Influence of Air Intake Holes's Position for Primary and Secondary Zones on the Pattern Factor for Gas Turbine with Tubular Combustors Designed for Ethanol

E. Oliveira, J.R. Barbosa, and W.P. Martignoni

***Abstract*—** This research relates the positioning of the air intake holes for the primary and secondary zones of a tubular combustion chamber designed for ethanol use and the pattern factor of the gas exhausted from the combustor. The combustor was designed based on the available literature on combustion chambers design to fossil fuel, adapted to the use of ethanol. For design is used operational envelope data of an existent midsize power gas turbine aircraft. Are used one-dimensional design criteria with subsequent verification of the flow quality inside the combustion chamber through computational simulations (CFD) to calculate the 3D flow, viscous, compressible, turbulent and reagent, with spray. Correlations between the results of 3D calculations and parameters used in sizing for ethanol are obtained for tubular chambers. This work is part of a larger effort in progress, covering a wider range of power, not only for tubular combustors as well as for annular chambers. The results are encouraging and show the possibility of using ethanol as fuel in gas turbines with efficiencies comparable to those obtained with traditional use of fossil fuels as well as the important role of the positioning of the air intake holes on the adaptation of engines to alternative fuels.

***Keywords*—** Gas Turbine,Tubular Combustor, CFD, Traverse Quality, Pattern Factor, Ethanol Fuel.

NOMENCLATURE

3D Three Dimension
CFD Computation Fluid Dynamic
TQ Traverse Quality $[(T_{4Max}-T_{4Ave})/(T_{4Ave}-T_3)]$
ETC Equivalent Tubular Combustor
GTCD Gas Turbine Combustor Design
NSLF Near Sea Level Flight
CENPES Centro de Pesquisas da PETROBRAS
ITA Instituto Tecnológico de Aeronáutica
CTA Centro Técnico Aeroespacial
VBA Visual Basic for Application
AR Area Ratio
RZ Recirculation Zone
PZ Primary Zone
SZ Secondary Zone
DZ Dilution Zone
NH Number of Holes
ALT Altitude
LHV Low Heat Value [kJ/kg]
$\%_{air}$ Mass Flow Air Parcel of $\dot{m}$ [%]
S_N Swirl Number
M Mach Number
MFC Model Fuels Consortium™
A Area $[m^2]$
D Diameter [m]
L Length [m]
V Velocity [m/s]
A_{ref} Reference Area
b Inlet Temperature Factor [K]
O_2 Molecular Oxigen
T Total Temperature [K]
P Total Pressure [Pa]
PR Pressure Ratio (P_3/P_1)
NO Nitric Oxide
NO_2 Nitrogen dioxide
NO_x Mono-Nitrogen Oxides (NO and NO_2)
Re Reynold Number
DO Discrete Ordinates Radiation Model
PDF Probability Density Function
k Constant [143.5]
$\dot{m}$ Mass Flow Rate [kg/s]
q Dynamic Pressure [Pa]
z Elemental Mass Fraction
f Mixture Fraction
$\overline{f}$ Mean Mixture Fraction
$\overline{f'^2}$ Mean Mixture Fraction Variance
$\overline{H}$ Mean Enthalpy
RANS Reynold Averaged Navier-Stokes

Greek Symbols

θ Correlation Parameter of Combustion Efficiency $[kg^{0.75} m \cdot s^{-3.5}]$
ϕ Equivalence Ratio $(O_2/\text{Fuel})_{Sto} / (O_2/\text{Fuel})_{Act}$

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Δ Delta
ψ Angle (Diffuser or Snout or Dome)[°]
β_{sw} Swirler Blade Stagger Angle (Flat Blade) [°]

Subscripts and Superscripts
$_1$ At Compressor Inlet
$_3$ At Chamber Inlet
$_4$ At Chamber Outlet
$_{Ref}$ Reference
$_{PZ}$ Primary Zone
$_{SZ}$ Secondary Zone
$_{DZ}$ Secondary Zone
$_{Max}$ Maximum
$_{Min}$ Minimum
$_{Ave}$ Average
$_i$ Chemical Element
$_{ox}$ Oxidizer
$_{fuel}$ Fuel
$_{diff}$ Diffuser
$_{air}$ Air
$_{act}$ Actual
$_{sto}$ Stoichiometric
$_{cas}$ Casing
$_{sw}$ Swirler, Swirl
$_s$ Snout
$_d$ Dome
$_{diff}$ Diffuser
$_{ov}$ Overall
$_h$ Hole
$_{we}$ Weak
$_{ri}$ Rich
$_{lim}$ Limit
$_{in}$ Inlet
$_{out}$ Outlet

I. Introduction

THIS work is part of an effort to develop a methodology to combustion chambers design of gas turbines facing the use of ethanol as fuel efficiently. In large part, this depends on the optimal placement of the air intake holes for the primary and secondary areas, regarding the temperature traverse quality, TQ (Traverse Quality) gases exhausted. To do so, we use one-dimensional design criteria with subsequent verification of the quality of flow within the combustion chamber through computational simulations (CFD) to calculate the 3D flow, biphasic (spray), viscous, compressible, turbulent and reactive. Results of 3D calculations and parameters used in sizing for minimum TQ are correlated to the end.

Started from the available data and obtained operational envelope of an existing gas turbine, using computational procedures for combustor design based on methodology developed by Lefebvre [1] and Melconian and Modak [2] and came to the preliminary dimensions of an Equivalent Tubular Combustor, ETC, object of the study. This strategy enables the analysis and correlation of results with the parameters of a well-known methodology, from which one derives ETC. Thus, it becomes possible, in large part, the shortage of data relating to existing combustors, resulting from industrial confidentiality common to engine manufacturers. With the dimensions specified, was sought to positioning row of holes of primary and secondary zones that allow the optimization of the distribution of temperature at the exit of the tubular chamber, using calculation results of the flow in the chamber for a finite set of these positions rows. For the research, the alternative fuel used is anhydrous alcohol. The engine from which data are used to get operational envelope for the respective ETC is the gas turbine aircraft Allison 3007A - 2 SAHFT ENGINE, medium power. Data for simulations with atomized fuel are obtained from laboratory tests of high pressure nozzle, used in various small and medium power gas turbine. Several scientific software are used to support the generation of data unavailable in the literature.

II. Classical Design

2.1 Classical Design

For the preliminary design of the combustor was developed a computational tool ("GTCD - Gas Turbine Combustor Design"), implemented in EXCEL; the code has been wrote in VBA. The GTCD is based on approaches zero and one-dimensional developed by Lefebvre [1] and Melconian and Modak [2]. With this tool it is possible to get the preliminary design of combustors tubular, annular and can-annular. The GTCD also enables the design of combustors fueled by both kerosene and ethanol, and may additionally be adapted to other fuels, provided that changed the thermochemical parameters of temperature increase as a function of equivalence ratio for fuel adopted.

Such a design methodology, in which GTCD is based, takes into account for the design of combustors, two criteria that must be met in all conditions of the operating envelope of the combustor: aerodynamic and thermochemical. Obtained for both criteria the reference area (Aref), corresponding to the cross-section of the casing of the combustor. It is adopted in designing the reference area that meets both criteria above. Defined Aref, obtained following calculations performed by the tool, the other parameters, the main ones being :

- Diameter of the flame tube ;
- Longitudinal lengths of the zones primary, secondary and dilution;
- Mass flows of cooling devices (if needed), swirler and primary, secondary and dilution holes;
- Dimensions of the diffuser, swirler and snout ;
- Flame temperatures in the three zones of the combustor.

2.1.1 Aerodynamic Criterion

Generally, if the combustor is dimensioned for a certain pressure loss, it will be large enough to accommodate the chemical reaction [2]. The mixing process of fuel and air is extremely important. A good mix in the primary zone is essential for high burning rate and to minimize NOx and soot formation. In addition, to obtain a proper temperature

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distribution at the exit of combustor it is also necessary a certain intensity of mixing for dilution air with the combustion products of that zone. A satisfactory mixture air-fuel inside the flame tube, and a relatively steady flow throughout the chamber, are objective in the design of combustor, leading consequently to shorter combustors and lower pressure losses.

By the aerodynamic criterion, preliminary casing and flame tube diameters are estimated using (1) and (2), taking account the typical values of Table 1 for the dimensionless parameters present in (1)

$$A_{ref} = \left[k \cdot \left(\frac{\dot{m}_3 \cdot \sqrt{T_3}}{P_3} \right)^2 \cdot \left(\frac{\Delta P_{3-4} / q_{ref}}{\Delta P_{3-4} / P_3} \right) \right]^{0.5} \qquad (1)$$

$$A_{ft}/A_{ref} = 0.7 \qquad (2)$$

The aerodynamic phenomena play a vital role in the design and performance of the combustion system for gas turbines. As already mentioned, generally, if the aerodynamic design is satisfactory and the fuel injection system is suitable for the combustor, so do not expect operational problems. Nevertheless, it is necessary to consider all possible factors before making a final choice, hence the need for design verification considering the thermochemical criteria.

TABLE I
REPRESENTATIVE VALUES OF PRESSURE –LOSS TERMS FOR AIRCRAFT ENGINE COMBUSTORS

Chamber Type	$\frac{\Delta P_{3-4}}{P_3}$ %	$\frac{\Delta P_{3-4}}{q_{ref}}$	$\frac{\dot{m} \cdot \sqrt{T_3}}{(A_{ref} \cdot P_3)}$
Multi-Can	5.3	40	3.0×10^{-3}
Annular	6.0	20	4.5×10^{-3}
Can-Annular	5.4	30	3.5×10^{-3}

$$\frac{\Delta P_{3-4}}{P_3} = 143.5 \cdot \frac{\Delta P_{3-4}}{q_{ref}} \cdot \left[\frac{\dot{m}\sqrt{T_3}}{(A_{ref} \cdot P_3)} \right]^2$$

2.1.2 Thermochemical Criterion

The primary zone must promote an increase in the temperature of the intake air through a combustion as efficient as possible. The□ parameter in (3) [1,2,3] indirectly relates the combustion efficiency to operating parameters (temperature, pressure and mass flow rate of air).

$$\theta = \frac{\left[P_3 \cdot A_{ref} \cdot D^{0.75} \cdot \exp(T_3 / b) \right]}{\dot{m}_3} \qquad (3)$$

It is known that all the combustors have combustion efficiency close to 100% when θ approaching 73 x 106 (SI units) [2,3]. Thus, attempts to calculate A_{ref} with θ in this value. The correction factor b, dependent on ϕ_{PZ} (which in turn depends on the type of fuel) is used in (1) to adjust T_3. The operating limits (flammability) of the combustor depend on minimum and maximum PZ equivalence ratio, ϕ_{PZ}, determined by the curves of this variable as a function of temperature in the primary zone, T_{PZ}. This parameter ϕ_{PZ}, in turn, depends on the fuel used. Moreover, the adiabatic temperature in the primary zone is also a function of ϕ_{PZ} and, within the flammability limits, varies according to the characteristic curves of each fuel. The effect of pressure on the minimum and maximum, as well as on the evolution of T_{PZ} with ϕ_{PZ} is not taken as significant for the preliminary design phase.

From the temperature in the primary zone, the temperatures are set in other areas. In GTCD these temperatures influence the other combustor dimensional parameters such as the distribution of film cooling devices (if required). In GTCD are implemented ϕ_{PZ} x T_{PZ} curves for both kerosene and ethanol. Of the latter, the curves were obtained from the work of Bohorquez, Barbosa et al [4], based on the methodology developed by Gordon and McBride [5], in turn based on thermochemical equilibrium and applied in the design of gas turbine combustors by Lazaroiu [6]. The impact of the fuel type in the combustor design is manifested in the distribution of flow between the rows of holes in the three zones of the combustor. This is reflected, finally, in geometric differences between equivalent combustors that use different fuels.

TABLE II
OPERATING ENVELOPE DATA OF ALLISON 3007A 2-SAHFT ENGINE

Variable	**Unit**	**Take-Off**	**Cruise**	**Relight**	**NSLF**
$\dot{m}_3$	kg/s	23.544	9.78	8.58	25.56
$\dot{m}_f$	kg/s	6,61e-1	2,34e-1	1,78e-1	7,25e-1
P_3	Pa	2,27e6	8,81e5	7,9e6	2,48e6
PR		22.72	22.138	21.82	22.245
T_3	K	787.04	686.720	656.30	801.62
ALT	m	0.00	10000,00	10668,00	0.000
M		0.00	0.80	0.30	0.40
V_3	m/s	127.60			
V_4	m/s	365.69			
A_3	m^2	1,55e-2			
A_4	m^2	1,77e-2			

TABLE III
RESULTS FROM GTCD VARIABLE UNIT ETHANOL KEROSENE INPUT

Variable	**Unit**	**Ethanol**	**Kerosene**	**Input**
$\dot{m}_3$	kg/s	2,94	2,94	Yes
$\dot{m}_f$	kg/s	0,13	0,13	Yes
LHV	kJ/kg	26800,00	43260,00	Yes
$\%_{min\ air,PZ}$	%	27,00	27,53	
$\%_{air,PZ}$	%	30,00	30,00	
$\%_{air,h,SZ}$	%	37,50	38,83	
$\%_{air,h,DZ}$	%	32,49	31,17	
$\%_{air,sw}$	%	6,66	7,20	
ϕ_{ov}		0,41	0,41	
$\phi_{we,PZ}$		0,54	0,35	
$\phi_{ri,PZ}$		1,78	2,29	

T_4	K	1738,23	1703,13	
$\Delta P_{3-4}/P_3$	%	5,17	5,17	
D_3	m	4,96E-02	4,96E-02	Yes
$D_{s,in}$	m	2,67E-02	2,91E-02	
D_4	m	5,46E-02	5,38E-02	Yes
D_{ft}	m	1,82E-01	1,90E-1	
L_{diff}	m	2,28E-01	2,34E-01	
L_{PZ}	m	1,36E-01	1,42E-01	
L_{SZ}	m	9,09E-02	9,48E-02	
L_{DZ}	m	2,25E-01	2,34E-01	
L_s	m	1,67E-01	1,68E-01	
L_{total}	m	7,49E-01	7,77E-01	
AR_{diff}		3,35	3,68	
ψ_{diff}	°	18,59	19,16	
ψ_s	°	24,89	25,53	
ψ_d	°	75,00	75,00	Yes
β_{sw}	°	70,00	70,00	Yes
$D_{sw,inner}$	m	2,23E-02	2,32E-02	
$D_{sw,outer}$	m	5,53E-02	6,09E-02	
S_N		2,04	2,02	
NH_{PZ}		8	8	
NH_{PZ}		8	8	
NH_{DZ}		8	8	
$D_{h,PZ}$	m	1,23E-02	1,24E-02	
$D_{h,SZ}$	m	1,32E-02	1,34E-02	
$D_{h,DZ}$	m	1,22E-02	1,19E-02	
V_4	m/s	364,36	358,59	

Table III displays the results of calculations made by GTCD. It presents the main geometric dimensions and flow rates resulting not only for operation with ethanol but also with kerosene (the latter for comparison only).

It is remarkable how little effect has exchanging fuel - kerosene by ethanol – on the values obtained during the one-dimensional design. This reinforces the need for research on the aerodynamic flow that best fits the thermochemical characteristics of the alternative fuel. Aerodynamics of flux for air and combustion gases, when burning ethanol, is a direct function of the positioning of rows of PZ and SZ holes. This analysis is possible in the following stage, via the CFD.

The relationship between engine annular combustor of reference and ETC has been established, whereas 1/8 of the mass flows of air and fuel in the combustor reference acting similarly to the areas of entry and exit of the combustor. Thus, for calculation purposes, the reference combustor would be equivalent to 8 ETCs. In other words, a hypothetical replacement of the reference combustor would be for a multi-can and not just a single tubular combustor, which would greatly distort the original engine diameter/length ratio. Therefore, the entire calculation performed in GTCD as well as in the subsequent stages of the work match one ETC, equivalent to 1/8 of the reference annular combustor.

III. CFD Optimization

Having the dimensions obtained from previous phase, it moved to the preparation of three-dimensional geometric model. A 3D model fully parameterized was developed in DesignModeler™ from scientific software package ANSYS 14.5 Workbench™®. Taking advantage of axi-symmetry inherent to the tubular combustor type, a sector accounting for 45° of the full casing circumference was taken as the computational domain, in order to reduce the computational cost, without considerable loss of results quality, once respected the periodicity in distribution of holes on primary, secondary and dilution. Fig 1 and 2 show, respectively, the geometric model and computational domain of ETC derivative thereof, which is used in the next step, numerical mesh generating.

The computational domain discretization (numerical mesh generation) software was realized in Meshing™, the same package of scientific software (ANSYS® Workbench™ 14.5). The domain was divided into five regions volumetric, seeking structured mesh, hexahedral mostly, for the most part of these regions (multi-block structured strategy) except swirler, totaling approximately 2.2 million of cells. Mesh independence tests showed that this degree of refinement in the discretization is satisfactory to ensure the quality of the results. The results were compared with meshes of 1, 1.5 and 2.2 million cells, indicating that the mesh used (2.2 million) meets the desired accuracy of the results.

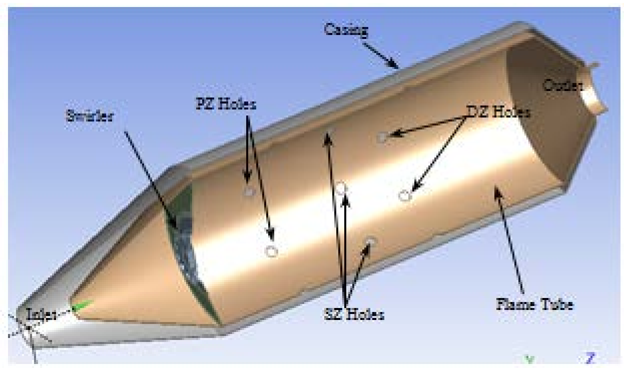

Fig. 1 ETC Geometric Model

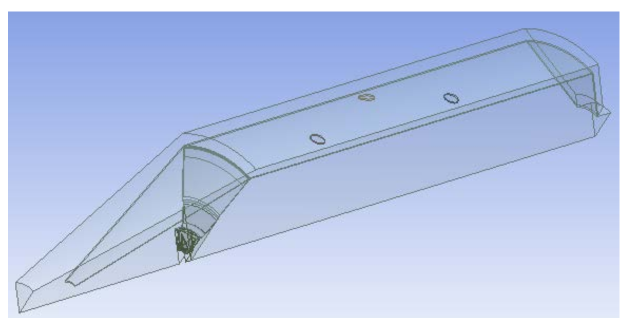

Fig. 2 Computational Domain – 1/8 of ETC

3D simulations were carried out using the CFD software FLUENT, which also integrates ANSYS□ package. In the RANS context, pseudo-transient [10], compressible, viscous, the turbulence model was adopted SST□-□ [7], based on the work of Mongia [8] and Gobatto et al [9] with corrections for curvature and low Re. For the radiation modeling was used Discrete Ordinates (DO) [10]. The fuel spray was modeled using Rosin-Rammler Diameter Distribution Method [10] from laboratorial data of the spray nozzle used on engines with similar power to the reference engine, the same pressures and temperatures. As laboratory results, was obtained droplet diameter ranging from 5 to 80□m and average diameter of 37.8 □m, with Spread Parameter of 2,706, equal number of streams 60 and particle velocity 29,00 m/s from injector outlet, at 30□C. The Vaporization Temperatu re was adjusted according to the Antoine equation [11]. Further refinements to the model were as follows:

- Particle Radiation Interaction;
- Thermophoretic Force;
- Pressure Gradient Force;
- Two- Way Coupling Turbulence.

For the combustion modeling, was the adopted Non-Premixed Combustion [10] approach. With this model, the solution of the transport equation for the mixture fraction, (4), is performed and the resulting thermochemical calculations are tabulated for look-up tables to be used in FLUENT during CFD running. The interaction between turbulence and chemistry follows a PDF function. For this treatment, the system was considered Non-Adiabatic; in other words, the enthalpy does not vary linearly with the fraction of the mixture, depending also on the heat transfer through walls and / or radiation.

$$f = \frac{(z_i - z_{i,ox})}{(z_{i,\,fuel} - z_{i,ox})} \qquad (4)$$

The Non-Premixed Combustion approach allows significant computational savings since the scalar combustion such as density, temperature and fraction of species become functions only , e . This allows the generation of a preliminary 3D look-up table for searching, during CFD calculation, as already mentioned, avoiding the need of calculating these scalar. The generation of the PDF table derived from the use of detailed kinetic mechanism for ethanol in a previous generation library flamelets [10], based on the concept developed by Peters et al [12,13,14].

The master kinetic model, detailed, for the combustion of ethanol is derived from the Model Fuel Library maintained by Reaction Design [15] – proprietary software CHEMKIN – and funded by investment consortium, MFC, consisting of industries, primarily from areas of propulsion, energy and petrochemical. The master kinetic mechanism considers 121 chemical species and 840 reactions. To be used in FLUENT, was required to reduce it, passing to 45 species and 343 chemical reactions. The mechanism reduction was performed with the scientific software CHEMKIN -MFC 6.5, specifically in Reaction Workbench□ module [15].

Were varied hole positions of the primary and secondary zone, keeping fixed the position of the dilution zone. Each row of holes positioning was allowed to four different points along the length of the respective zone. For this purpose each zone (primary and secondary) has its length divided into 4 parts: 25%, 50%, 75% and 100% of their respective length. Thus, a 4x4 array with 16 different configurations was obtained.

Each case demanded about 10 hours of processing in 176 processor cluster with 84 machines, each with two Intel Xeon E5-2679 (8 cores per processor), installed on CENPES. The machines have 32GB of memory and interconnection network, Infiniband 40 Gbps. After time consuming step of post-processing and mathematical treatment of the results, these might be condensed in the graphs of Fig. 3 and 4.

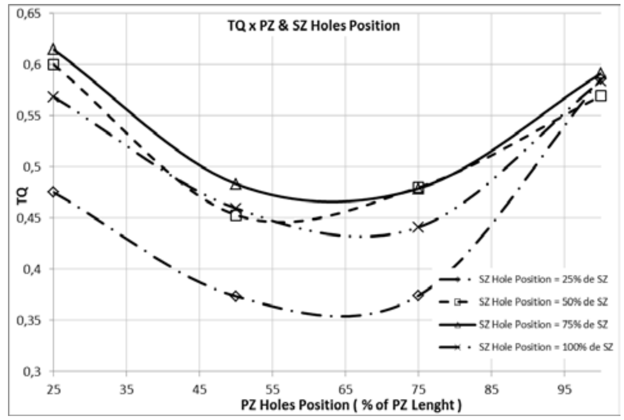

Fig. 3 TQ x PZ & SZ and SZ Holes Row Position

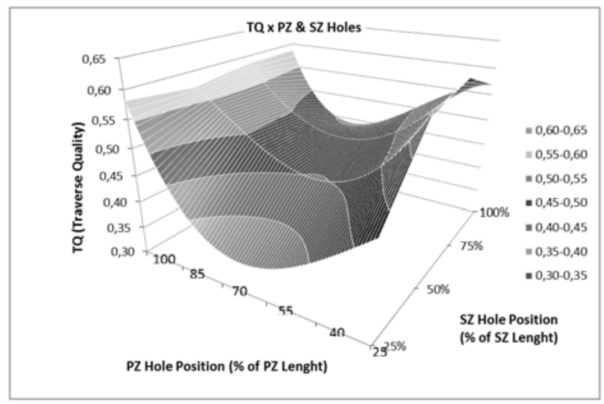

Fig. 4 3D Grafic for TQ x PZ and SZ Holes Row Position

Figure 5 shows, for case of minimum TQ, the temperature distribution in an axial plane passing through a hole in the PZ, distributed combustor exit in detail.

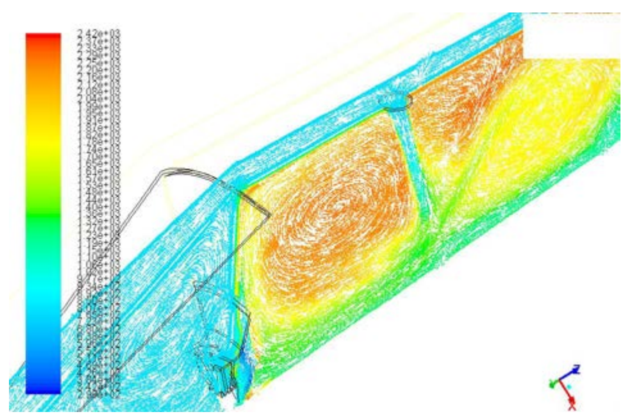
Fig. 5 Flow Vectors in RZ for PZ Holes at ¾ of PZ Length (Vectors Colored by Static Temperature (K)

By Fig. 3 and 4, it can be concluded that the positioning of the PZ holes has an sharper influence on TQ than the positioning of SZ holes, except for positions in the first half of the SZ length it also has significant influence. TQ proves very sensitive to rows of holes displacements of in this region. Particularly for the row of PZ holes, a plausible explanation is based on the fact that there is a strong recirculation zone in the first three quarters of the PZ length. This condition is observed when positioning the PZ row in downstream these ¾, in other words, between 75% and 100% of the PZ length. This is consistent with Melconian and Modak [2] work which recommend, for the preliminary design of combustors, to place the row of PZ holes on the axial position indicated by the tangent (perpendicular to the axial direction of the combustor) of the "Magic Circle" which, by the GTCD results, corresponds about 90% of the PZ length. One possible explanation for the strong influence on TQ that has the row position of SZ holes on the the first half of the length of this area is that part of the amount of momentum flux from these air jet holes enhances the recirculation zone installed on PZ. The more intense this phenomenon, the greater the rate of mixing, residence time of fuel and combustion efficiency in the PZ, thereby reducing the demand on the downstream zones in obtaining lower TQ's.

The values obtained for CO in mole fraction in the best TQ condition are lower than those obtained with some of the detailed kinetic mechanisms for methane combustion in the various conditions reported by Brewter et al. [16] are also consistent with experimental data from actual combustors operating with conventional fuels, presented in Mongia et al. [8]. Finally, it was found that the concentration of CO at the exit of the combustor is substantially insensitive to the position of the PZ holes row, since these holes are positioned downstream of half the length of the area. Positioning the row of holes before this point favors the increase in the amount of CO at the exit of the chamber. One explanation for this would be the decreasing intensity caused in the recirculation installed on this region, which in turn would decrease the rate of mixing, reducing the efficiency of combustion in the PZ.

IV. Conclusion

The main objective of this study is to analyze the influence of the placement of holes row of primary and secondary zones in a gas turbine combustor operating with anhydrous ethanol, over the distribution of the gas temperature ("Traverse Quality") at the combustor outlet.

The methodology of combining computational tool for one-dimensional design with subsequent use of CFD for checking the quality of the flow inside the combustion chamber was effective; a powerful resource in the study of complex flows such as occur inside gas turbine combustors, involving viscous, compressible, turbulent, and reactive flow, with spray. The results obtained are consistent with numerical data and the limited experimental information available in the literature.

The use of the artifice of a tubular combustor equivalent (ECT) proved useful to link the study characteristics and operating ranges of existing engines, which are not available geometric information and specifics of the design methodology used. Having the model of a 'generic' combustor, corresponding to an existing combustor, and relying on the classical methodology of design, available in the literature [1,2], known in detail and automated by computational resource (GTCD), it is possible establish useful correlations to later use this same methodology, optimized and adapted to alternative fuels.

Based on the results, we can say that the placement of rows of holes of the primary and secondary zones is an important factor in optimizing the distribution of temperature at the exit of the tubular combustion chamber for ethanol, as well as combustion efficiency, as suggested by the results obtained for CO and TQ.

The dimensions obtained from one-dimensional calculations, in general, vary little when switching from kerosene to ethanol. Despite the differences between thermochemical kerosene and ethanol, the optimal position of the rows of holes in the PZ and SZ also shows no great variation with respect to that obtained for conventional fuel combustors. This suggests reasonable interchangeability between ethanol and kerosene in existing combustors, without significant geometric modifications, despite being required adjustments in injection systems, control and possibly materials.

For the combustor simulated in this work, corresponding to ethanol engines of medium power, the placement of the PZ holes row to get the lowest rates of CO is best located as close to ¾ of the length of the PZ. It is necessary to assess the extent of this conclusion for an widened range of power that also covers ethanol engines for small and large power in accordance with classification Melconian and Modak [2].

Acknowledgments

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