

Influence of Thrust Level on the Architecture and Optimal Working Process Parameters of a Small-scale Turbojet for UAV

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Abstract. This article describes how the thrust level influences the turbojet architecture (types of turbomachines that provide the maximum efficiency) and its working process parameters (turbine inlet temperature (TIT) and overall pressure ratio (OPR)). Functional gasdynamic and strength constraints were included, total mass of fuel and the engine required for mission and the specific fuel consumption (SFC) were considered optimization criteria. Radial and axial turbines and compressors were considered. The results show that as the engine thrust decreases, optimal values of working process parameters decrease too, and the regions of compromise shrink. Optimal engine architecture and values of working process parameters are suggested for turbojets with thrust varying from 100N to 100kN. The results show that for the thrust below 25kN the engine scale factor should be taken into the account, as the low flow rates begin to influence the efficiency of engine elements substantially.

1. Introduction

Small-scale gas turbine engines are widely used as a source of mechanical energy or propulsion for electric generators, power plants, UAVs (cruise missiles and target aircraft), auxiliary power units, etc [1, 2].

Design process of a gas turbine engine sometimes spreads over 8-10 years and begins with conceptual design stage: setting the engine architecture and values of working process parameters. This problem is usually solved using multi-criteria optimization.

As the size (thrust level) of small-scale engines decreases, so does the size of engine blades (vanes) and other characteristic sizes. Thus, the Reynolds number decreases, the relative axial/radial clearances and thicknesses increase and the relative boundary layer thickness increases as well. This impairs the efficiency of turbomachinery and finally the efficiency of engine [3]. Therefore, the first task of this investigation is to determine the value of engine thrust to begin taking the sizing factor into the account.

Radial turbomachinery is affected by the scale factor to a much lower extent, but generally have less efficiency. Finding the trade-off point (in terms of thrust) between these factors for both compressors and turbines is the second task.

2. Problem setting



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This investigation is based on the results of multi-criteria optimization of the working process parameters (turbine inlet temperature T_4^* and overall pressure ratio of the compressor $\pi_{c,2}^*$) of turbojet (as a propulsion unit of UAV) with thrust varying from 100 N to 100 kN.

Axial/axicentrifugal/centrifugal compressors and axial/radial turbines were examined for each value of thrust, thus providing the following engine architectures: centrifugal compressor + radial turbine (CC+RT), centrifugal compressor + axial turbine (CC+AT), axicentrifugal compressor + axial turbine (ACC+AT), axial compressor + axial turbine (AC+AT).

As engine thrust decreases, correction to the compressor and turbine efficiency was made depending on the type of turbomachine and the mass flow rate as described in [1, 4, 5].

As the turbojet is an element of higher-level system, aircraft efficiency criteria should be used as optimization criteria. Total mass of fuel required for mission and engine M_{g+f} and the fuel consumption per ton of payload per km of distance C_{t*km} are usually used describe the efficiency of aircraft in terms of mass and fuel efficiency. Both C_{t*km} and SFC provide similar results of optimization for a long-distance missions, thus the SFC was considered an optimization criterion for this investigation.

The following gasdynamic and strength constraints were taken into account: height of blades at the exit of compressor (Hc), height of blades at the inlet of turbine (Ht), circumferential velocity at the compressor blade tips (Uc), turbine pressure ratio (π_t^*), turbine inlet temperature at take-off mode ($T_{4,0}^*$). Impossibility to satisfy the constraints was the indicator for changing the architecture of engine. Principal design data of the turbojet and aircraft is shown in table 1.

Table 1. Principal design data

Parameter	Description	Value
$F\{cr\}/F\{t.o\}$	Cruise to take-off thrust ratio	0,5
H	Altitude, km	0,8
M	Mach number	0,85
$L\{f\}$	Flight range, km	2000
$\eta^*\{pol.c.b\}$	Baseline value of compressor polytrophic efficiency	0,86
$\eta^*\{t.b\}$	Baseline value of turbine efficiency	0,86
$H\{cf\}$	Minimal height of the centrifugal compressor blade, m	0,005
$H\{c.ax\}$	Minimal height of the axial compressor blade, m	0,01
$H\{t.ax\}$	Minimal height of the axial turbine blade, m	0,01
$U\{c\}$	Maximum circumferential velocity of the compressor, m/s	600
$\pi\{t\ max\}$	Maximum value of turbine pressure ratio	3

3. Results of optimization

Results of optimization were obtained using the computer-aided system ASTRA, developed at the Samara national research university and are listed in table 2. The computer-aided system ASTRA [6, 7] has built-in optimization module, which was used to obtain the results described in this article. If the optimization problem includes more than 10 variables, use of specialized design optimization software (e.g. IOSO [8, 9]) would be more effective.

For each value of thrust the locally optimal regions were determined. The value of deviation was set to 2%, ensuring the intersection of locally optimal regions while satisfying the constraints. The optimal point was determined at the trade-off area as equally spaced from the locally optimal points and having minimal value of $T_{4,0}^*$ (as providing higher TIT is more complicated task than providing higher OPR values). The results for thrust of 1kN are shown in figure 1 (the optimal point is marked with “x”).

The figure 2, 3 shows the influence of thrust value on the optimal regions for the M_{e+f} and SFC (C_{sp}) criterion. The results show that for a given aircraft parameters and mission the optimal regions shrink with the decrease of thrust.

The optimal engine architectures for a set of thrust ranges were identified:

- 0.1-0.7 kN – centrifugal compressor and radial turbine;
- 0.7-1.3 kN – centrifugal compressor and axial turbine;
- 1.3-7 kN – axicentrifugal compressor and axial turbine;
- 7-100 kN – axial compressor and axial turbine.

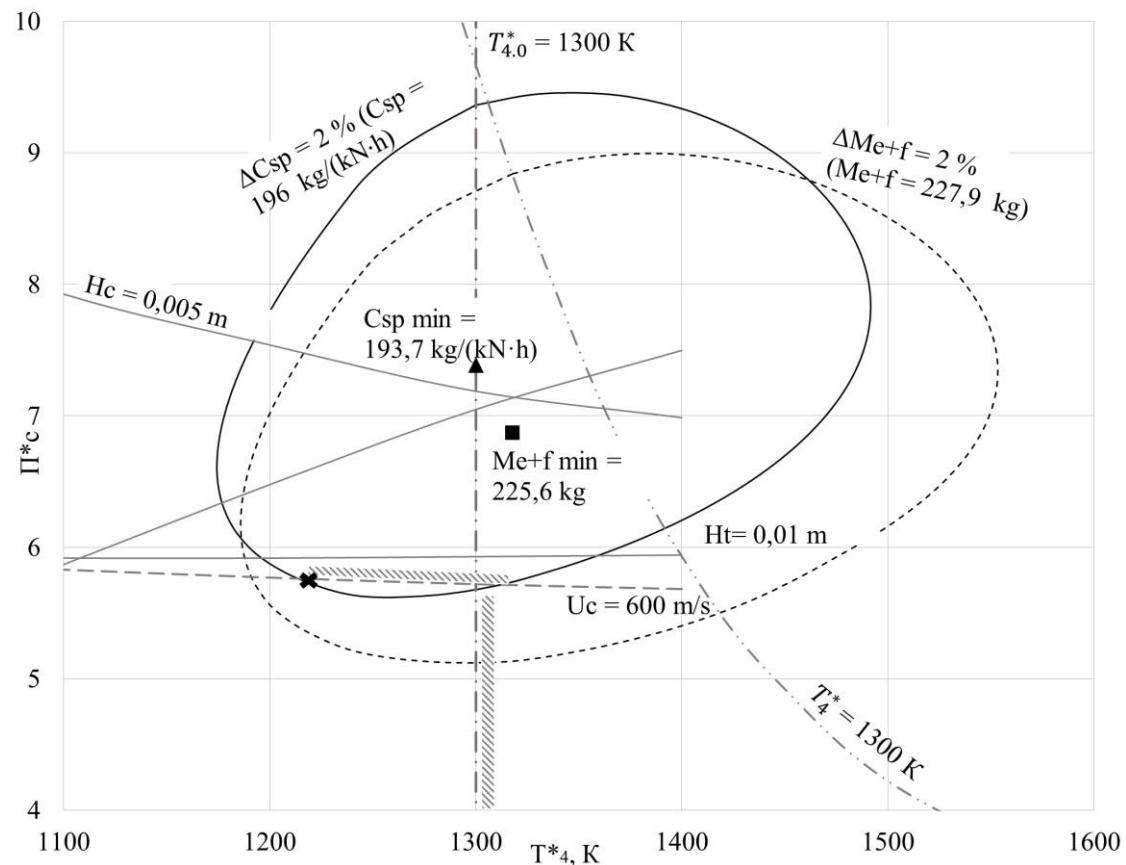


Figure 1. Locally optimal regions, constraints and optimal point for the turbojet with 1 kN of thrust (CC+AT architecture).

The optimal values (using both criteria) of overall pressure ratio and turbine inlet temperature against thrust values are shown in figure 4 and 5.

Table 2. Results of optimization for the thrust values from 0.1 kN to 100 kN

F	π_{cI}^*	$T_{4,0}^*$	$G_{a.sp,0}$	M_{e+f}	C_{sp}	$C_{sp,0}$	Compressor	Turbine
kN		K	kg/s	kg	kg/(kN*hr)	kg/(kN*hr)		
0,1	2,7	1160	0,24	35,5	295	173	centrifugal	radial
1	5,4	1225	1,64	230	199	118	centrifugal	axial
2	7,5	1275	3,03	418	181	108	axicentrifugal	axial
10	13,5	1325	13,8	1882	154	93,9	axial	axial
25	15,8	1335	34,3	4613	149	90,9	axial	axial

50	16,7	1345	68,2	9183	148	90,3	axial	axial
75	16,8	1347	102	13761	148	90,2	axial	axial
100	16,9	1350	136	18338	148	90,2	axial	axial

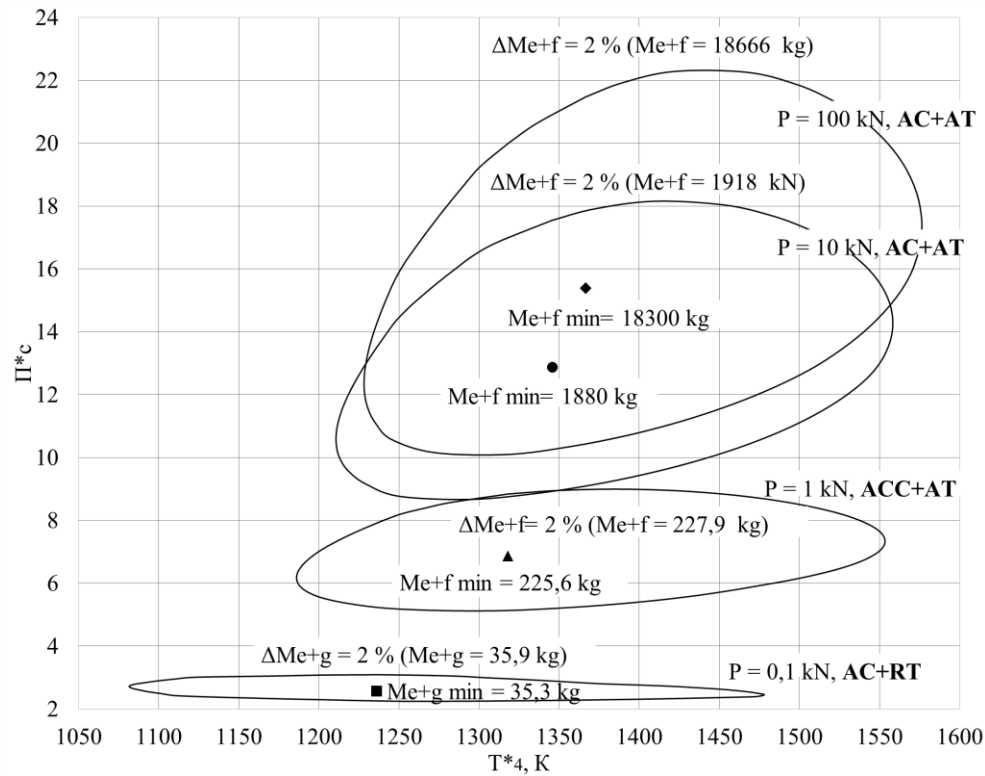


Figure 2. Influence of turbojet thrust on the locally optimal regions for the M_{g+f} criterion.

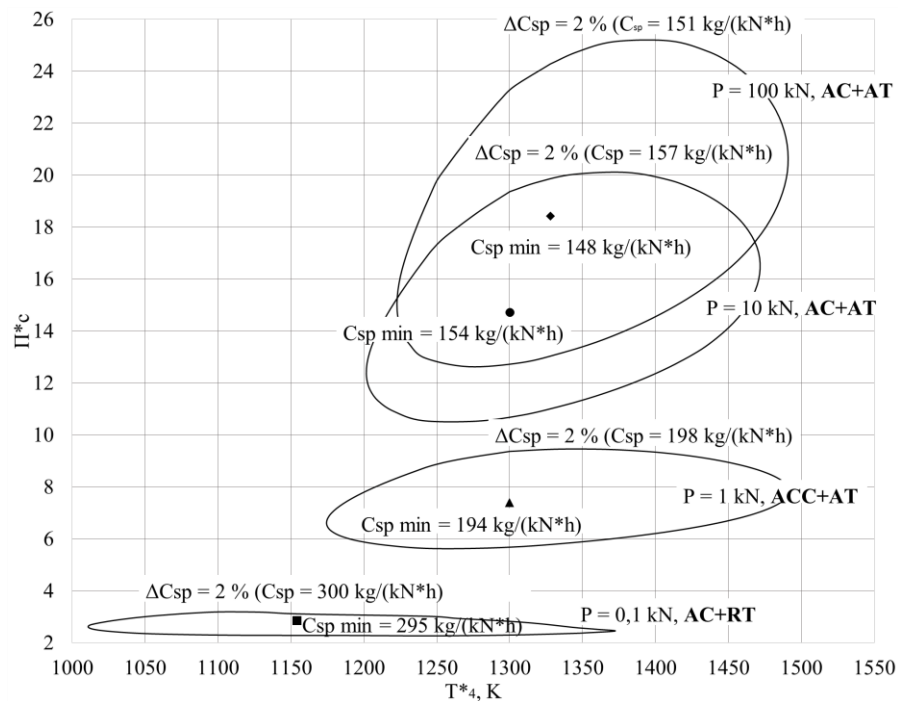


Figure 3. Influence of turbojet thrust on the locally optimal regions for the C_{sp} criterion.

4. Conclusions

As the thrust of turbojet at the take-off conditions decreases from 100kN to 0.1kN, the optimal value of overall pressure ratio becomes 6 times less and the turbine inlet temperature becomes 10-15% less and the locally optimal regions shrink as well.

The results of optimization with and without taking the correction into the account show that the engine scaling factor should be taken into account for the thrust values of 25 kN and lower.

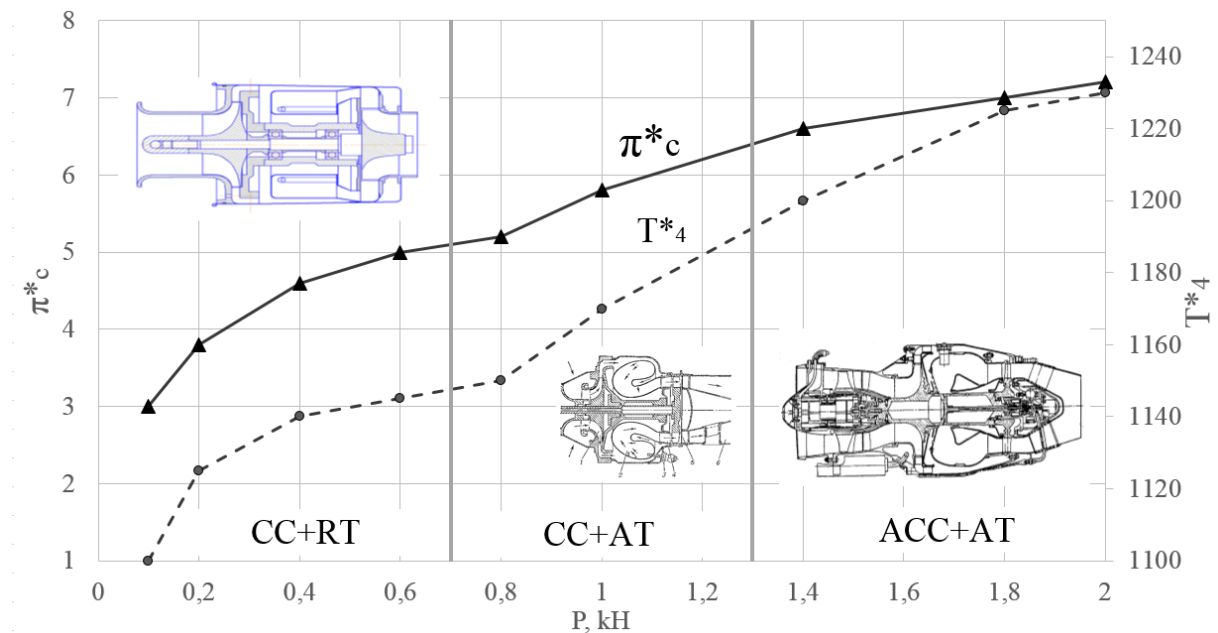


Figure 4. Optimal values (multi-criteria) of OPR and TIT and engine architectures of turbojets, thrust from 0,1 to 2 kN

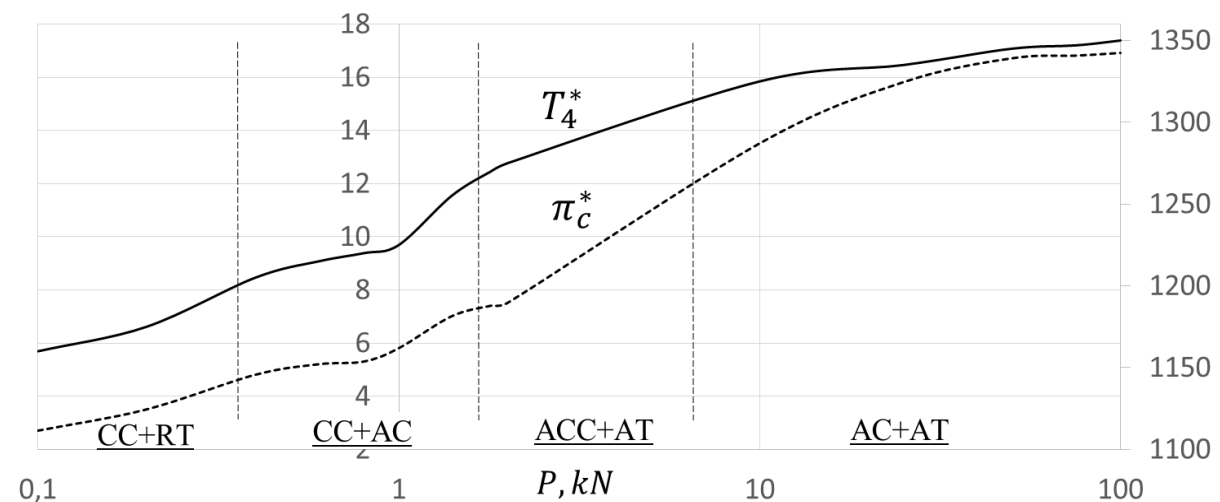


Figure 5. Optimal values (multi-criteria) of OPR and TIT and engine architectures of turbojets, thrust from 0,1 to 100 kN

The results of this investigation may be used to identify the optimal engine architecture for a given value of thrust. Axial compressor is optimal for thrust of 7 kN and higher, and as the thrust decreases, axicentrifugal compressor becomes more appropriate down to the 1.3 kN of thrust. For the thrust

lower than 1.3 kN centrifugal compressor provides higher efficiency. Axial turbine is effective down to the 0.7 kN of thrust, and radial turbine – for smaller engines. It should be noted that these results correspond to the turbojet as a propulsion unit of cruise missile.

Acknowledgments

This work was supported by the Ministry of education and science of the Russian Federation in the framework of the implementation of the Program of increasing the competitiveness of Samara University among the world's leading scientific and educational centers for 2013-2020 years.

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