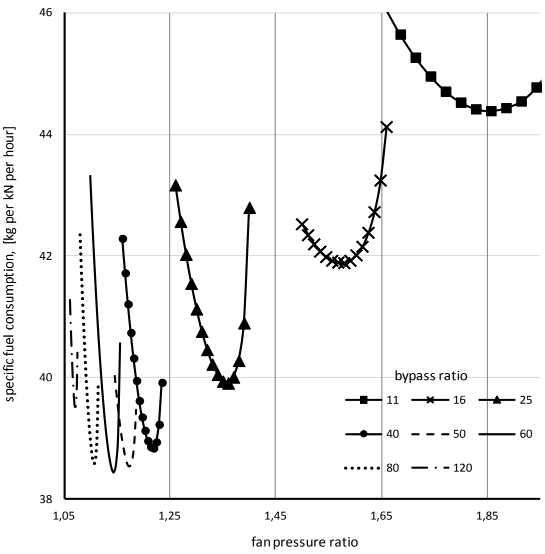

Figure 5. Specific fuel consumption against the bypass ratio and fan pressure ratio (variant 2).

The third variant of engine with optimized parameters is characterized by the bypass ratio of 50, fan pressure ratio of 1.14 and provides the 20% increase of engine efficiency compared with a baseline engine (Fig. 5 and Fig. 6).

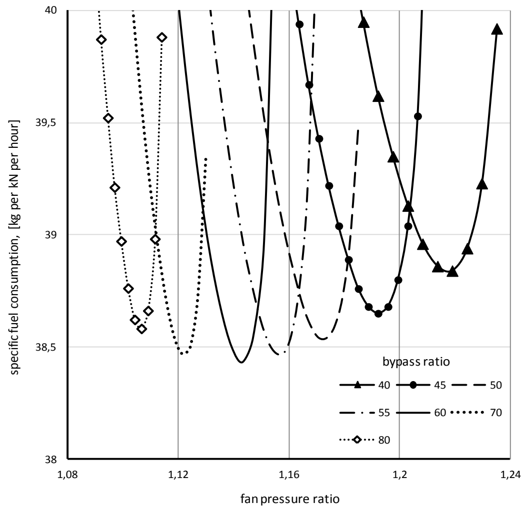

Figure 6. Specific fuel consumption against the bypass ratio and fan pressure ratio (variant 3).

The results lead to the following conclusions.

1) The optimal type of gas turbine engine for the examined altitude and airspeed is a turbopropfan engine (with a bypass ratio of 35…50). Increase in the bypass ratio value would lead to relative decrease of the engine core size (for the same level of thrust), which may lead to the problems of providing the efficiency of high pressure turbomachinery. The diameter of this type of engine may also be higher than the space under the plane wings.

2) Turbopropfan engine with a thermodynamic cycle parameters of a baseline engine would provide a 6% increase in engine efficiency. The thermodynamic cycle parameters corresponding to the short-term perspective jointly with bypass ratio optimization would provide a 15% increase.

3) Values of specific fuel consumption change slowly around the optimal values of bypass ratio: two times less bypass ratio (40 versus 80) provides less than 1% change in C_{sp}.

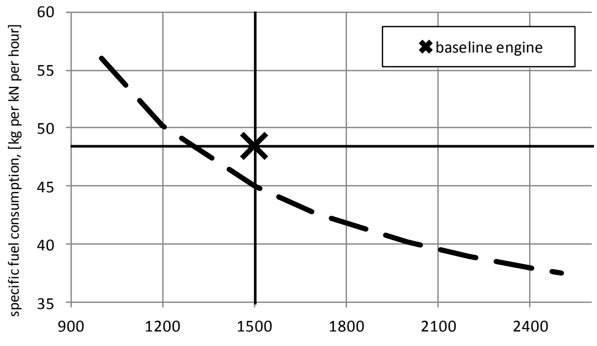

Figure 7. Specific fuel consumption of the optimized engine curve along the turbine inlet temperature.

V. Integrated Approach to the Engine Development

To estimate the efficiency enhancement capabilities of the traditional-cycle turbofan engines series of numerical simulations (with turbine inlet temperature varying from

1000 K to 2500 K) were performed and the following parameters were optimized during these simulations:

- Overall pressure ratio;
- Bypass ratio;
- Pressure ratio of the bypass part of the fan $\pi^*_{\text{fII}opt}$ (characterizing the energy distribution between the primary and secondary flows).

Table VII and Fig. 7-Fig. 8 show the results of these simulations. The value $\delta C_{\text{sp}}^{opt1500}$ shows the relative specific fuel consumption difference from the value of optimized engine with turbine inlet temperature of 1500 K and the value of $\delta C_{\text{sp}}^{baseline}$ shows the relative specific fuel consumption difference from the value of baseline engine.

TABLE VII. OPTIMIZED ENGINE PARAMETERS AGAINST THE TURBINE INLET TEMPERATURE

T_4^*, K	1000	1200	1500	1700	2000	2200	2400	2500
m_{opt}	15.3	23	35.5	46	63	73	85	92
$\pi^*_{\text{fII}opt}$	1.1539	1.1485	1.1496	1.144	1.1424	1.1449	1.1453	1.1425
$\pi^*_{\text{c}\Sigma opt}$	16.94	29.96	60.2	94.5	161	231	322	399
C_{sp}, $\frac{kg}{kN \cdot hr}$	56.03	50.26	45	42.69	40.23	39.01	38.01	37.55
$\delta C_{\text{sp}}^{opt1500}$	24.5%	11.7%	0.0%	-5.1%	-10.6%	-13.3%	-15.5%	-16.6%
$\delta C_{\text{sp}}^{baseline}$	15.6%	3.7%	-7.2%	-11.9%	-17.0%	-19.5%	-21.6%	-22.5%

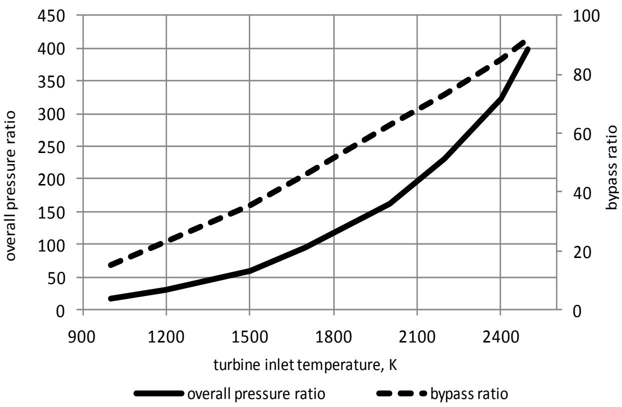

Figure 8. Optimal bypass ratio and total pressure ratio curves along the turbine inlet temperature

The results show that the increase in turbine inlet temperature up to 2200 K with optimization of the other principal parameters (overall pressure ratio, bypass ratio and the fan pressure ratio) would increase the engine efficiency by 19%. It should be mentioned, that providing the corresponding bypass ratio of 60-70 is a serious technical problem to solve. The further increase in turbine inlet temperature would provide only a slight enhancement of the specific fuel consumption (additionally by 2-3 %).

VI. CONCLUSION

1) Improving the efficiency of engine components reduces the specific consumption by 5% in the short-term, and approximately by 20% in the extreme case; however, the limit value is unreachable.

2) Reducing the cooling air flow-rate in two times increases the efficiency of the turbofan by 2.3%, and the exclusion of cooling 3.5%. This way does not provide a significant decrease in specific consumption, but achievable in the short-term perspective by use of advanced materials.

3) Increase in parameters of the engine thermodynamic cycle improves the efficiency by about 8% for the current bypass ratio value. It should be noted that the optimal value of the turbine inlet temperature is attainable in the short-term (2200K), while the optimal value of the total pressure ratio is about 500; providing the gasdynamic stability and high efficiency of the compressor (especially during the transient conditions) entails considerable difficulties, so it is unlikely that such a value would be reached within the next decade. Increase in parameters of the engine thermodynamic cycle is more reasonable in connection with bypass ratio optimization.

4) The optimal value of bypass ratio for the examined altitude and flight speed is about 35-55 and corresponds to the turbopropfan engine. Optimization of the bypass ratio would increase the efficiency of modern engines by 6%, by 15% for the short-term perspective (5-10 years) and by 20% for the long-term.

5) Integrated approach to the engine development is the most reasonable way to enhance the efficiency of gas turbine engines: it provides the capabilities to decrease the specific fuel consumption by 17-19% in a short-term perspective (turbine inlet temperature of about 2000-2200 K). The further increase of the working process parameters doesn't provide substantial increase in engine efficiency.

6) The bypass ratios optimal for the turbine inlet temperatures higher than 1800 K correspond to the turbopropfan engine (considering the traditional schemes of gas turbine engines). However, one of the possible ways to provide bypass ratios of 60-70 is the use of distributed propulsion, including integrated into the airframe [8], [9].

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