Thermodynamic designing of the small-scale gas turbine engine family with common core

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Abstract. The paper describes the method of selecting the working process parameters of a family of small-scale gas turbine engines (GTE) with common core. As an example, the thermodynamic design of a family of small-scale gas turbine engines (SGTE) with common core was carried out. The engine family includes a small-scale turbojet engine (STJE) and a gas turbine plant (GTP), which electric generator is driven by power turbine. The selection of rational values for the working process parameters of STJE and GTP was carried out in CAE system ASTRA on the basis of nonlinear optimization of these parameters, taking into account functional and parametric constraints. The quantitative results of deterioration in the performance of the engines of the family with common core are obtained in comparison with the engines with the optimum core for each type. However, the advanced creation of a common core can reduce the cost and timing of the engine creation, ensure its higher reliability (due to the development of the base common core) and reduce the cost of its production. The method of selecting the parameters of the working process of the GTE family with common core presents the solution to more complex problems, such as the possibility of developing a family consisting of five engines: a turbojet engine, turbofan engine, turbofan engine with a complex cycle, GTE with power turbine (GTE-PT), GTE-PT with recovery.

1 Introduction

The designing of a modern gas turbine engine "from the scratch" requires a large financial cost and it takes from 7 to 15 years to complete. In the face of ever-increasing demands for efficiency and increasing competition, this approach is unacceptable. The engine will turn out to be technically obsolete and uncompetitive both in its characteristics and in its cost.

One of the solutions to this problem is the advanced creation of a common core, on the basis of which it is possible to create a family of gas turbine engines with a wide range of applications covering the needs of aircraft and industrial enterprises. This allows shortening the time of release of new equipment, increasing its reliability and reducing the cost.

It is obvious that GTE with common core in terms of efficiency will be somewhat worse than the optimal gas turbine engine, designed for a particular purpose with optimum core. In this case, the difference in characteristics will be the greater, the wider the scope of application of the family of engine designs. For example, a turbofan engine (TFE) for medium-and long-haul aircrafts with common core has fuel consumption on one ton payload per kilometer higher by 3.6 and 10.9%, respectively, than optimal for these aircrafts analogues [1]. When designing the turbofan, turboprop and turboshaft engines using core of turbofan engine, the specific fuel consumption of turboprop and turboshaft engines is higher by minimum 5.6% and 23% [2] compared to the optimum engine.

The peculiarity of designing engines based on common core is the need to take into account a much larger number of constraints, and the number of constraints will be greater the higher the level of unification.

According to the research by Bradbrook [3], the unification of the engines can be multilevel and reach 5 levels. The 0th level is the level of the least unification, and the 4th level are the engines that have the common layout, the turbomachinery of the same scale and with the same aerodynamics and design, which are manufactured on the same production area using same rigging and workpieces. The engine parts at the 4 level of unification have the same catalog numbers.

2 Problem statement

In this paper, an example of the search for rational parameters of the working process for a small-scale turbojet engine (Fig. 1) with maximum thrust of 1.5 kN in bench conditions at air standard conditions and for a gas turbine unit for driving an electric generator (Fig. 2) with a power of 250 kW with common core. Unification of the common core corresponds to 3-4 levels, i.e. compressors and combustion chambers are identical, and the turbines are slightly different. According to the classification of the gas turbine engine in accordance with the dimensions given in [4], engines with air flow rate through the main duct from 1 to 10 kg/s, which corresponds to the flow rate referred to the parameters after the compressor of 0.25...1.5 kg/s are related to small-scale engines.

The selected engine parameters must correspond to the core scheme with a centrifugal compressor (CC) and an axial turbine (AT). The turbine of the core must be uncooled (intended use of the STJE is to ensure its lowest cost, and, consequently, simplification of the engine design).

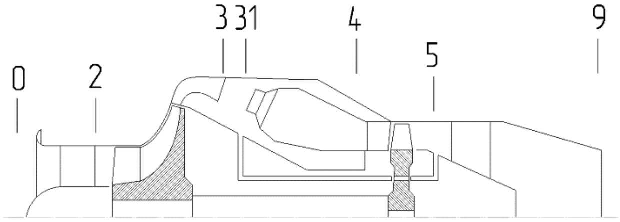

Figure 1. Structural design of STJE.

The selection of the most rational parameters of the engine working process is one of the most important tasks of the GTE conceptual design. The generalized statement of the task of selecting the parameters of the working process of the GTE family with common core is the following [5]: it is necessary to determine the rational values of the working process parameters of the common core for the GTE family and the parameters of the working process of each of the engines of this family. The required parameters should ensure the maximum possible efficiency of the projected engines in terms of a set of engine evaluation criteria in a higher hierarchical level system, for example, an aircraft, when performing a specified set of functional and parametric constraints.

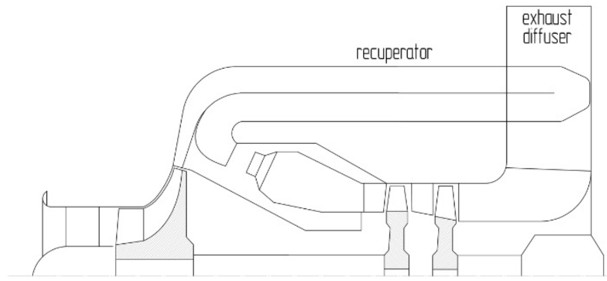

Figure 2. Structural design of GTU.

The multicriteria task of selecting the working process parameters of the GTE family with a common core can be mathematically formulated as follows:

$$\Omega = \arg\left\{ \min_{X_j} \max_{Z_k} \left[\min_{X_l} \max_{Y_i} \delta Y_{jkli} \middle| q_{jl}\left(X_j, X_l, b\right) \le 0 \right] \middle| Q_j\left(X_j, b\right) \le 0 \right\},$$

where $Y_i = \{C_{f.km}, M_{pp+f}, a, C_f \ldots\}$ – a set of criteria for the effectiveness of the GTE in the aircraft system or another system that includes the engine ($C_{f.km}$ – fuel costs per ton-kilometer of cargo carried; M_{pp+f}, – total mass of the power plant and fuel; a – cost of transportation; C_f – effective fuel consumption);

$X_l = (\pi^*_{airII}, m, \pi^*_{LPC})$ – vector of optimized parameters of the engine working process (π^*_{airII} – pressure ratio in the fan of the external duct; m – bypass ratio;
π^*_{airII} – pressure ratio in the low-pressure compressor);

$Z_k = \{TFE_1, TFE_2, \ldots, GTP_1, \ldots\}$ – set of family engines;

$X_j = (\pi^*_{c\,core}, T^*_{4\,ref\,in\,core}, G_{a\,ref\,in\,core})$ – the vector of optimized parameters of the core working process ($\pi^*_{c\,core}$ – pressure ratio in the compressor of the core, $T^*_{4\,ref\,in\,core}$ – temperature of the gas at the inlet to the turbine, referred to the parameters in the cross section at the inlet to the core, $G_{a\,ref\,in\,core}$ – the air flow rate through the core, referred to the parameters in the section at the inlet to the core);

$\delta Y_{jkli} = \dfrac{Y^*_{ki} - Y_{jkli}}{Y^*_{ki}} \cdot \rho_k \rho_i$ – normalized value of the efficiency criterion (Y^*_{ki} – the value of the efficiency criterion for optimization by a particular criterion, ρ_k – coefficient of "weight" of the engine in the family; ρ_i – coefficient of "weight" of the *i-th* criterion);

$q_{jl}\left(X_j, X_l, b\right)$ – constraints when optimizing the engine parameters;

$Q_j\left(X_j, b\right)$ – constraints in the optimization of core parameters;

b = (efficiency of components, loss coefficients in components, etc.) is a vector of dependent variables and initial data.

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b = (efficiency of components, loss coefficients in components, etc.) is a vector of dependent variables and initial data.

With this formulation, two nested optimization problems are solved: optimization and selection of rational parameters of the common core for the entire engine family and optimization of the parameters of each family engine using the specified common core [6].

3 Materials and methods

The solution of the task of selecting the working process parameters of the GTE family with common core consists of the following main stages:

1. Determination of efficiency criteria Y_{ki}^* when optimizing the parameters of the working process of each engine from the set Z_k (including core parameters) by each performance criterion from the set Y_i.
2. Determination of the efficiency criteria Y_{jkli} of each engine from the set Z_k by each performance criterion from the set Y_i with the parameters of the common core working process X_j and the parameters of the engine working process X_l (for example, a turbofan for a TFE).
3. Determination of the normalized values of performance criteria δY_{jkli}.
4. Optimization of the working process parameters of the common core X_j and the parameters of the engine working process X_l. Checking constraints q_{jl} and Q_j.

In general, the algorithm for selecting the working process parameters of the GTE family with a common core is shown in Fig. 3.

A similar method for modeling a family of engines with common core is used in [2]: at the first stage, a design calculation of the core parameters is carried out, and then each engine of the family with a common core is calculated. The use of one platform in the general case and a core in particular is also considered in [6, 7, 8]. In presented in the paper formulation, in general, in contrast to [2], the selection of a rational solution is made on the basis of optimization of the parameters of both common core and the engine of the family.

4 Selection of the working process parameters of the STJE and GTP

Optimization and selection of rational values for the parameters of the working process of STJE and GTP were carried out in the CAE system ASTRA [9]. According to the methodology of optimal design, the optimization criterion must reflect the quality index of a higher level system. As optimization criteria, specific fuel consumption (SFC) C_{sp} was selected for STJE as an analogue of the system criterion of fuel efficiency (fuel consumption per ton-kilometer of the transported payload). For GTP, effective efficiency η_e was selected. The optimized design variables in this case are the pressure ratio in the compressor π_c^* and the gas temperature before the turbine T_4^*.

The initial data for designing a family of engines are presented in Table 1.

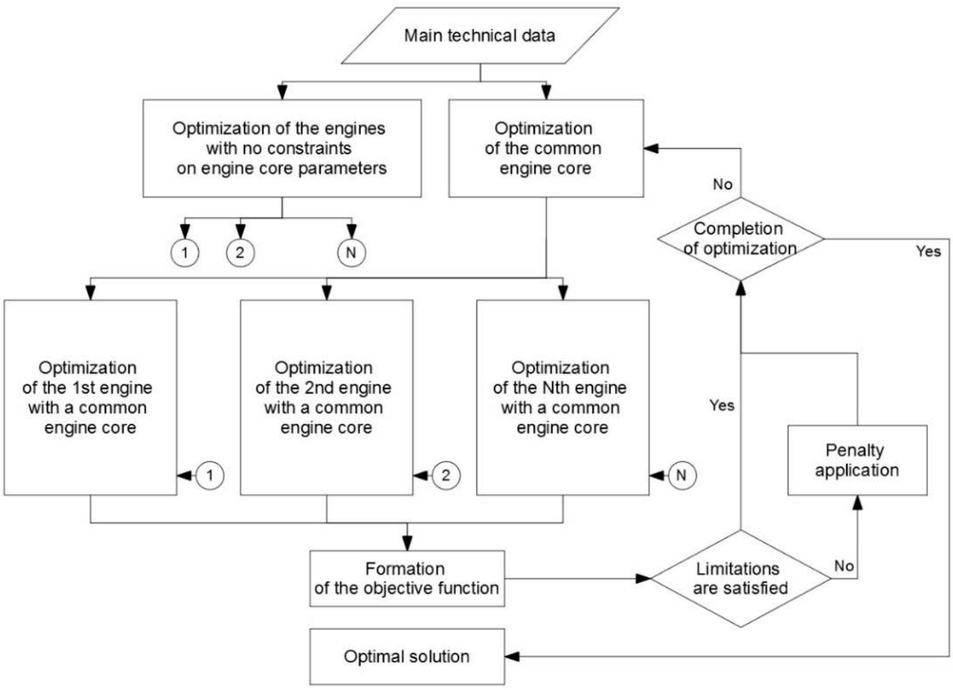

Figure 3. Algorithm of the method of selecting the working process parameters of the GTE family with common core.

Constraints π^*_{ct} and T^*_4 are introduced to make the gas turbine as single-stage and uncooled. Due to the limitation of G_a, the diametrical size of the engine is kept in the required range.

Table 1. Initial data for designing STJE and GTP.

Parameter	Name	Value	
		STJE	GTP
σ_{in}	Total pressure recovery coefficient in the inlet system	0.99	
$\eta^*_{p.cc.base}$	The base value of the polytropic efficiency of the compressor	0.87	
η_c	Fuel combustion efficiency	0.98	
$\eta^*_{p.ct.base}$	The base value of the efficiency of the core turbine	0.90	
$\eta_{m.ct}$	Mechanical efficiency of core turbine	0.99	
σ_{he}	Total pressure recovery coefficient in the heat exchanger duct	—	0.95
$\theta_{th.r}$	Thermal ratio in heat exchanger	—	0.85
$\eta^*_{pt.base}$	The base value of the efficiency of a power turbine	—	0.91
$\eta_{m.pt}$	Mechanical efficiency of a power turbine	—	0.99
η_{eg}	Efficiency of the electric generator	—	0.97
φ_{jn}	Velocity coefficient of the jet nozzle	0.98	0.70
$g_{cool.rot.core}$	The relative value of the air bleeding for cooling the rotor of the core	0.02	
π_{na}	Available gas expansion ratio in the nozzle duct	—	1.03
P_{ref}	Maximum thrust in bench conditions at air standard conditions	1.5 kN	—
N_{eg}	GTP power for electric generator drive	—	250 kW

Optimization of the working process parameters of STJE and GTP is carried out according to two criteria min SFC C_{sp} and max η_e, respectively.

Regions of locally optimal parameters are formed for each of the criteria, corresponding to the deviations of the optimization criteria from their optima (by 5, 10, 20%):

$$X_i = \left\{ x \mid Y_i\left(x_i^{opt}, p\right) \le Y_i\left(x\ p\right) \le \left(\ + \delta Y_i\ \ \rho_i\right) Y_i\left(x_i^{opt}\ p\right) \right\}$$

where $\delta Y_i = (Y_i\left(x, ?p\right) - Y_i\left(x_i^{opt}\ ?p\right)\ / Y_i\left(x_i^{opt}, ?p\right)$ – specified relative deviation of the optimization criterion from the optimal value (criterion tolerance);

ρ_i – coefficient allowing to take into account the degree of importance (significance) of the *i-th* criterion $(0 < \rho_i \le 1)$;

p – vector of initial design data.

The area of trade-offs (Fig. 4) is defined as the intersection of regions of local optimal parameters, taking into account constraints on design variables and functional limitations:

$$X_{\cap} = \bigcap X_i \mid q\left(x, ?p\right) \le\ \ ; ?a_j \le x_j \le b_j ,$$

where a_j, b_j – constraints on design variables;

$q(x,p) = \{T^*_4, \pi^*_{ggt}, G_a\}$ – set of functional constraints.

From the area of compromises, taking into account the constraints, the most rational solution is chosen with minimum values of the gas temperature and pressure ratio in the compressor $X^*_{\cap} \in X_{\cap}$ (RT point). Fig. 5 also shows the set of Pareto-optimal solutions. The point OT corresponds to the minimax principle of optimality.

Table 2 shows the results of a comparison of the performance of family engines with a common core and with cores that are optimal for each engine.

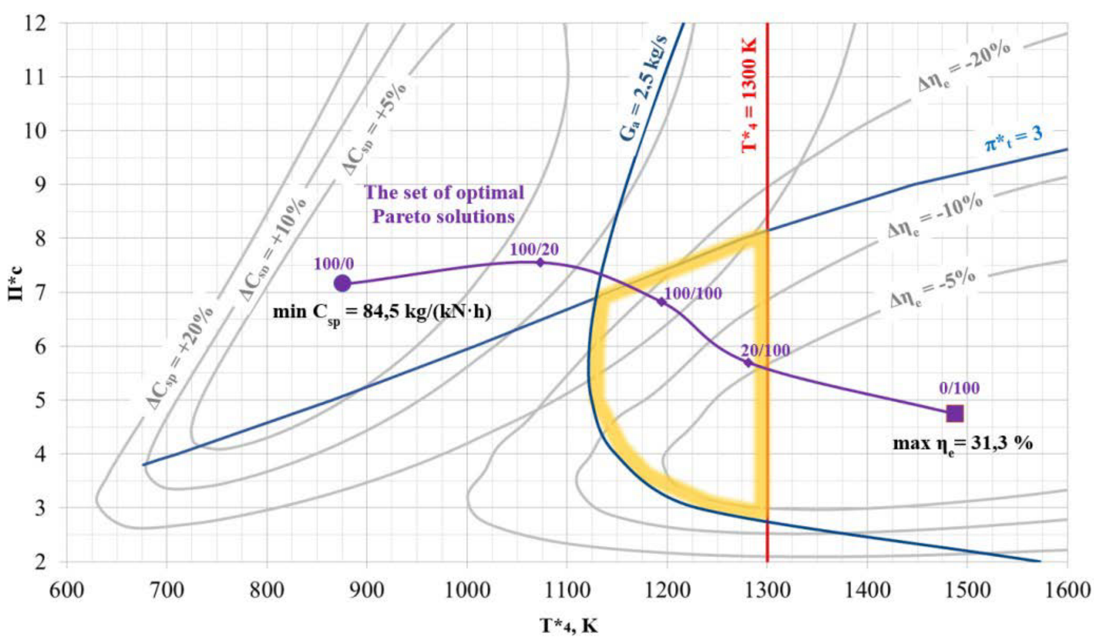

Figure 4. Region of optimal parameters of STJE and GTP.

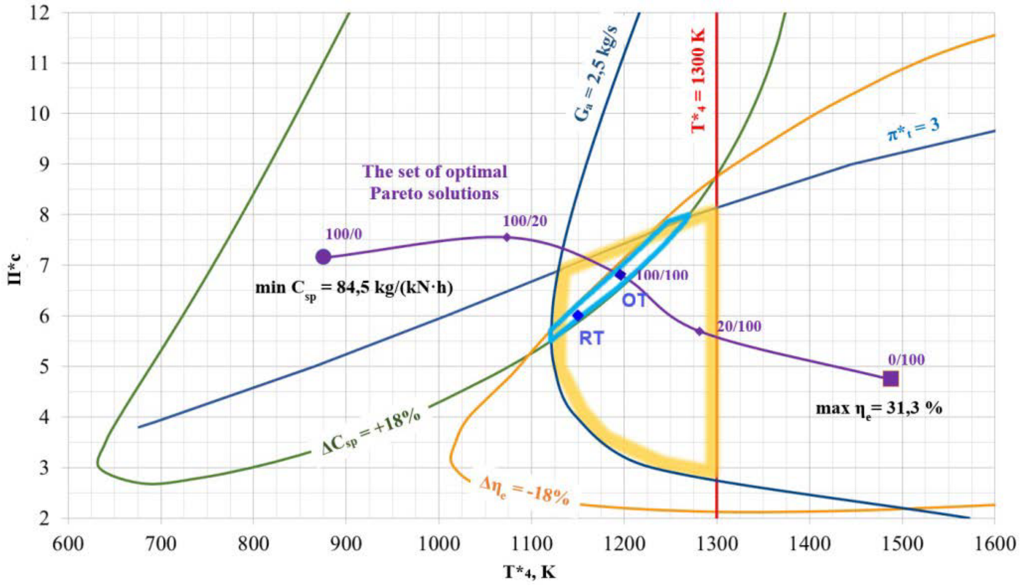

Figure 5. Region of rational parameters of STJE.

Table 2. Measures of efficiency of STJE and GTP with common and optimal core.

Parameter	STJE		GTP	
	Optimal core	Common core	Optimal core	Common core
T_4^*, K	876	1150	1403	1057
π_c^*	7.1	6.0	3.9	6.0
$G_{a\,ref\,in\,core}$, kg/s	4.1	2.42	1.9	2.42
η_e	—	—	0.31	0.26
C_{sp}, kg/(kN·h)	84.5	100.0	—	—

5 Conclusion

A method for selecting rational parameters for the working process of a family of small-scale GTE with a common core based on nonlinear multi-criterion optimization under constraint conditions is proposed. The method allows to simultaneously optimize both the parameters of the core and the engine. As an example, the results of optimization and selection of the working process parameters of small-scale TJE and GTP are given. The obtained results show that the rational parameters of the working process of the STJE and GTP turned out to be 18% worse than their optimal variants. However, the advanced creation of a common core can reduce the cost and timing of the creation of the engines, ensure their higher reliability (due to the development of the base core) and reduce the cost of their production. The method of selecting the working process parameters of the GTE family with common core presents the solution to more complex problems, such as the development of a family consisting of five engines: a turbojet engine, turbofan engine, turbofan engine with a complex cycle, GTE-PT, GTE-PT with recovery.

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