The integrated design of the combustion chamber for a gas-turbine engine using cad/cae systems

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Abstract. At the moment the combustion chamber (CC) is the major unit of a gas turbine engine (GTE), the improvement of which in the long term will determine the improvement of its environmental, resource and others characteristics. The combustion chambers have been designed using conventional methods for quite a long time, where the CC basic geometrical dimensions, the air distribution law and the integral parameter distribution in the basic sections have been determined by calculations. As the design of both the GTE and its combustion chambers became more complicated, there appeared a need to assess at the design stage not only the integral parameters distribution, but also their local values. It provides, for example, a longer fault-free performance of the flame can wall or the turbine engine, and, consequently, a longer engine lifetime in general. In this paper, the approaches to the CC integrated design of the aircraft GTE are expounded in the form of the implemented solution of the designer's objectives. These approaches will ensure the implementation of the main requirements to them. It has been shown how to achieve the desired characteristics of the combustion chamber by improving the performance of its main elements, such as a diffuser, and in case of a multi- injector circuit also by optimizing the distribution of fuel between the injector circuits. The outlined approaches allow solving practical objectives to reduce emissions of air pollutants by a projected combustion chamber and to improve the engine service life rate.
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Introduction

The development of the GTEs in the last 20 years has led to a significant change in their parameters [1]. The thrust and air flow have increased, the weight-to-power ratio and fuel consumption have reduced [2]. At the same time the compression ratios in the compressor, the inlet gas turbine temperatures and bypass ratio have increased. In the future it is planned to increase them. It is impossible to ensure the GTE high parameters without the overall improvements in design, the completion technology and the engine combustion chamber production. The combustion chamber of the aircraft GTE is one of its main components and determines not only the basic characteristics of the engine, but also the characteristics of the aircraft [3, 4, 5]. However, the design of this particular engine element currently presents great difficulties. Today there is no complete and reliable mathematical description of the CC work process. Therefore, the CC design in the present and in the foreseeable future is associated with large material and time consumption.

The additional design complexity of the GTE combustion chambers is due to a number of different requirements, the implementation of which is a complex problem that requires iterative solutions [6]. Thus, the combustion chamber should provide: high combustion, the required resource; a reliable ignition and the engine performance in a wide range of modes; given diagram of the temperature distribution at the engine outlet; environmental characteristics in accordance with the regulations of ICAO, they must have small size, weight and pressure losses that reduce engine thrust [7,8]. The traditional technology of the GTE CC production, when the design study is followed by an improvement of full-size products, does not provide, in accordance with the requirements of the present day, the development of the optimal by different criteria design in the timescale available. The practical use of CAD / CAE systems for designing GTD CC does not allow solving all related problems autonomously. About ten years ago, it was assumed that this mathematical method for studying technical devices processes would significantly reduce the design time with reducing the requirements for the engineer qualification. However, it has not fully happened, as it turned out that the engineer-analyst's qualification in this case, on some issues (such as the knowledge of physical phenomena, underlying the work process) should be significantly higher than an average statistic one.

This led to the conclusion of the necessity to solve the above mentioned problems of designing GTE CC by means of a comprehensive approach, including traditional design and experimental methods, as well as a widespread use of CAD/CAE systems. This experience has been acquired through the joint work of the employees of JSC "Kuznetsov" and Samara State Aerospace University named after academician S.P. Korolev (SSAU) on the development of the future GTE combustion chambers.

Methods

The numerical simulation of the GTE combustion chambers work process included the following main steps:

- Construction of a geometric model of the pack Siemens PLM Software NX 8.5;
- Generation of the grid model ANSYS Meshing (ANSYS 13 WorkBench);
- The creation of a mathematical model;
- Performing calculations in ANSYS Fluent (ANSYS 13 WorkBench);

The calculations were performed on a multiprocessing personal computer and the supercomputer "Sergei Korolev" as well. The personal computer has the following specifications: processor Intel (R) Core ™ i7 CPUX980 @ 3.33 GHz with the installed RAM of 24 GB. Supercomputer "Sergei Korolev" has the following characteristics: 896 processors 2xIntelXeon X5560, 2.80GHz; common RAM of 1.3125 TB.

Results

The development object was an annular combustion chamber of the gas turbine engine for a civil aircraft shown in Fig. 1, and the purpose of the work was to ensure a given level of its parameters.

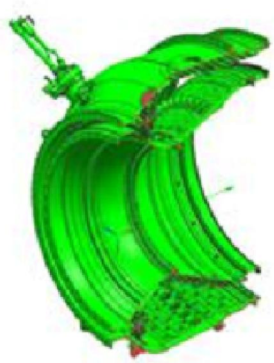


Fig. 1. The projected combustion chamber

Its concept with the basic dimensions was obtained at the stage of conceptual design basing on a traditional design study. The CC geometric model was created on its basis. The computational place, the periodic recurrence of which allows recreating the whole product, was allocated. Several unstructured grid models were created for the computational place. After performing preliminary calculations the computational grid including 14 million elements was chosen out of those grid models for the further work (Figure 2).

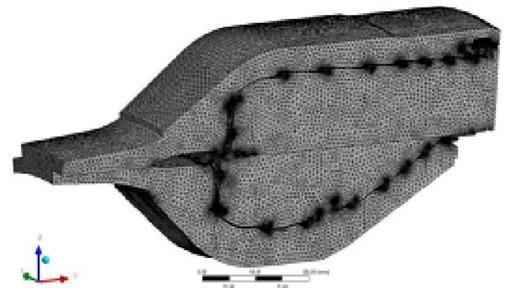


Fig. 2. The computational grid

The chosen CC design was considered as a base, and the distribution of various parameters for it, some of which are shown in Fig. 3 ... 6, has been determined by calculation.

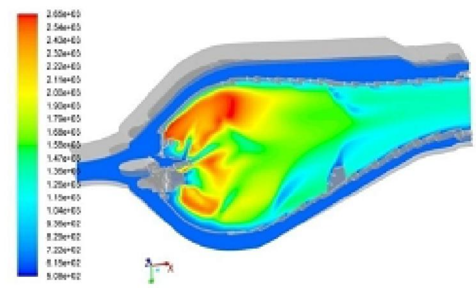


Fig. 3 The temperature distribution along the CC length

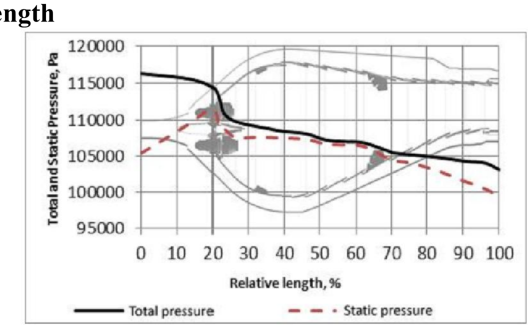


Fig. 4. The total and static pressure distribution along the CC length

Fig. 5. The temperature change along the length of the flame can (Not shown)

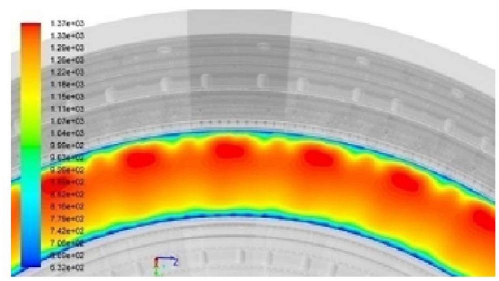


Fig. 6. The temperature distribution at the CC outlet section

The compliance of the obtained characteristics with the technical requirements was analyzed. As a result, it was concluded that the improvement of the number of CC parameters was necessary. While completing the combustion chamber, several calculations were performed for a few structures of the CC diffuser, which differed in size (see Fig. 7).

Variants of diffuser geometry for a low emission combustion chamber.

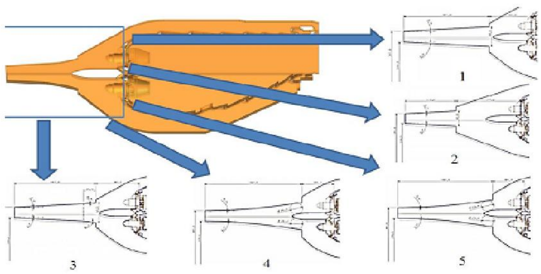


Fig.7. The considered variants of the CC diffuser

The performed calculations allowed choosing the diffuser variant providing an acceptable pressure drop and the minimum level of nitrogen oxide [9].

For improving the reliability of a number of calculations for the CC, it is necessary to have qualitative data on the fuel distribution in the combustion chamber volume. This requires the knowledge of the fuel tongue characteristics. With injectors at hand, such data may be available at the workbench, equipped with laser-optical systems. In developing the experimental design it is not possible to test all of the injector variants under consideration due to their high production cost. In the present study the following solution to this problem was used. First, different variants of injector design were calculated using computers. Then non-metallic injector models of the variants with the best characteristics were made by rapid prototyping. The necessary characteristics for these models were determined under bench testing conditions. The best variant was a base for a metal injector, for which the full amount of bench research was carried out (see Fig. 8).

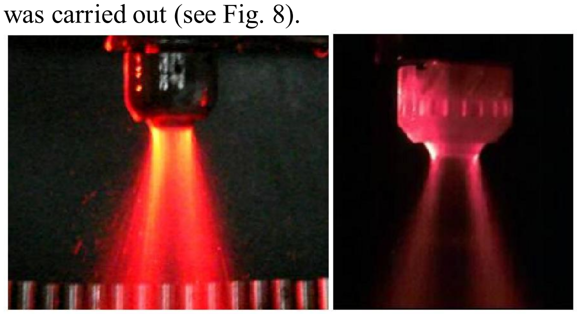


Fig. 8. Bench testing for a metal injector (left) and the injector made by prototyping.

The evaluation of the computational data of the projected CC with the best diffuser variant has shown that for providing the required turbine resource it is necessary to improve the heat flow field at the CC outlet. At the same time we should comply with the existing regulations on the emission of air pollutants. For further calculations a set of possible actions for changing the CC geometry was planned, by which we were supposed to reach the required characteristics:

1. Reducing the number of cooling holes in the flame can;
2. Increasing the pistons length;
3. Reducing the pistons diameter;
4. Reducing the pistons length;
5. Moving the pistons closer to the CC outlet; and
6. Reducing the number of cooling holes in the flame can.

The CC scheme with these improvement places is shown in Figure 9.

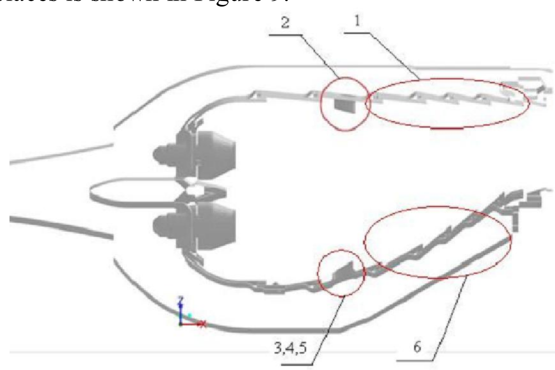


Fig. 9. The scheme of the CC design improvement

After taking these suggestions into consideration, a set of CC variants was developed, for which the calculations were carried out using the methods of numerical simulation that allowed choosing the design that provided the required temperature distribution at the chamber outlet. The computational data for some variants are shown in Figure 10.

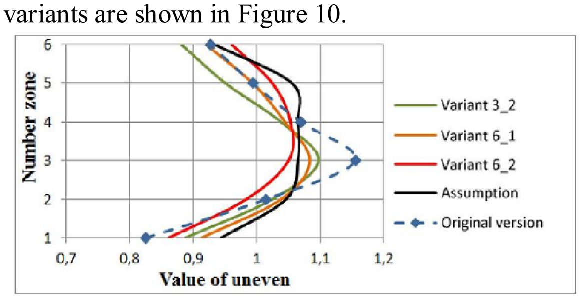


Fig. 10. The calculated radial temperature diagrams at the CC outlet.

The calculations were performed for the developed for the time CC structure variant, which allowed determining the position of high temperature zones in the CC volume responsible for the increased formation of nitrogen oxides and the diagram of the temperature distribution at the CC outlet (see Fig. 11).

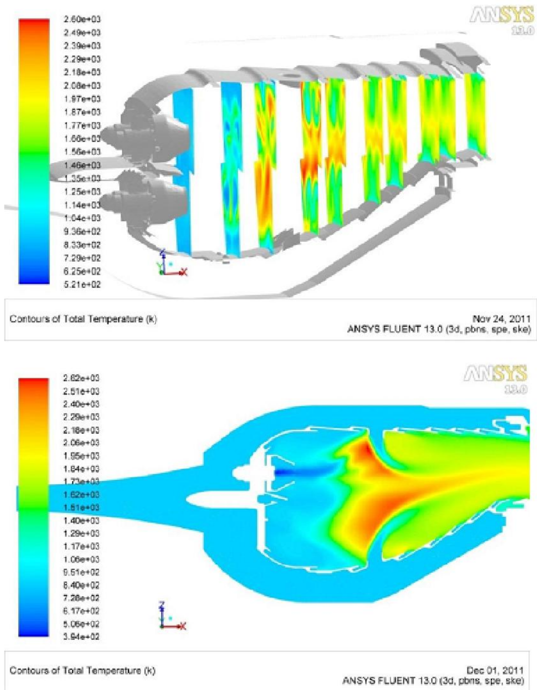
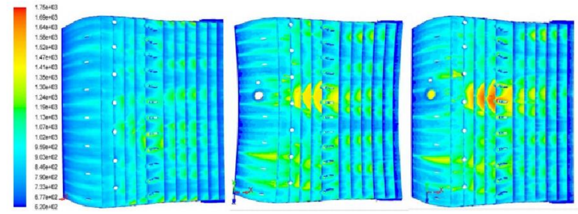


Fig. 11. The temperature distribution at the CC cutaway and along the length

Since the projected combustion chamber is multi-injectional with two fuel circuits, it has been suggested that it has some performance enhancement reserve by changing the fuel distribution between the circuits due to a constant flow rate. The performed calculations have shown that the dual fuel supply system does allow changing the NOx emission level within the set limits and the type of gas temperature radial diagrams at the CC outlet without changing the design. Herewith, the fuel distribution within the considered variation range of excess air ratio (0.70 ... 1.20 for the outer row and 0.84 ... 1.55 for the inner row of injectors) has no effect on the CC total pressure loss and air distribution in its elements.

From the point of view of reliability of aviation technology, it is important to know not only the integral, but also the local parameters distribution within the CC. To investigate the characteristics, the calculations for assessing the impact of the flame can (FC) suspension and the igniter in it were performed. It has been found that the presence of the suspension and the igniter in the FC contributes to:

- Cooling system performance degradation (see Fig. 12);
- Increase in the total loss of the CC total pressure;
- Change in the law of air supply and position and size of the oxides nitrogen formation zones and the temperature field distortion at the CC outlet.



а) б) в)

Figure 12 - The FC wall temperature

a) with regard to the suspension (variant 3)
b) with regard to the igniter (variant 2)
c) with regard to the suspension and the ignition module (variant 4)

Based on these calculations results, the design of the FC suspension and the igniter have been changed, resulting in the improved technical characteristics of the combustion chamber.
Based on the optimized version of the designed CC a full-scale specimen was made. Its tests have shown a fine precision with the numerical simulation results.

Discussions

This article perhaps is the first to amplify the entire way of designing the combustion chamber with the help of CAD/CAE Systems beginning from the design calculation to the production of natural samples. The calculations performance with the required degree of reliability was contributed by the preliminary work for developing calculated methodology and its verification by bench testing models and full-scale specimen of combustion chambers for small turbine engines, including the use of laser-optical measurement methods [10,11]. The advantage of this particular work is an established possibility to achieve the best CC performance not only by changing its geometry, but also by the optimization of the fuel system [11,12].

Results

The work on the design of a low-toxic CC has shown that the integrated use of new and traditional computational technologies not only reduces the time of creating a new CC, but also achieves much better results. The performed calculations and experiments have shown that the dual system of fuel distribution allows to change the NOx emissions level and the type of radial diagrams of the gas temperature at the CC outlet without changing its design. The work to develop a complex technique of the CC design and improvement using CAD / CAE systems is in progress. Its goal is to develop the calculation of the CC performance in the gas generator turbine engines.

Conclusions

1. High quality results of the CC design can be obtained only by using both the numerical and physical experiments.

2. Improving only one of the CC elements does not allow obtaining the desired result, so it is advisable to carry out optimization calculations for investigating the effect of each of the CC elements at its work process and characteristics.

3. The GTE environmental performance can be improved not only by changing the combustion chamber design, but also by optimizing the fuel distribution among all injectors.

4. The CC diffuser design has a significant effect on the primary zone work process and on the formation of nitrogen oxides emissions.

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