Numerical simulation of an influence of a compressor and a turbine on characteristics of a combustion chamber of a small-sizes gas turbine engine

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Abstract. The objective of the presented study is an investigation of gas turbine engine's (GTE) combustion chamber (CC) characteristics with a consideration of a compressor and a turbine by means of numerical simulation. Combustion chamber of GTE determines its basic characteristics, therefore, an accurate calculation of its operating procedure is of great importance. However, nowadays, an accuracy of combustion chambers' calculation is limited by a number of factors. In particular, those are problems associated with the correct setting of operation parameters at an inlet and an exhaust of a combustion chamber. At the time of beginning of a combustion chamber's calculation, data on nature of parameters' change after a compressor is often unknown. Therefore, as a general rule, researchers specify them in a form of a uniform distribution over a cross-section. At the same time, the way how it influences combustion chamber's characteristics is unknown. The same can be said about parameters at a turbine's inlet. A verification by means of numerical simulation of a presence or an absence of an influence of parameters' distribution after or before a compressor on a combustion chamber's characteristics is impeded by a need to ensure a harmonization of geometric and grid models of calculated areas, as well as by a number of conditions, such as a harmonization of revolutions of rotors of a turbine and a compressor. In the presented study the objective of an investigation of an influence of parameters after a compressor and before a turbine on CC characteristics was achieved in a consecutive manner. Initially, a calculation was performed for a combustion chamber with a specified input and output parameters in a form of diagrams with average values of parameters. As a results, basic characteristics of a combustion chamber are obtained. It is established, that taking into account a turbine and a compressor changes a distribution of parameters in a combustion chamber and influences its performance. On a basis of results of the conducted study, a new methodology for a design of a combustion chamber is proposed.
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Introduction

A combustion chamber (CC) is one of the most important parts of a gas turbine engine (GTE). It defines GTE's main characteristics, as well as guarantees a stable and reliable operation. Traditional methods of CC characteristics calculation, so far, do not allow to solve all existing problems related with its design [1-3]. Using those methods, integral distribution parameters for a calculated cross-sections are obtained, whereas for a designer it is important to know also individual, local values of calculated parameters [4, 5]. A search for opportunities to address that problem, a complexity of calculations during a design of CC and a desire to reduce time of its fine-tuning, has led to an increased use of three-dimensional numerical simulation methods [6, 7]. Technologies of such calculations at present time are not worked through enough because of a lack of an accurate mathematical description of physical processes, occurring in CC and an insufficiency of data on a verification of results [8]. In order to ensure a reliability of numerical simulation, a long period of time and a development of new effective methods is still necessary.

Methodology

In the presented study a technology of numerical modeling an operating procedure of CC as a part of GTE’s gas generator is used. It consists of following major stages [8]:

– setting of goals and objectives of modeling;
– a determination of assumptions and a selection of a calculated area's borders;
– a creation of geometric models of a calculated area for each units, pertaining to a gas generator;
– a discretization of a calculated area's geometry for each element by finite element grid;
– an assignment of boundary conditions and a description of links between the borders of units.
– calculation, processing and analysis of obtained results .

As a study object a small-sized GTE (CGTE) with a counter-flow CC was selected. Its layout is presented in figure 1. *Gaseous methane (CH_4) was used as fuel, oxidizer is atmospheric air.*

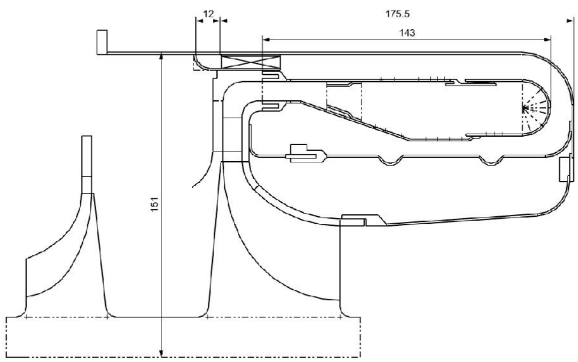

Figure 1. Layout of CGTE

In order to reduce time expenditures, not an entire combustion chamber volume, but a specially assigned periodic sector was selected as a calculated area. It is limited by longitudinal planes, located at angle of 45 ^{0} to each other. Grid model, which was generated on a calculated area, is three-dimensional, unstructured, with total number of elements qual to 4.5 million.

Calculations were performed in ANSYS Fluent software package. In order to ensure desired quality of grid model, its condensation on elements such as the injectors, rings of flametube, air pockets and openings were conducted using an internal tool of ANSYS software package.

For a calculation of the volumetric chemistry of single-phase gas media Species transport model was used. That model determines a process of components' mixing, solves equations of convection, diffusion and change of concentration in a process of chemical reactions for each component of a mix. As the most labor-intensive from a calculation point of view, it has a high degree of accuracy. As analytical model of chemical reactions a single-step reaction of methane's combustion was used:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O.$$

That model and necessary for a correct calculation reaction parameters and components' properties were selected from a standard database of ANSYS.

A change in density of methane and air was determined using ideal gas law. A relationship between isobaric thermal capacity and temperature was set in a form of polynomial, which was selected from a standard database of ANSYS package.

As turbulence model, k-ε Realizable semiempirical model was selected, which is realized in ANSYS. An advantage k-ε Realizable model is a better modeling of twisted flows, boundary layers, which are prone to strong pressure gradients, separated and recirculating currents, i.e. modeling phenomena, which are characteristic for CC.

The calculation was carried out using a multi-processor personal computer, as well as with an implementation of "Sergei Korolev" supercomputer. Personal computer has following characteristics: Intel(R) Core™ i7 CPUX980 @ 3.33 GHz processor, installed memory – 24 GB. Supercomputer "Sergei Korolev" has following characteristics: 896 processors 2xIntelXeon X5560, 2.80 GHz; the total RAM memory 1.3125 Tb.

Results

A realization of each of the above mentioned stages of numerical modeling of operation procedure of gas generator is connected with a solution of a number of important problems. One of those problems is setting correct boundary conditions, which correspond with real object. The majority of gas-dynamic calculations of CC are performed with assumptions of flow parameters' uniform distribution at an input of CC diffuser [4-7]. In some studies nonuniformity of flow after compressor is set on a basis model's velocity profile [8, 9], but it is different from a real situation. At the same time, an influence of a turbine at an exhaust of CC is not taken into account. The above mentioned facts affect quality of a combustion chamber's design . Therefore, it is necessary to develop methodologies for its numerical simulation, which allow to study a operation procedure of a combustion chamber as a part of GTE. The aim of the presented paper is to study CC characteristics, taking into account an influence of a turbine and a compressor.

Nowadays, capabilities of numerical simulation allow to approach a solution of a problem of a calculation of processes, occurring in an air-gas channel for a whole engine in general, taking into account an influence of interactions between neighboring units on an engine's characteristics.

An autonomous calculation (without taking into account a compressor and a turbine) of changes in parameters of an air-gas channel of a combustion chamber was carried out using Ansys Fluent software package. As turbulence model, semiempirical k-ε Realizable was implemented. During the calculation following characteristics were determined:

- images of flow in the combustion chamber;
- fields of velocities and pressures in characteristic cross-sections;

- loses of a full pressure along a combustion chamber length;
- temperature fields at an exhaust of a combustion chamber.

After that, a calculation of a combustion chamber with a nozzle block (NB) and a turbine was carried out. Since, calculated areas, which are specified for each element, in places of their contact (CC with NB and then CC with a turbine) have different areas, it complicated a calculation. To address that problem an internal tool of ANSYS software – CFX, which automatically applied periodicity condition for each calculated sector, was used.

As a result of calculations for CC with NB and a turbine, fields of velocity, pressure, and temperature were obtained, which are qualitatively similar with the data of autonomous calculation, performed for an individual CC (figure 2). However, for obtained data there are discrepancies in numerical values. Air velocity at an exhaust of CC in a case of a calculation with a turbine appeared to be lower than in an autonomous calculation which may be related with an influence of a turn of flow in a nozzle block and upthrust of a turbine; losses of a full pressure in a combustion chamber in the calculation with the turbine increased to 5.6 % as against 4.1 % in an autonomous calculation.

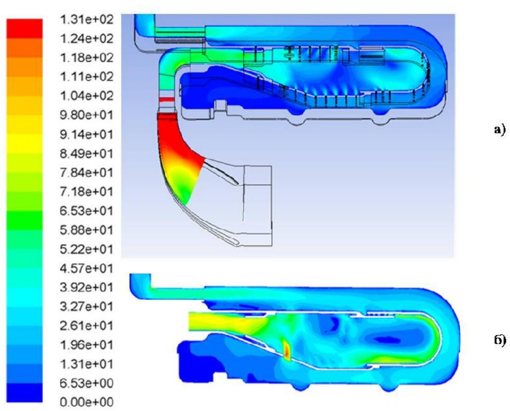

Figure 2. Velocity field:
a) in a case of CC calculation with a nozzle block and a turbine
b) in a case of an individual calculation of CC

An area with high temperature in a flametube of CC in a case of an autonomous calculation has large dimensions (figure 3), and radial nonuniformity of temperature distribution is lower. This is a result of a lower penetration depth of secondary air flow and, as a consequence, deteriorating conditions of mixing of combustion products with air that is diluting them.

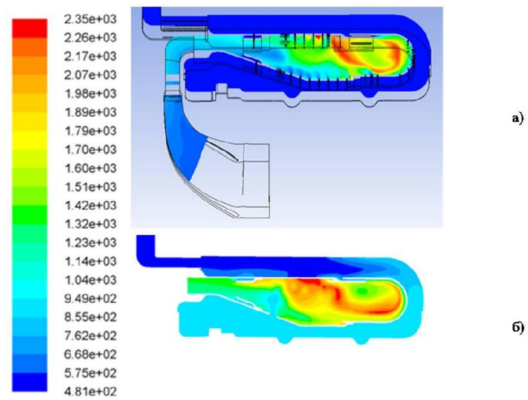

Figure 3 – Temperature field:
a) in a case of CC calculation with a nozzle block and a turbine
b) in a case of an individual calculation of CC

At the next stage, during a calculation of a combustion chamber's characteristics, in addition to a nozzle block and a turbine, an influence of a compressor was estimated. Nonuniformity of flow parameters, appearing after a compressor, at an inlet of CC was specified by a 5th power polynomial equation. The diagram, which was simulated in that manner, is presented in figure 4. Because of a presence of straitening vanes at an inlet of a chamber, twisting of flow was not simulated.

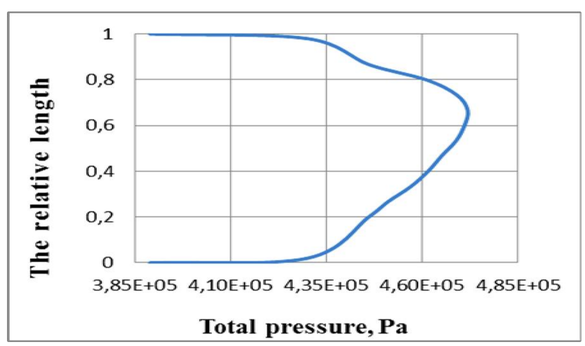

Figure 4. Diagram of a nonuniformity of pressure field at an inlet of CC

Obtained calculated data showed, that in comparison with a previous joint calculation of CC with NB and a turbine, flow speed at an exhaust of CC decreased, and a penetration depth of air flow decreased [10, 11]. An area with high temperatures in a flametube became bigger, due to a decrease in a penetration depth of air flow and, as a consequence, lower influence of incoming cold air on combustion products.

A comparison of diagrams of nonuniformity of temperature fields at an exhaust of CC showed (figure 5), that local casting of temperature, taking place during a calculation of a combustion chamber with a turbine and together with a compressor and a turbine, to a large extent changes its form in comparison with an autonomous calculation. In a practice, disregarding that feature (actual growth of maximum temperature after CC), can cause a burn-out of turbine blades of CGTE.

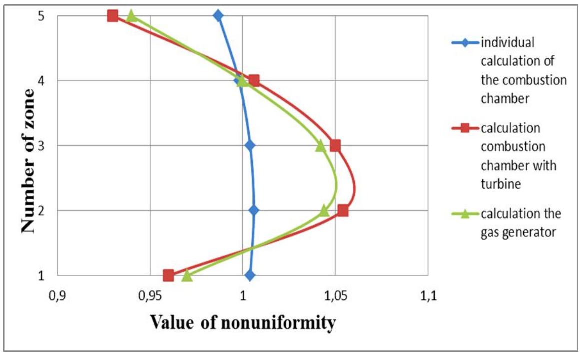

Figure 5. Diagram of a nonuniformity of temperature field at an inlet to CC

Discussion

In the presented study an estimation of a compressor was set using a nonuniform pressure field, which was obtained from a centrifugal compressor's calculation. That assumption was made because of a heavy grid model of a compressor. Because of a presence of straitening vanes, twisting of flow was not simulated. Also, studies were analyzed, in which gas generator was calculated in a whole [12, 13], and calculations were carried out using ANSYS CFX software package. But in those studies combustion was calculated using models, which take into account only one equation of oxidation.

Closing remarks

The presented study showed that results of CC calculations with a consideration of effect of a compressor and a turbine are qualitatively and quantitatively different from results of a calculation of a combustion chamber only.

Conducted study allows to propose a methodology for CC design, which differ from the traditional one. The algorithm of the new methodology's implementation is presented in figure 6. In accordance with the algorithm, first, on a basis of GTE thermogas dynamic calculation's data, a one-dimensional (traditional) design calculation of CC is carried out. In a course of that calculation, a construction arrangement of CC and its main dimensions are designated, a selection of air distribution air is conducted and, finally, an image of designed CC is obtained. Then, using numerical simulation, checking calculation of CC is conducted. It allows to assess main characteristics of CC: a nonuniformity of temperature fields at an exhaust, loss of a full pressure etc. If it is, that those characteristics approximately correspond to requirements of target specification, then a final adjustment of CC, composed of gas generator, considering an influence of neighboring units, is conducted.

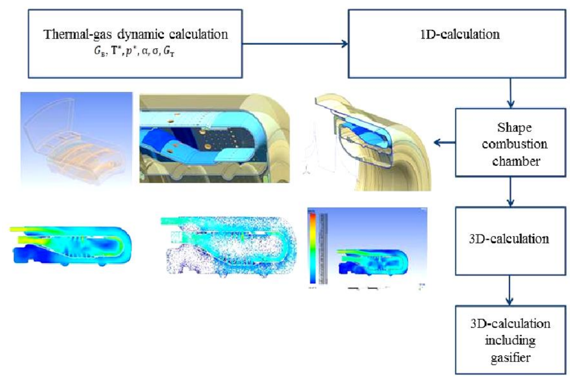

Figure 6. Algorithm of a design of CC of a small-sized GTE

Conclusion

In the presented study following results were obtained:

1. A new method for GTE CC operation procedure simulation is developed, which allows to take into account an influence on CC characteristics of neighboring units (a compressor and a turbine) without averaging parameters along path's cross-sections.

2. In a calculation of a combustion chamber with a turbine it is established, that a diagram of temperatures field's nonuniformity at an exhaust of CC, is by its nature very different from a similar diagram, obtained during an autonomous calculation of CC, which must be taken into account during a design of CC.

3. It is established that a nonuniformity of flow parameters at an exhaust of a compressor significantly influences characteristics of CC as a part of a gas generator.

4. During a calculation of a combustion chamber as a part of a gas generator it is established, that its characteristics are different from the characteristics obtained during an autonomous calculation and in a case of a calculation of CC together with a turbine, which demonstrates an

actuality of CC calculation as a part of a gas generator.

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