DEVELOPMENT OF A COMBUSTION CHAMBER DESIGN METHODOLOGY AND AUTOMATION OF THE DESIGN PROCESS

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Abstract

The design of state-of-the-art low emission combustion chambers is based on a multitude of design rules. To use the know-how incorporated in these design rules more effectively, an automated design methodology is developed within the European project INTELLECT D.M. (Integrated Lean Low Emission Combustion Design Methodology).

By automating the combustor design process, the generation of a new preliminary combustion chamber design can be done within hours, while current development times for a preliminary combustor layout are in the range of weeks. Hence the market demands for faster product development can be met, ensuring higher accuracy of the design at the same time.

The paper presented here describes the methodology used to draft a new preliminary combustion chamber. Due to the nonlinear interdependence of the different parameters and rules specifying the combustor design, the layout has to be done within an iterative process. A description of the key parameters, rules and the data link to the parametric CAD model is part of this paper.

The iteration loop is closed by utilizing the parametric CAD model as basis of an automatic grid generation and CFD analysis. Resting upon the experience from former combustor design campaigns, the CFD results are judged and design rules are adapted if necessary.

Nomenclature

a, b, c...	empirical constants	[-]
p	pressure	[Pa]
T	temperature	[K]
V	volume	[m^3]
W	mass flow	[kg/s]
Λ_{Si}	loading factor	
η	film cooling efficiency	

Subscripts

cc	combustion chamber
fu	fuel
hs	heatshield
i	injector
mix	mixed gas
pz	primary zone mixing air
res	residence time
sf	starter film
sz	secondary zone mixing air
3	combustor inlet
4	combustor outlet

1 Introduction

Reducing development times and costs assuring lower emissions and higher efficiency at the same time are challenging tasks for the engine manufactures in order to stay competitive. The development of a preliminary combustion chamber design methodology and the automation of the design process would help to meet these demands. Therefore such a system is developed based on knowledge data captured within the European project INTELLECT D.M.. It allows to automatically generate a parametric combustor CAD model as basis for automated CFD analysis, which is compatible with design rules captured.

Following the recent advances of CAD and CFD tools some parametric design systems have already been developed within the last few years. Shakariyants [1],[2] published a generic combustor design tool, mainly based on geometric rules, not taking into account the heat transfer at the liner walls. Tangirala [3] and Lai [4] demonstrated parametric modeling approaches, but no layout criteria or design rules were published.

The capturing of knowledge based rules and their formalization displays the main difference between the present paper and the already published approaches of automatizing a combustor design system. The methodology of the combustor design and the automatization of the whole layout process is described in the paper.

2 Aero Engine Combustor Design

The first step in the specification of a new combustor is done at the preliminary design stage within the development of new aircraft engines. The basis of the preliminary design is always the current state of the art, which is characterized by suitable design rules specific to the engine manufacturer. Limitations on the design space are provided by customer requirements, project targets and design experience gained from previous combustor designs and tests.

Based on the customer requirements, project targets and incorporating requirements from the emission certification regulations, the new engine is characterized by a performance model, from which a compressor and turbine preliminary design is derived. The engine performance parameters, compressor exit aerodynamics, and turbine entry conditions are boundary conditions for the combustor preliminary design (Fig. 1).

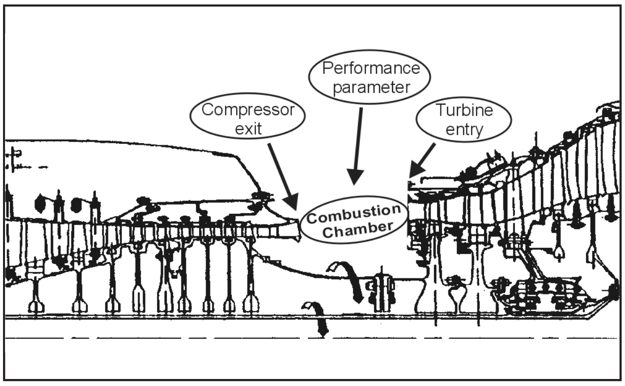

Fig. 1 Initial combustor design parameters

2.1 Low Emission Combustor Design Requirements

Newly designed aircraft engines have to fulfil the CAEP (Committee on Aviation Environmental Protection) emission certification rules, which are getting more stringent with time (1986 CAEP/1, 1991 CAEP/2, 1995 CAP/3, 1998 CAEP/4, 2001 CAEP/5, 2004 CAEP/6). The CAEP certification process currently requires engine emissions to be measured at some well-defined thrust levels at sea level and for durations typical to an aircraft mission on the airport.

Specifically, the emissions are measured at thrust levels 7 %, 30 %, 85 % and 100 % for 26, 4, 2.2 and 0.7 minutes, respectively. These thrust levels correspond to typical engine settings during the operation of the aircraft near the airport defined by the ICAO (International Civil Aviation Organization) [5] as shown in Figure 2.

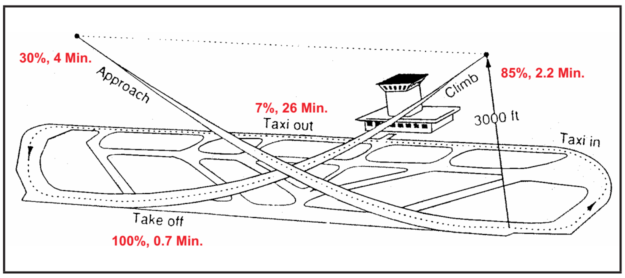

Fig. 2 ICAO Landing and Take-Off (LTO) cycle

To fulfil all operation and emission requirements conventional combustors are segmented into different zones [6]. Fig. 3 shows the fuel-rich primary zone, were soot production takes place. It is followed by an intermediate and a dilution zone, in which the soot, CO and UHC (unburned hydrocarbons) components are consumed. Since there is a continuous admixture of air over the whole combustor length, the mean air-fuel mixture is getting weaker along the combustor.

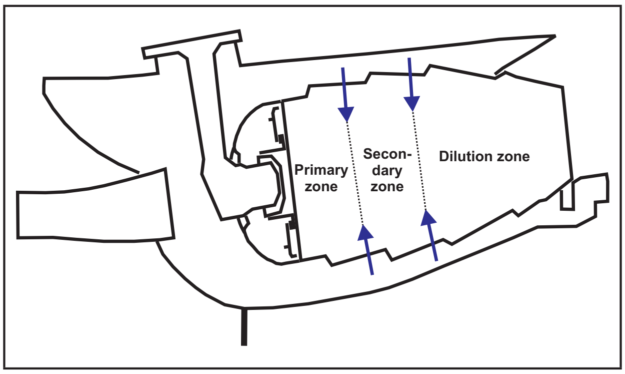

Fig. 3 Combustor Zonal Layout

2.2 Combustor Performance and Operability Requirements

Besides the emission certification rules, performance and operability requirements have to be fulfilled. One of the restrictions for combustor design is the requirement for altitude relight [7]. Reestablishment of the combustion after a flame-out usually has to be possible at an altitude of about 30.000 feet within the whole flight envelope (Fig. 4). This requirement can be translated into a condition on the residence time in the primary combustion zone and its stoichiometry.

Another important operability requirement of a combustor is the weak extinction limit. The extinction occurs earlier, i.e. at a lower air-fuel-ratio (AFR), if the air into the engine is mixed with water components, which may occur in inclement weather like rain, hail or snow. Suitable safety factors have to be incorporated to meet these requirements for a safe operation.

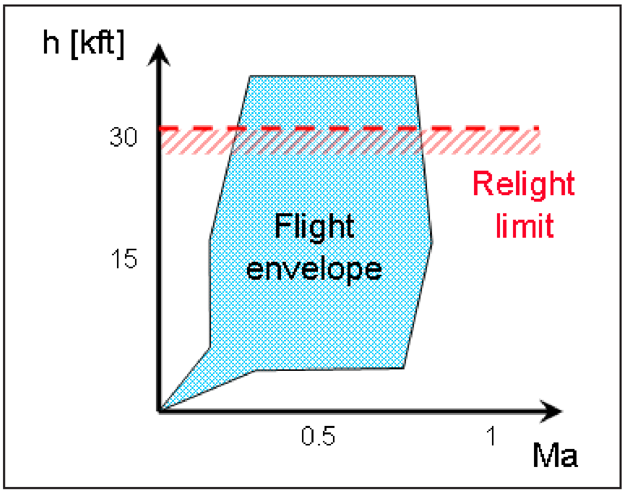

Fig. 4 Flight Envelope

2.3 Basic Design Data and Volume Estimation

During the initial stage of the engine preliminary design, first a performance deck is generated based on project and potential customer requirements [8]. From that basic design, data for compressor and turbine preliminary design are derived. These data form the basic design data, on which the combustor preliminary design process is based. Among these basic design parameters are the overall compressor exit air mass flow W_3, the fuel flow W_{fu}, the compressor exit temperature T_3 and pressure p_3 at several important operating points.

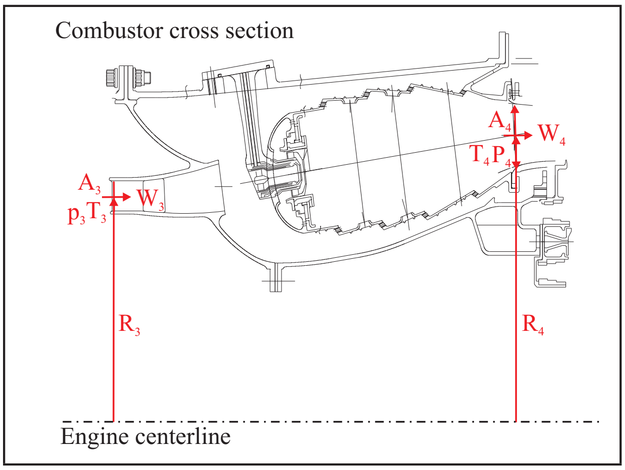

Fig. 5 Basic combustor design parameters

Most notable operating points for the combustor design are the emission certification points, the leanest combustor operation condition and a thermal design point (highest thrust at hottest day plus certain increments added to have some margin against tolerances of components). Beside these aerothermal parameters also the radii and areas of the compressor exit and the turbine entry annuli are usually fixed already, when the combustor design starts.

The first step in finding a combustor layout is the determination of a combustor volume consistent with the basic design data. The volume size determines the total residence time t_{res} of the mixture in the combustion chamber and therefore the burnout efficiency.

The burnout efficiency can be correlated with parameters like the loading factor Λ_{SI} [9]. Typically a value of Λ_{SI} is defined as part of the combustor design rules. As the compressor exit pressure p_3, the compressor exit temperature T_3, and the air mass flow W_3 are fixed by the performance deck, the necessary volume V_{CC} can be estimated.

$$V_{cc} = \frac{W_3 \cdot a}{p_3^b \cdot \Lambda_{Si} \cdot \exp(\frac{T_3}{c})} \qquad (1)$$

Here a, b, c are empirical constants, valid for a certain type of combustors. Additional criteria for fixing the combustor volume, e.g. altitude relight and pullaway requirements, may result in a bigger combustor volume.

2.4 Parameters characterizing state-of-the-art combustor technology

A simplified geometrical form of existing combustors is used for a first indication of the preliminary combustor layout. The shape is defined by parameters like lengths, depths, widths or angles, sometimes combined into dimensionless quantities. Further design rules are criteria for the zonal AFRs, i.e. the local stoichiometry inside the combustor zones.

Options for wall cooling are film, effusion or tile cooling, which differ in cost and efficiency. The cooling efficiency can be enhanced by wall

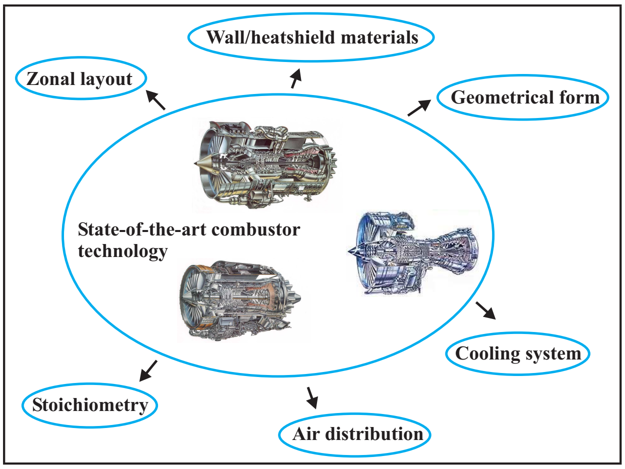

Fig. 6 Knowledge based on existing combustor technology

roughening or impingement cooling. The amount of cooling air depends on the area of the combustor wall, the cooling method, the local hot gas temperature and the maximum allowable wall temperature, which depends on the material used and the life requirements and thus on the requirements of the particular engine project.

After choosing the cooling system and the wall/heatshield materials, the air feed layout process can be iterated to achieve the desired zonal stoichiometries. This iteration is necessary since only some part of the cooling air participates in the combustion process of the combustor zone.

3 Combustor Design Iteration Loop

The nonlinear interdependence of the different parameters specifying the combustor design leads to an iterative process during the preliminary combustion chamber design process. The initial point is represented by the engine performance parameters, the flight envelope and the geometric requirements. These basic data are connected to design rules, which are fixed by state-of-the-art combustion chamber design. Based on these parameters and rules, combustor form and size, air distribution, and zonal stoichiometry are derived. To provide these data a database was generated in EXCEL containing the most import design parameters of different state-of-the-art RR

(Rolls-Royce) combustors.

Via data interface the layout data is transferred to the commercial CAD software tool Unigraphics. Thereby a parametric CAD model is derived. This model provides the basis for the automatic grid generation and CFD analysis. Commercial software is utilized for the automated grid generation (ICEM-CFD) as well as for the CFD analysis.

The initial combustor design layout is iteratively adjusted using (mostly computerized) preliminary design tools. Such tools calculate for example the air distribution and flow angles into the combustion chamber. Calculations are based on a fixed arrangement of combustor wall and casing contours. Air distribution and size of the mixing and cooling holes respectively are also fixed. Using the hole areas and arrangements of the mixing holes, the tool calculates the discharge coefficients c_d from suitable correlations. Then the mass flow and local pressure distribution can be calculated using a network solver. Other preliminary design tools are used for example to estimate further requirements like relight or pullaway capabilities.

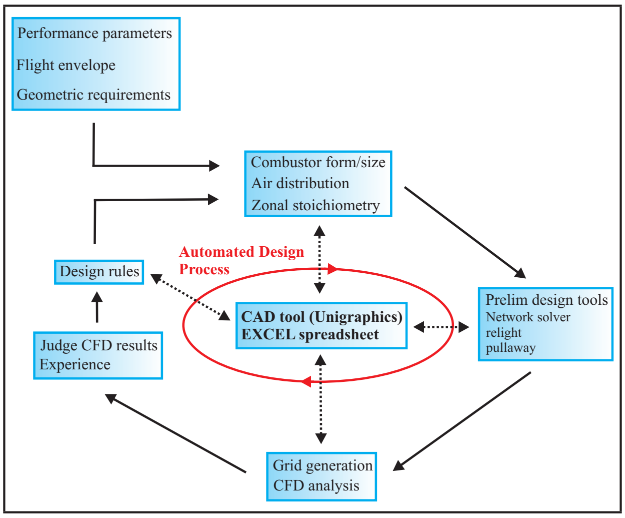

Fig. 7 Iterative preliminary combustion chamber design process

After iterating the preliminary combustor design to achieve the basic performance characteristics, a CFD-grid is generated, using calculated parameters as aerothermal boundary conditions. The CFD simulation then yields fluid flow and temperature fields. From this, the gaseous emissions and tendency towards smoke emissions can be calculated. Resting upon the experience from former combustor design campaigns, the CFD results will be judged and the CFD model will be adapted if necessary.

As a last step the preliminary model is checked concerning the conformity with all relevant design rules prescribed by the engine manufacturer. At this point, additional particular geometrical and aerothermal rules can be incorporated. The whole process is iterated, changing the input parameters, until all requirements are fulfilled adequately. An overview of the process flow, critical parameters and the conformity with influencing variables and conditions is given in figure 7.

4 Preliminary Design Process Chain

The usage and interconnection of the aerothermal and geometrical parameters and the steps in which the preliminary combustor model is built up can be specified in a process chain. The design steps, beginning with the layout of the contour and ending with the CFD analysis, are described in the following.

4.1 Layout of the combustor contour

Starting the combustion chamber design process certain layout parameters are already fixed. These initial parameters are the performance parameters and the geometric data for the compressor exit and the turbine entry.

Based on the geometric data, geometric gauge points are derived defining the combustor entry and exit levels and areas. Assuming a design rule for the cowl entry level, e.g. compressor exit and cowl entry level are placed on the same radius, another gauge point is fixed. Based on formula 1 the volume, required for an efficient combustion is calculated.

Gauge points specifying the combustor contour can be derived from state-of-the-art combustion chambers. The combustor contour is moved axially along the specified line of the position of the combustor head (figure 8) until the required volume V_{CC} is reached. This calculation is done by an EXCEL spreadsheet.

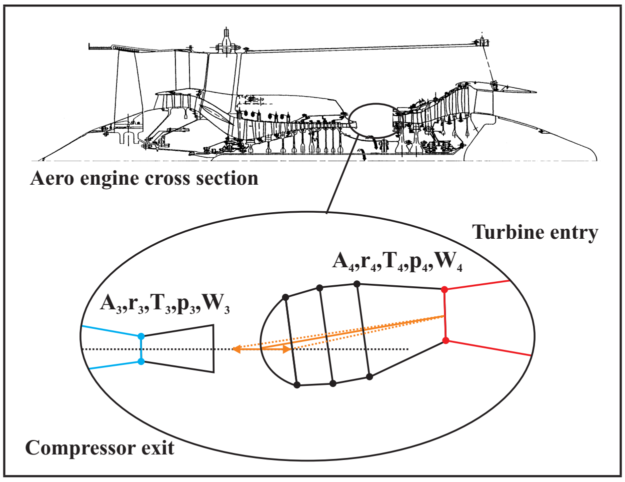

Fig. 8 Compressor exit and turbine entry

4.2 Combustor cooling

As the lengths of the combustor liners and the heatshield dimensions are fixed by the contour design, the cooling layout can be started. First a cooling system has to be chosen. At present two types of combustor wall cooling are available in the combustor design system, z-ring and effusion cooling.

For both types one dimensional heat transfer equations are solved by the EXCEL spreadsheet. Radiation, convection at the liner inner and outer wall and the conductive heat flow through the wall is taken into account. For the effusion cooled system convection inside the effusion cooling holes is also included in the heat flow balance. In terms of a z-ring cooled liner this heat transfer inside the cooling holes can be neglected (figure 9).

The EXCEL spreadsheet calculates the heat transfer coefficients based on well-known correlations [10]. As the zonal AFRs are fixed by design rules to guarantee a high combustion efficiency and low emissions, zonal equilibrium temperatures can be calculated to approximate

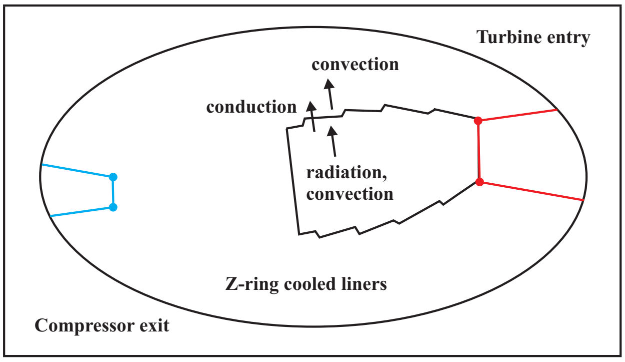

Fig. 9 One dimensional heat transfer at z-ring liners

the real temperature levels inside the combustor. Based on these temperature values the cooling layout is done [11].

4.3 Zonal stoichiometry and air distribution

The mixing air flows are adjusted until the zonal AFRs fixed by the design rules are reached.

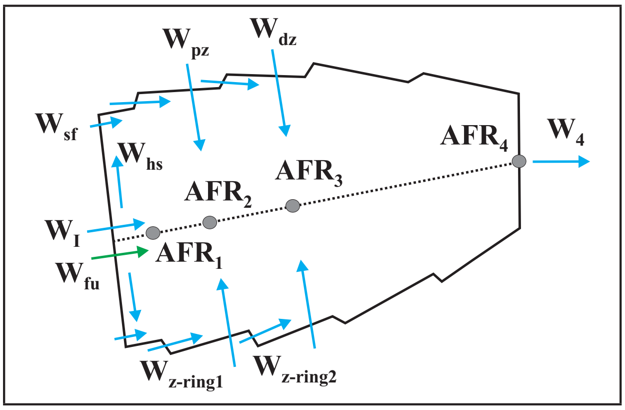

Fig. 10 Combustor air distribution

The layout process is described here for the primary mixing ports layout.

Based on the fixed AFR_4 and mass flow W_4 at the combustor outlet, the required fuel flow W_{fu} is calculated:

$$W_{fu} = W_4 \cdot AFR_4 \tag{2}$$

As the fuel flow and the AFR_1 at the injector are fixed, the injector air flow W_I is calculated:

$$W_I = W_{fu} \cdot AFR_1 \tag{3}$$

Based on the definition of AFR_2 the required cooling air provided by the primary mixing ports is calculated:

$$AFR_2 = AFR_1 + (d \cdot W_{hs} + e \cdot W_{sf} + f \cdot W_{z-ring1} + g \cdot W_{pz}) \quad (4)$$

$$W_{pz} = \frac{1}{g} \cdot (AFR_2 - AFR_1 - d \cdot W_{hs} - e \cdot W_{sf} - f \cdot W_{z-ring1}) \quad (5)$$

The same procedure applies for the layout of the dilution and post dilution holes respectively. As the mass flows, which have to be provided by the holes are fixed, the hole diameters are designed based on type of hole (plain, plunged or chuted hole) and discharge coefficient c_d. Moreover the jet penetration is taken into account utilizing well-known correlations [9].

4.4 Prediffuser, casing and cowl design

In a next step, prediffuser, casing and cowl are designed (figure 11).

The prediffuser has to reduce the flow velocities to a minimum for assuring maximum available static pressure in the combustor at low weight and costs. Therefore maximum diffusion at minimum length is desired. The area ratio required to allow for a fixed tolerable pressure loss is calculated based on the continuity equation. Area ratio and maximum allowable prediffuser length are derived from suitable correlations [9] in order to prevent flow separation. Moreover friction losses are minimized.

The casing is designed based on the requirements of fixed flow velocities in the inner and outer annuli. The flow in the combustion chamber can be approximated as incompressible because of the low velocities downstream of the prediffuser [12]. Hence the velocities only depend on the geometry, i.e. inner and outer annuli height respectively. These values are calculated within the EXCEL spreadsheet at certain gauge points and connected by a spline function.

Geometric rules, in this case length to depth ratios and a maximum flow deflecting angle define the cowl geometry and the dump gap between cowl and prediffuser.

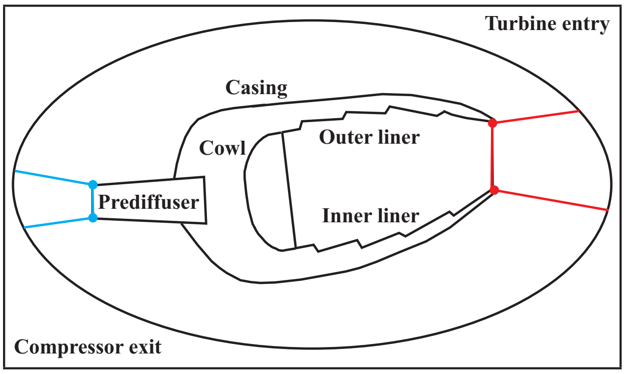

Fig. 11 Combustor parts

4.5 Parametric combustor CAD model

All combustor parts are defined and stored within the EXCEL database. For visualization purposes and to provide the geometry for the automated mesh generation, a parametric CAD model has to be designed. This is done via the CAD software Unigraphics internal interface "knowledge fusion". The interface allows for a data transfer between the EXCEL spreadsheet and a parameterized CAD geometry (figure 12).

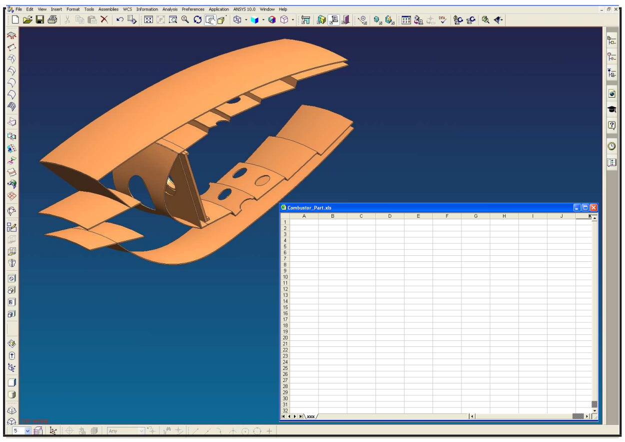

Fig. 12 Parametric combustor CAD model

4.6 Automatic mesh generation

On the basis of the parametric CAD model, the automated mesh generation is performed utilizing the commercial grid generation tool ICEM-CFD. Via the ICEM direct CAD interface, the Unigraphics data is transferred directly to ICEM, no data exchange format (Step or IGES) is necessary. Therefore geometrical discontinuities are avoided.

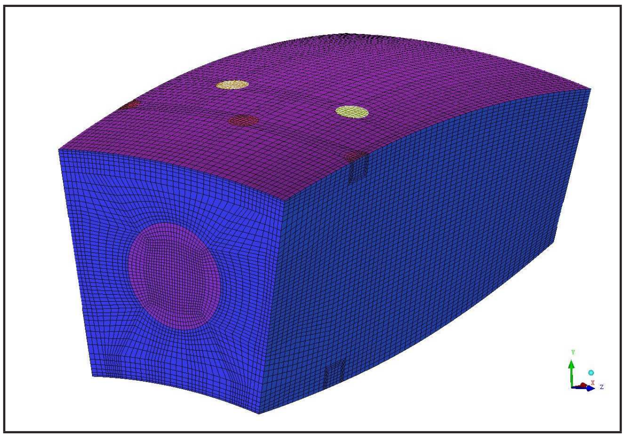

Fig. 13 Automatically generated combustor mesh

A block structured grid is used to assure reproducibility concerning the automated mesh generation (figure 13). Moreover, different CFD calculations show more consistent trends, if computational grids are similar. Due to the same mesh topology for all geometries, the results are nearly mesh independent.

The automated grid generation is performed using an ICEM-CFD replay file. This file comprises the import of the CAD model, the definition of blocks, the association to the defined Unigraphics geometry and the adjustment of the mesh fineness. At present the automated mesh generation is done for the effusion cooled combustor.

4.7 CFD analysis

Utilizing the automatically generated mesh a CFD analysis is done. The CFD analysis is set up manually at present, but will be performed fully automatic in the future. A preliminary CFD result is shown in figure 14.

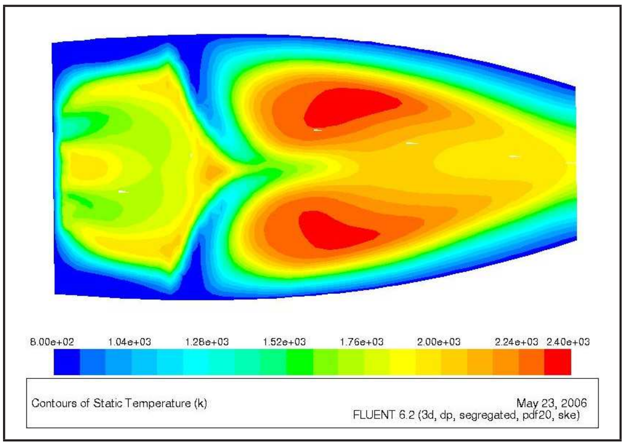

Fig. 14 Preliminary CFD result (temperature distribution)

The CFD analysis represents the last step of the combustor design iteration loop. Temperatures, emissions and mainly the zonal stoichiometry values and the mixing air distribution have to be judged by experience. If necessary input parameters or design rules are adapted and the layout process is iterated, until the combustor fulfills all requirements.

5 Performance parameter variation

The functionality of the combustor preliminary design system was proven by a variation of the performance parameters. As pressure, temperature or other input parameters change, the combustor geometry is adapted automatically.

Based on a temperature and pressure increase, the combustor volume decreases (figure 15). This is due to the calculation of the required volume V_{CC} (formular 1). Temperature and pressure accelerate the chemical reaction, so that a smaller volume is required to guarantee the same combustion efficiency.

A variation of the cooling system demonstrates the advantages of the effusion cooled combustor. As a result of the higher cooling efficiency more mixing air is available in the case of the effusion cooled combustor, for the same zonal

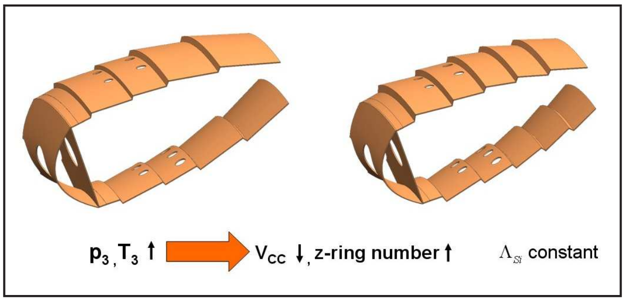

Fig. 15 Parameter variation

stoichiometry, allowing for larger mixing ports in the combustor walls (figure 16).

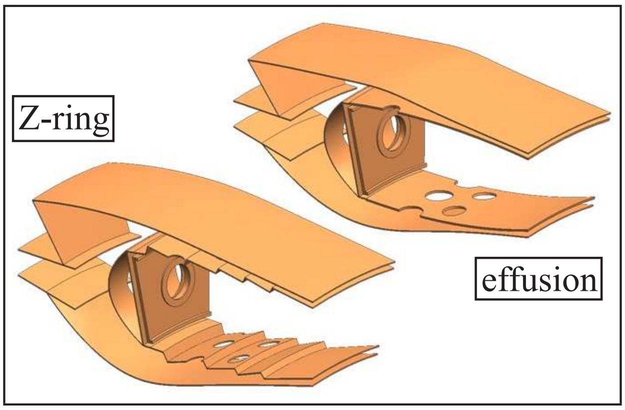

Fig. 16 Cooling system variation

The performance parameter variation and the variation of the cooling system show the advantages of the automated design system. New design evaluations can be done very fast and allow e.g. for parametric studies, to optimize the combustor design at a very early stage of the design process.

6 Conclusions

The automatic preliminary combustion chamber design seems to be very promising, as it helps the designer to get much quicker estimation concerning a new combustor layout. Therefore a methodology was developed to realize such an automated process. This contains the capturing of knowledge based rules and main low emission combustor design parameters.

These rules have to follow certain requirements, like the CAEP emission certification standards, combustor performance regulations and the requirements concerning the operability. The captured design parameters and rules are stored within an EXCEL database, which together with the parametric CAD model represent the main part of the automated design process. Due to the nonlinear interdependence of the different parameters specifying the combustor design, the combustor layout is done within an iterative design process.

Initially the combustor contour is designed. Since the liner and heatshield dimensions are fixed on the basis of the contour layout, the cooling calculations are performed. The remaining air is distributed through the mixing ports to satisfy the zonal layout criteria. In a next step prediffuser, cowl and casing are designed.

All combustor parts are defined within the EXCEL spreadsheet and visualized utilizing the CAD software Unigraphics. Via an internal interface the whole combustor geometry is generated using the EXCEL data. Based on the CAD model an automated mesh is generated using the commercial software ICEM-CFD and its direct CAD interface. At the end of the process chain CFD analysis are performed.

Utilizing this automated combustor design system a drastic time reduction from weeks to hours can be derived. Due to the short process runtime a lot more preliminary combustor configurations can be checked and changes required in the design are identified at a very early stage of the overall design process. In addition, the automated process chain allows easily the coupling to automatic optimization tools.

In the future the system will be improved by more detailed design rules and the incorporation of tile cooling. Moreover the CFD analysis will be performed automatically to close the automatic process iteration loop.

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