Modeling and computer-aided design of combustion chambers for aircraft engines and gas turbine plants using an expert system

A E Kishalov, V D Lipatov and P V Soloviev

Ufa State Aviation Technical University, 12, Karl Marx st., Ufa, 450006, Russia

E-mail: kishalov@ufanet.ru

Abstract. The modeling issues of the working process and the design of combustion chambers for aircraft engines and gas turbines are considered. The developed modeling tool is shown: the "AM" expert decision-making system. A brief description of the expert system and module aimed at modeling and designing of the combustion chamber structures is given. The results of the computer-aided design of combustion chambers for the AL-31F aircraft engine and the AL-31ST gas turbine engine are presented. The results obtained are verified on the basis of the basic design and the values obtained using three-dimensional models of the real structure. A comparison of materials selected by an expert system with those used in a real design is performed. The parametric studies results of the various parameters influence of the combustion chambers working process on their design are also shown.

1. Introduction

The development of both aviation technology and gas turbine plants is inextricably linked with the methods and approaches underlying the design of these products. Modern aircraft engines differ from previous generations by an extremely high level of parameters of the gas flow of the flow path, low specific fuel consumption, low specific gravity and high specific thrust. At the same time, to speed up the design process and, consequently, to reduce the development time of a product as a whole, various software complexes and expert systems (ES) are currently widely used. These complexes make it possible to carry out complex thermogasdynamic calculations of installations of any schemes and structures, perform their strength analysis considering the existing loads, and also solve various optimization problems that are aimed at finding parameters that can meet the requirements for modern aircraft engines and gas turbines.

Combustion chambers of modern aircraft engines are extremely complex devices that operate in conditions that are quite difficult for a design. The main characteristics of the engine and its operational characteristics depend on the qualitative organization of the combustion process. Engines for civil aviation are subject to requirements for the level of emissions of harmful substances, which tend to become more stringent. In addition, the level of emission of harmful substances also largely depends on the organization of the combustion process. The design of the combustion chamber for modern aircraft engines is a complex iterative process, as a result of which a certain set of conditions is met. The overall dimensions of the combustion chamber are determined by the required combustion efficiency and the residence time of the fuel-air mixture in the flame tube. Attempts to improve the characteristics of the combustion chamber while fulfilling a number of conflicting requirements for the organization of the
combustion process lead either to an increase in the mid-section of the engine (which negatively affects its aerodynamic drag) or to an increase in the length of the combustion chamber (which leads to an increase in the length of the gas generator shaft and to an increase in mass and increasing complexity of the design).

At the early stages of design, it is necessary in a short period of time to model and analyze many possible design options, ensure the compatibility of the designed node with neighboring ones, optimize individual structural elements and its characteristics [1]. One of the possible ways to speed up this stage is the use of various systems for decision support and ES. The article describes one of the elements of the developed ES for the modeling and computer-aided design of the structures of the main units of aircraft engines and gas turbine engines, the choice of materials for their main parts and assembly units [2, 3].

2. Modeling of combustion chambers

2.1. Generic modeling

To check the performance of the developed ES and the database (DB) of materials, a number of combustion chambers (CC) of aircraft engines and gas turbines were simulated. The simulation results were compared with a real design [4-6].

When modeling already developed and serially produced products, their topological model was developed, then its identification was carried out according to known parameters, parameters were set at the input and output of the unit (reduced velocity in the input and output sections).

The modeling results of the combustion chamber's design of the 4th generation afterburning turbofan CC (AL-31F family) for a highly maneuverable military aircraft and their comparison with the real design of the unit are shown in figure 1 [7, 8]. Comparison of the characteristic sizes and masses of the main elements was made using 3D solid models in Siemens NX (figure 2).

The average relative error in modeling the basic geometric dimensions is 4.5%. The error in the weight determining of the flame tube was 10%, the error in the body weight determining was 18%. Such a rather high error is explained by the presence of elements that increase the rigidity and stability of the structure (four shrouds on the inner casing of the combustor) and the greater length of the outer casing of the combustor at the outlet from the combustor as compared to the inner casing. In the inlet part of the CC, the outer casing also serves as a casing for the double guide vane of the last HPC stage. In the outlet part, the outer casing of the CC passes outside the high-pressure turbine and contains thickenings for mounting various devices [9].

When choosing materials for flame tube and the case of the CC, in the first place in the list for both the flame tube and the case are the materials used in the real design of the simulated engine.

If we consider the modeling of another 4th-generation afterburning turbofan (RD-33 family), then in this case the average relative error in modeling of the main geometric dimensions is 14.2% (figure 3). The largest error is when the length determining of the smooth section of the diffuser. In this case, the error in determining of the total length of the CC is less than 4%. When choosing materials for flame tube and case of the CS ES offers materials used in the design of a commercially available engine [10, 11].

When gas turbine engine modeling (AL-31ST), ES proposed a design corresponding to the design of the simulated CC. The average relative error in modeling of the basic geometric dimensions is 9.3%. The increase in the error is caused by the complex configuration of the outer and inner casing of the CC, a large range of thicknesses (from 1.7 to 5.7 mm, ES proposed a design with a thickness of 2 mm), a double-walled outer casing, the presence of studs in the smooth part of the inlet diffuser, bands on the inner hull and longer structure of the outer hull of the CC (figure 4). This also explains the high error in the mass determining of the CC case which is 48.9%. For comparison, the error in the flame tube mass determining is 18%.
Figure 1. Comparison of the design of the 4th generation afterburning turbofan and the design proposed by the ES (dashed line).

Figure 2. 3D-solid geometric model of the CC of 4th generation afterburning turbofan.

Figure 3. Comparison of the design of gas turbine engine and the design proposed by the ES (dashed line).

Figure 4. 3D-solid geometric model of the flame tube of CC (AL-31ST).

It should be noted that the ES algorithms include the design procedure of circular direct-flow CC. At the same time, using the example of a turbofan engine CC of the PS-90 and D-30 family, which are CC [2, 3, 12, 13]. The average relative modeling error is about 14% (figure 5). The temperature levels of elements and materials determined by the ES correspond to the modeled node [2, 7, 9].

Figure 5. Design and model scheme of the turbofan (D-30 family).
2.2. Parametric study of turbofan’s combustion chamber

For the turbofan of the D-30 family, a study was made of the influence of the average speed in the midsection and the material of flame tube on the overall and mass characteristics of the assembly.

According to the study, the higher the speed in the midsection, the smaller the cross-sectional area of the CC. With a fixed outer diameter of the CC, this means that the higher the velocity $V_{\text{mid}}$, the larger the inner diameter of the flame tube and the diameter of the inner body of the CC. Since with an increase in speed, the residence time of the fuel in the flame tube decreases, in order to maintain the specified completeness of combustion, the length of the flame tube increases, and, accordingly, the length of the combustion chamber increases. As the length of the CC increases, its mass increases (figure 6 and 7).

Moreover, not every of the considered materials can be used in the design of the CC. The main factor is that the working temperature of the material must be higher than the temperature of the flame tube in all modes. Figure 8 shows a graph showing the distribution of points for the operating temperature of each of the analyzed materials depending on the average speed in the midsection. Figure 9 shows the distribution of the total points scored by the materials.

At low velocities ($V_{\text{mid}} < 29$ m / s), the average temperatures of the flame tube are of the order of 1000 K, the VKNA-4 nickel-based alloy (no. 95) was considered optimal as the material for the flame tube. At high speeds, with a fixed outer diameter of the CC, the inner diameter of the flame tube also increases, so its temperature decreases and reaches the operating temperature of the VT-18 titanium alloy (650 °C). Alloys EP-648 (number 45) and EP-718 (number 62) also gain the maximum number of points. In the manufacture of flame tube of CC from EP-648 alloy (at the minimum of the considered
speeds), the weight of the flame tube is 15.3 kg, and the weight of the CC is 40.3 kg. In the manufacture of flame tube from the VKNA-4 alloy, its mass is 14.8 kg, and the mass of the CC is 39.8 kg.

We also studied the influence of the parameters of the flame tube cooling system (the thickness of the slot and the distance between the slots) on the efficiency of the cooling system (figure 10). With a given distance between adjacent cooling slots of 45 mm and a cooling slot thickness of 3.5 mm, the cooling efficiency is 0.934, which indicates that the cooling air film is practically not washed out and does not heat up along the entire length of the protected section of the flame tube. The average temperature of the cooling air film is 803 K, and the temperature of the flame tube wall is 1005 K. With an increase in the distance between the slots to 60 mm and an increase in the slot height up to 4.5 mm, with approximately the same cooling air flow rate with the original design, the average flame tube temperature is 19K below (figure 11).

![Figure 10](image1.png) ![Figure 11](image2.png)

**Figure 10.** Changes in the efficiency of cooling the flame tube depending on the distance between the slots and their height  
**Figure 11.** Change in flame tube temperature depending on the distance between the slots and their height

3. **Conclusion**
As a result of the modeling, it was found that the ES quite accurately simulates the design of the CC of both aircraft engines and a gas turbine engine. The average relative modeling error is about 10%. The materials offered by the ES correspond to the materials used in the construction of the unit. Thus, the developed ES shows a fairly good performance both in modeling the design of the CC and in the selection of materials for them and can be used in the early stages of designing aircraft engines and gas turbine engines. In addition, the considered expert system can be used as a tool for performing parametric modeling in order to identify the type of dependences of the key parameters of the combustion chambers on the design features.

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