PAPER • **OPEN ACCESS**

Optimal design of a combustion chamber of gas turbine engine by a Combustion chamber 1D-2D computer program

To cite this article: Y B Aleksandrov and B G Mingazov 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **240** 012006

IOP Conf. Series: Materials Science and Engineering **240** (2017) 012006 doi:10.1088/1757-899X/240/1/012006

Optimal design of a combustion chamber of gas turbine engine by a Combustion chamber 1D-2D computer program

Y B Aleksandrov[1] and B G Mingazov[1]

[1]Kazan National Research Technical University named after A N Tupolev, Kazan, Russian Federation

alexwischen@rambler.ru

Abstract. The paper shows a method of modeling and optimization of processes in combustion chambers of gas turbine engines using a computer program developed by a team at the Department of Jet Engines and Power Plants (DJEPP) of Technical University named after A N Tupolev KNRTU-KAI.

Introduction

Modern gas turbine engines and power plants are among the most complex technical objects. They are characterized by a large number of structural and circuit design. Their operating conditions are characterized by a variety of operating modes under different external conditions, whereby there are conflicting requirements imposed to them concerning power, specific fuel consumption, weight, dimensions, pollutant emissions, noise, etc. All this is a very complicated process of creating a modern gas turbine engine.

This process has now been inconceivable without the use of computer technology and mathematical models at all stages of the design. The use of mathematical models provides an opportunity to explore a wide range of issues related to the creation of GTE and thus can significantly reduce their full-scale tests.

One of the most difficult for the design of the engine components is the combustion chamber (CC), which takes into account the development of gas-dynamic processes, the chemical interactions of combustible components of fuel with the oxidant (air), thermal mass transfer processes. Working conditions, safety and environmental performance of the whole engine directly depend on the efficiency of this engine unit.

Main part

The process of designing and creating the combustion chamber can be divided into a series of sequential steps shown by block diagrams in Fig. 1. Let us consider a phased combustion chamber design process.

Stage 1. The stage in which the original data of the combustion chamber (flow rate and pressure of air and gas and other) and design of the compressor and turbines serve as material for creation of a 1D model. There are two possible courses of action: 1) use of a prototype, 2) creation of a constructive image of a combustion chamber on the basis of statistical data. After calculation of this model it is possible to obtain: distribution of secondary air, mixing of fuel with air, and graphs of dependence temperature and nitrogen oxides, fuel combustion completeness and other parameters. The important point is fast results, allowing to sort out a significant number of options for modifications of the combustion chambers and determine the 1D image of the combustion chamber, which will give information on the optimal design of the combustion chamber. This stage is fully realized in the created computer program «Combustion chamber 1D-2D» [1]. The scientific basis for the program creation were the approaches outlined in works of Mingazov BG [2]. The calculation of combustion processes for one-dimensional model can be carried out quickly enough, which will help to organize the design optimization for various operating and design parameters at the entrance. This is a very important advantage of one-dimensional program in practical calculations of a combustion chamber.

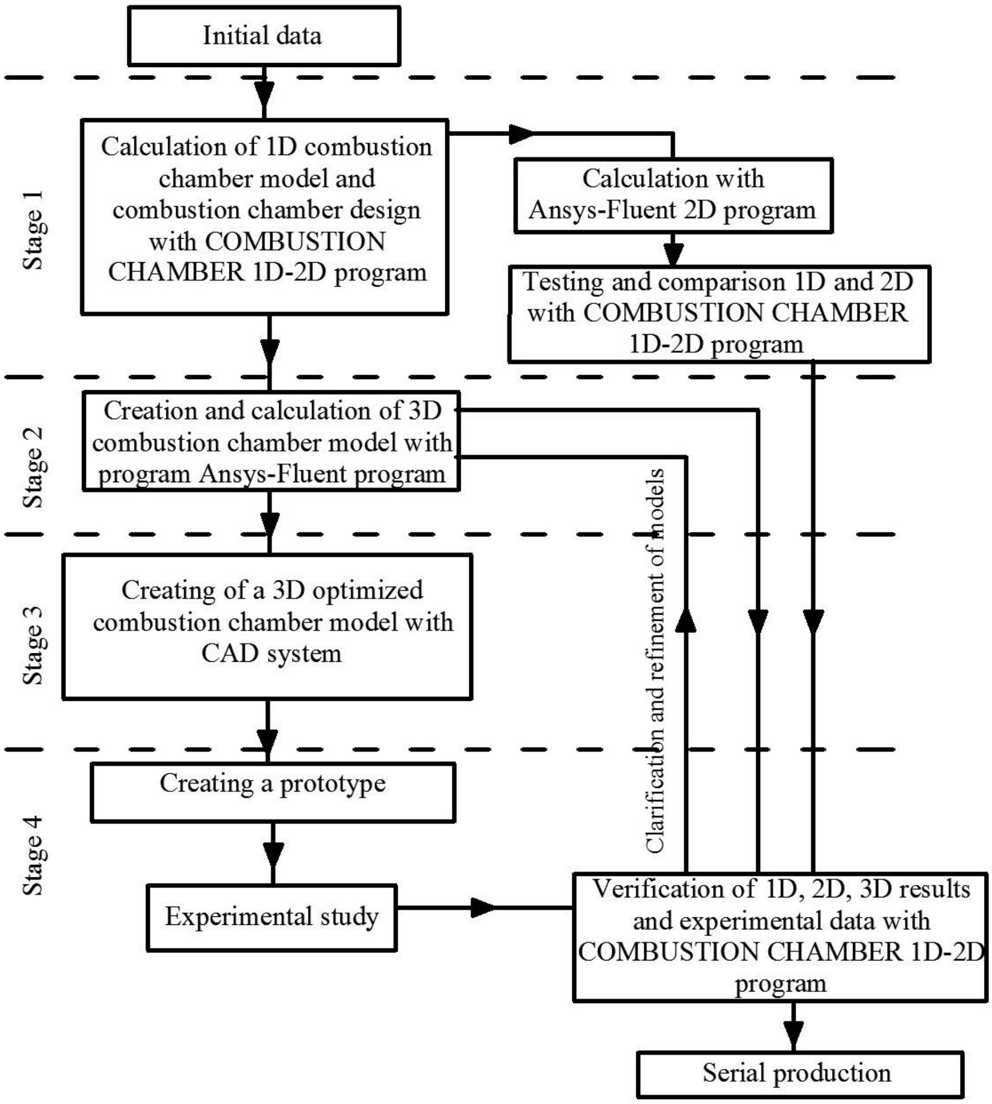

Fig. 1. Stages of the combustion chamber design using the program «Combustion chamber 1D-2D»

Stage 2. Based on the results obtained in the first stage of the work a 3D model is created. This model takes into account the additional design features assigned by a designer, such as design of a burner, twist flow, district unevenness of cooling zones holes and secondary air supply. Results of the calculation in CFD (Computational fluid dynamics) software are the most complete and serve to optimize the final design of a combustion chamber. It should be noted that this is the most time-consuming step. At the end of the stage make additional results calculation is needed to compare 3D with 1D and 2D.

IOP Conf. Series: Materials Science and Engineering **240** (2017) 012006 doi:10.1088/1757-899X/240/1/012006

Stage 3 design layout of the combustion chamber image. Calculation 3D optimized design is transferred to CAD (Computer-aided design / drafting) program, where all necessary design and technological documentation for the prototype is prepared.

Stage 4: Creating a prototype of the combustion chamber and conducting the experiment; it is the most expensive and a fairly long work stage. The above mentioned 1D, 2D and 3D optimization approaches allow to minimize costs and time of the final quarter of the stage. The experimental data is verified (compared) with the calculations of 3D data and in case of discrepancies calculations and improvements are carried out to refine the results, such as elaboration of models of turbulence and combustion (hybrid approach). For final image approval you must complete a combustion chamber prototype and carry out a research. The experiment takes precedence over numerical calculations. If the prototype parameters satisfy requirements specification, the design is transferred to serial production.

In practice of this calculation a layered approach is applied and 1-, 2- and 3-dimensional models are used. Recently, with the growth of computer performance 4-dimensional combustion models have become a reality (taking into account non-stationary processes). To clarify, one can make a rough comparison of speed calculation made on average computers - calculation of combustion with 1-dimensional model takes less than one second, with two-dimensional models – ten of minutes, with three-dimensional models from several hours to days, with 4-dimensional model calculations are relevant only on supercomputers.

From the point of view of the consistent implementation of multi-level calculations of intra-chamber processes, the one-dimensional model of the combustion chamber should be used initially. The calculation of combustion processes with one-dimensional model can be carried out quickly enough, which will organize the design optimization in various operating and design parameters at the entrance. This is a very important advantage of one-dimensional program in practical calculations of combustion chambers.

One-dimensional and two-dimensional approach for calculation and optimization of a combustion chamber

When calculated with 1D and subsequently 2D axisymmetric models, some simplifications will be entered into the model:

- flow model assumes a quasi-dimensional approach and the impact of flow swirls from blade twists on the formation of mixture and combustion is being taken into account using the mixing ratio which contains a twist parameter stream n φ;
- calculation of a fuel plume is measured on influence of fuel supply pressure and fuel injector nozzle size the average size of fuel droplets;
- air distribution along the length of the combustion chamber is performed by supplying air through the orifice zones taking into account impact of consumption and mixing coefficients;
- formation of local compositions of mixture in each section is calculated on vaporized fuel and residual and secondary air mixed with the flow;
- mixture burns on the surface of a combustion mechanism in a turbulent flow with turbulence intensity along $\rho \approx 0.4$ chamber length.

Despite the simplifications in 1D or 2D models, they allow to calculate a variety of options and identify areas to optimize the air distribution in a short period of time.

Result of a 2D calculation, unlike 1D is obtained for a longer time, but it is possible to analyze the flow parameters change, not only along the flow, as implemented in 1D, but also in transverse directions, which provides an additional advantage when analyzing a combustion chamber.

Initial data for 2D calculation are: air consuming, air pressure and temperature through the CC; fuel gas consuming and temperature. There can be variants, for example, instead of the air consuming sometimes inlet air speed is specified. These data can be obtained from a preliminary 1D calculation.

A one-dimensional and two-dimensional calculation of the combustion chambers is implemented fully in the "Camera" software. It has automated laborious process of creating a model of the combustion chamber geometry for 2D calculations. As an example, in Fig. 2 shows these files: a demo version of the 3D geometry of the combustion chamber of a gas turbine engine NK-16-18ST for visual representation (Fig. 2a.) and computed 2D axisymmetric option of applying of a contour fill depending on temperature (Fig. 2b.).The color scale on the left, displays the value. Color changes from red to blue varying rom largest to smallest respectively.

In the designated area of the combustion chamber calculations are performed sequentially using an iterative method: gas dynamics with the "cold" mode, combustion processes with the "hot", calculation of nitrogen oxides.

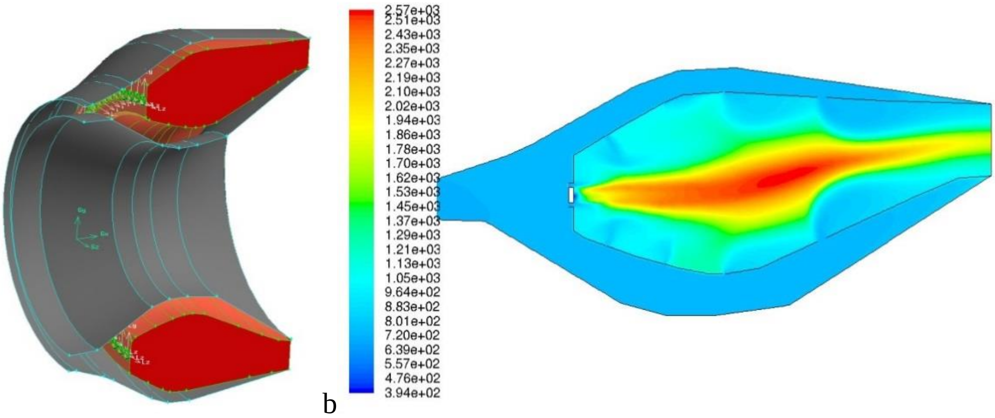

Fig. 2. a - spatial model of the combustion chamber, 180º sector; b - result of 2D calculation, contour temperature filling with "hot" mode

For a complete picture of the correspondence of data the results of 1D and 2D calculations are being compared. Comparison can be performed on any desirable parameters calculated along combustion chamber length. As an example, Fig. 3 shows a comparison of the average temperature along the cross section of the flame tube.

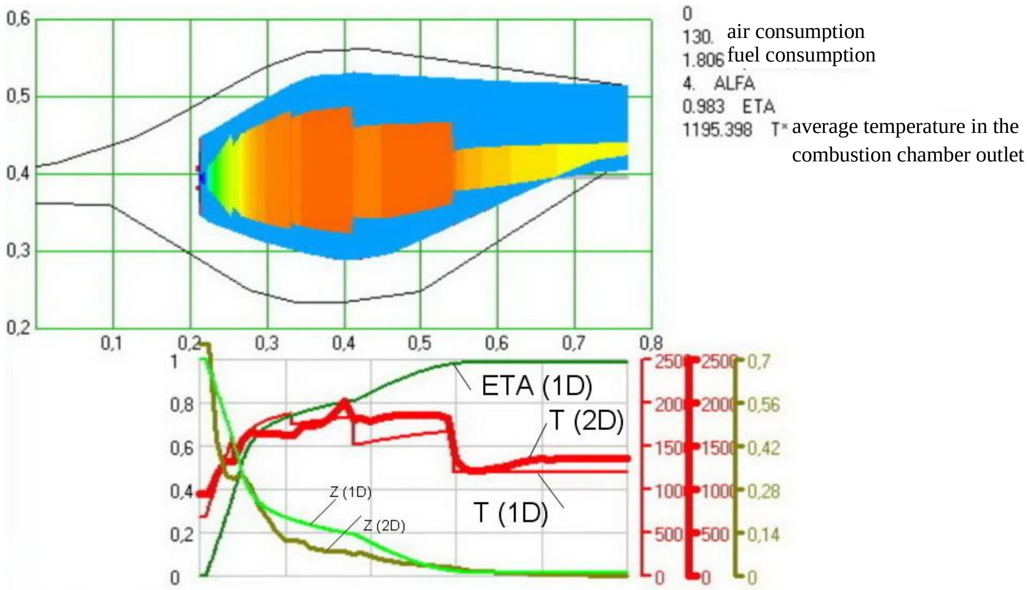

Fig. 3. Graphic dependences of 1D- and 2D- calculations comparison

Thicker lines in Fig. 3 indicate the design parameters, chosen by a user, calculated in the program “Fluent” (2D calculation), thinner lines were defined using the "Camera" program (1D calculation). By comparing the temperature dependences (T) there is a slight discrepancy along the combustion

IOP Conf. Series: Materials Science and Engineering **240** (2017) 012006 doi:10.1088/1757-899X/240/1/012006

chamber flame tube length. The obtained results indicate the possibility of using 1D model on the first stage.

Three-dimensional approach to a combustion chamber calculation

A combustion chamber is a relatively complex structure in terms of the implementation of its spatial computer model and construction of computational grid in its area. High-quality grid in such a model will contain at least one million cells and require considerable time to complete its calculation, for example, using a standard dual core computer it will take at least three days. In this regard, its design is simplified as much as possible, for example, remove the rivets, bolts, and all that makes a small contribution to the formation of gas-dynamic flows and heat transfer processes in a CC. For a preliminary calculation of gas dynamics and combustion chamber, a segment is often chosen so that it is symmetrical with respect to other ones which surround it on two sides [3]. In his segment a nozzle model is detailed.

As an example there is shown a combustion chamber of a gas turbine installation made in a 3D setting with a comparison of various parameters, distributed along the length of the combustion chamber, in one-dimensional and two-dimensional formulation.

The boundary conditions were inlet air flow in the combustion chamber diffuser G = 125.82 kg/s with a homogenous distribution of the flow parameters, fuel gas temperature T = 724.9 K, fuel gas consumption Gg = 1.388 kg/s, gas temperature Tg = 353 K. At the output there was set a condition of the static pressure constancy $p^* = 19{,}156$ kg/cm^2.

To calculate the 3D model a 1/42 combustion chamber sector was selected containing 1.5 million grid elements. Due to the presence of a swirling flow pattern from a swirler, a viscosity model RNG k-e was used in the 3D model with standard wall functions, which provides the most appropriate picture of the current and provides stability when performing calculations. Burning of gas fuel was calculated using laminar micro-flame models for unmixed mixture. This approach is equivalent to the definition of a turbulent flame front as an ensemble of laminar micro-flames (flamelets). Laminar flame parameters are preliminary calculated and stored in a table, and then the laminar flame is introduced into turbulent flow using statistical methods. As a set of chemical reactions of methane oxidation the Kee mechanism (18 mixture components and 58 chemical reactions) is considered [4].

Parameters distribution along the combustion chamber was controlled by a specially designed control surfaces (3D) or lines (2D), using the program of the automated processing and analysis of the calculated parameters of gas dynamics and combustion processes in a combustion camera [5].

As a result of the calculation there has been obtained comparable data distributed over the length of the combustion chamber and shown in Fig. 4.

IOP Conf. Series: Materials Science and Engineering **240** (2017) 012006 doi:10.1088/1757-899X/240/1/012006

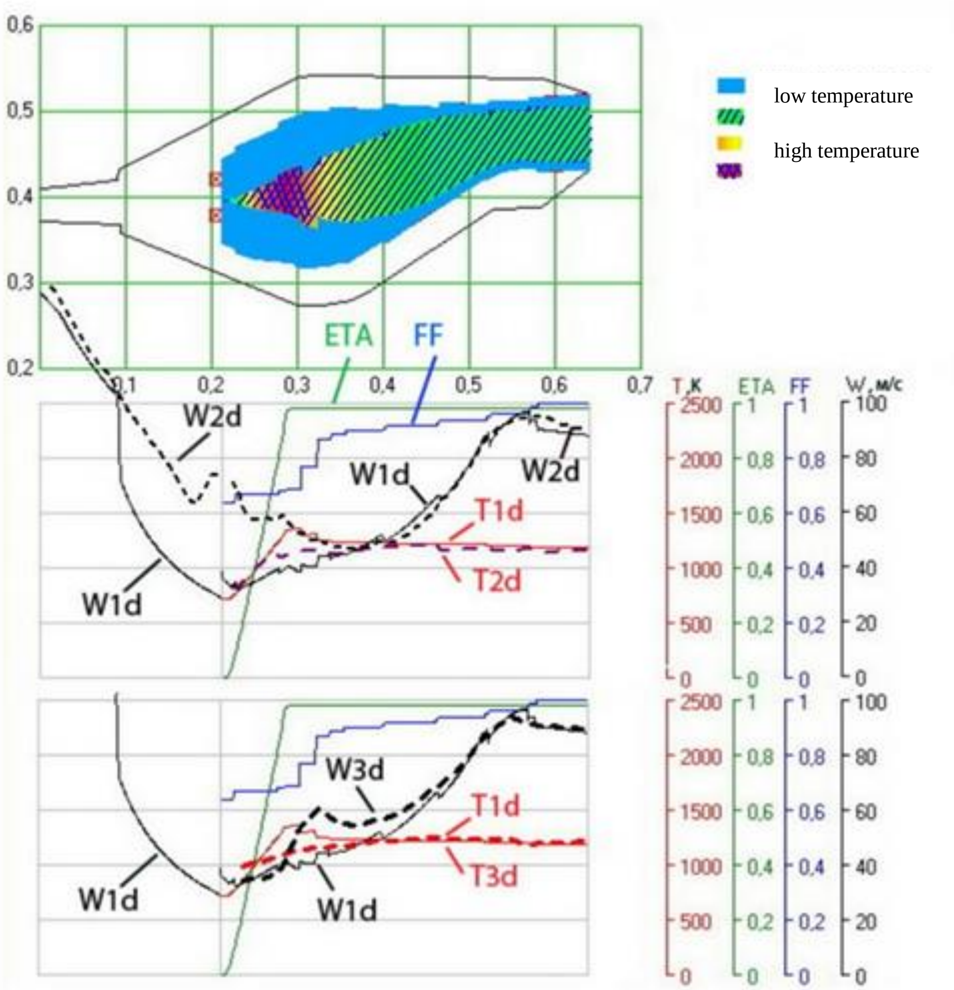

Fig. 4. Distribution of temperature (T) and velocity (W) along the length of a combustion chamber

Based on the results of one-dimensional calculation by a color field Fig. 4 shows the temperature distribution from blue to red, respectively, from the minimum to the maximum gas flow temperature values. Blue background in the outer zone of the flame tube - corresponds to the air temperature not involved in burning and mixing processes. Colors and shading show the area of the flame tube where air, fuel and fuel combustion are uniformly mixed. FF parameter – a relative area, it shows the distribution of areas of zones openings in the flame tube. ETA shows completeness of fuel combustion. Graphical dependence of the temperatures, averaged at cross sections, are shown in Fig. 4. They demonstrate their sufficient convergence at 2D and 3D setting, the only differences are observed in the primary air inlet area in the combustion zone and 1D. This can be explained by a simplified scheme model of a mixture formation. At flow speed rates differences are manifested in a greater degree and can be explained by the simplified scheme model of a mixture formation of 1D and 2D models, in comparison with the model made in 3D setting.

Conclusion

The foregoing methodology allows to carry out comprehensive studies in design and finishing in GTE combustion chambers creation; a developed program of one-dimensional calculation «Combustion chamber 1D-2D» can be successfully applied in a preliminary design stage to predict the characteristics of a combustion chamber.

IOP Conf. Series: Materials Science and Engineering **240** (2017) 012006 doi:10.1088/1757-899X/240/1/012006

References

[1] Aleksandrov Y B, Mingazov B G and Tokmovtsev Y V *The program of one- and two-dimensional calculation and optimization of combustion chambers of gas turbine engines* (Combustion chamber 1D-2D) (Certificate of state registration of the computer program №2016611770, application № 2015662645, received 22.12.2015, registered 10.02.2016, Moscow)
[2] Mingazov B G, Aleksandrov Y B, Kosterin A V and Tokmovtsev Y V 2015 *Combustion processes and automated design of combustion chambers* GTE and GTU teaching guide (Kazan: KNITU-KAI Press) 160 p
[3] Sabirzyanov A N, Aleksandrov Y B and Yavkin V B 2016 The rationale for reducing the number of sectors of the annular GTE combustion chamber in the modeling of work processes. *Problems and prospects for the development of engine building: materials of the reports of the international. Scientific-technical conference* of 22-24 June 2016, Vol 1 (Samara: Samara University Press) p 223-4
[4] Peeters T 1995 *PhD thesis on Numerical Modeling of Turbulence Natural-Gas Diffusion Flames* (Delft: Delft Technical University) p 263
[5] Aleksandrov Y B, Mingazov B G and Tokmovtsev Y V *Program for automated processing and analysis of gas dynamics and combustion processes in combustion chambers of gas turbine engines* (Servis 3D) (Certificate of state registration of the computer program №2016611856, application №2015662627, received 22.12.2015, registered 11.02.2016, Moscow)