Influence of Air Intake Holes's Position for Primary and Secondary Zones on the Pattern Factor for Gas Turbine with Annular 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 an annular 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) in order 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 annular chambers. This work is part of a larger effort in progress, covering a wider range of power, not only for annular combustors as well as for tubular 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, Annular Combustor, CFD, Traverse Quality, Pattern Factor, Ethanol Fuel.

NOMENCLATURE

3D	Three Dimension
CFD	Computation Fluid Dynamic
TQ	Traverse Quality $[(T_{4Max}-T_{4Ave})/(T_{4Ave}-T_3)]$
EAC	Equivalent Annular Combustor
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

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Greek Symbols

θ	Correlation Parameter of Combustion Efficiency $[kg^{0.75} m \cdot s^{-3.5}]$
ϕ	Equivalence Ratio $(O_2/\text{Fuel})_{Sto}$ / $(O_2/\text{Fuel})_{Act}$
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 of combustion chambers design for gas turbines facing the use of ethanol, efficiently, as fuel. 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 quality verification of the flow inside the combustion chamber through computational simulations (CFD) to calculate the 3D, biphasic (spray), viscous, compressible, turbulent, radiant and reactive flow. 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 with the aid of computational tool [22], [23], 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 Annular Combustor, EAC, 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 the EAC. Thus, it becomes possible, in large part, overcome 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 annular 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 EAC 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 computation programs are used to support the generation of data unavailable in the literature.

II. Classical Methodology

For the preliminary design of the combustor was developed a computational tool ("GTCD - Gas Turbine Combustor Design"), implemented in EXCEL; a code of approximately, 5.000 lines 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 tubular, annular and can-annular combustors. The GTCD also enables the design of combustors fueled by both kerosene and ethanol, and could 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 of the casing cross section (A_{ref}), corresponding to the combustor in study. It is adopted in designing the reference area that meets both criteria above. Defined A_{ref}, obtained the following calculations performed by the tool, 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.

A. 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 NO_x and soot formation. In addition, to obtain a proper temperature 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 aimed 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 I 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 x 10-3
Annular	6.0	20	4.5 x 10-3
Can-Annular	5.4	30	3.5 x 10-3

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

B. Thermochemical Criterion

The primary zone must promote an increase in the temperature of the intake air through combustion, as efficient as possible. The θ parameter in (3) [1]-[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 10^6 (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 summarizes the data from the operational envelope of the aircraft engine used as the basis for the design of the EAC. The data refer to the operation of the engine with jet fuel (43,000 MJ / kg).

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 FOR ATC

Variable	Unit	Ethanol	Input
$\dot{m}_3$	kg/s	$2{,}94^{(23.544/8)}$	Yes
$\dot{m}_f$	kg/s	0,13	Yes
LHV	kJ/kg	26800,00	Yes
$\%_{min\ air,PZ}$	%	27,00	
$\%_{air,PZ}$	%	30,00	
$\%_{air,h,SZ}$	%	37,50	
$\%_{air,h,DZ}$	%	32,50	
$\%_{air,sw}$	%	7,07	
ϕ_{ov}		0,41	
$\phi_{we,PZ}$		0,54	
$\phi_{ri,PZ}$		1,78	
T_4	K	1738,23	
$\Delta P_{3\text{-}4}/P_3$	%	11,62	
D_{ft}	m	1,01E-01	
L_{diff}	m	1,20E-01	
L_{PZ}	m	7,54E-92	
L_{SZ}	m	5,03E-02	
L_{DZ}	m	1,24E-01	
L_s	m	1,04E-01	
L_{total}	m	4,08E-01	
AR_{diff}		1,12	
ψ_{diff}	°	23,17	
ψ_s	°	24,99	
ψ_d	°	75,00	Yes
β_{sw}	°	60,00	Yes
$D_{sw,inner}$	m	1,38E-02	
$D_{sw,outer}$	m	2,96E-02	
S_N		1,33	
NH_{PZ}		$8^{(64/8)}$	
NH_{PZ}		$8^{(64/8)}$	
NH_{DZ}		$8^{(64/8)}$	
$D_{h,PZ}$	m	8,91E-03	
$D_{h,SZ}$	m	1,46E-02	
$D_{h,DZ}$	m	1,25E-02	
V_4	m/s	364,36	

Table III displays the results of calculations made by GTCD. It presents the main geometric dimensions and flow rates resulting for operation with ethanol.

For comparison, Table IV shows a version of Table III, with the results obtained in [21] also with the GTCD, now to the case of a tubular combustor equivalent (ETC), not only for use ethanol as fuel, but also for 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.

Comparing both type of combustors is remarkable a significant difference in the liner diameter, $D_{ft,}$ between the both type of combustors. To the AEC, D_{ft} corresponds to distance between the external and internal diameters of the flame tube cross section of the. The classical methodology of combustor design, more specifically the one summarized by Melconian and Modak [2], provides mathematical framework for three different design alternatives within the criterion thermochemical – Lefebvre-Halls [19], Bragg [17] and Odgers-Carrier. Among these three alternatives of designing, adopting the latter is discouraged by the lead authors because, almost always, the flame tube diameter obtained from this alternative is far superior to those obtained with the first two routes calculation. In GTCD, arbitrarily, the third route (Odgers-Carrier) is only considered when the diameter of the flame tube obtained does not exceed twice that the maximum one obtained with the other two routes (Lefebvre-Halls and Bragg). In this case, the route Odgers-Carrier was left out for not meeting the requirement above, exceeding by 3.7 times the greatest diameter obtained with Lefebvre-Halls and Bragg .

TABLE IV
RESULTS FROM GTCD FOR ETC

Variable	Unit	Ethanol	Kerosene	Input
$\dot{m}_3$	kg/s	$2{,}94^{(23.544/8)}$	$2{,}94^{(23.544/8)}$	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	
$\Delta P_{3\text{-}4}/P_3$	%	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	

For the case of tubular equivalent combustor (ETC) aforementioned, 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 of the ETC used in the comparison aforementioned. 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 EAC, equivalent to $^1/_8$ of the reference annular combustor.

III. CFD Optimization

The computational domain discretization (numerical mesh generation) software was realized in Meshing™, the same package of scientific software (ANSYS® Workbench™ 14.5). The domain encompasses one swirler and each row of holes of the three combustion zones (primary and secondary dilution) has four holes in the inner wall and four holes in the outer wall of the flame tube, considering the fact that AEC is designed to have Swirlers 8 and 64 holes in each zone, equally distributed between inner and outer wall of the flame tube. 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 3.5 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 (3.5 million) meets the desired accuracy of the results.

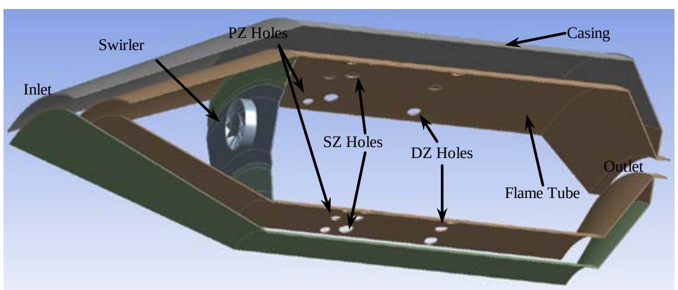

Fig. 1. EAC Geometric Model

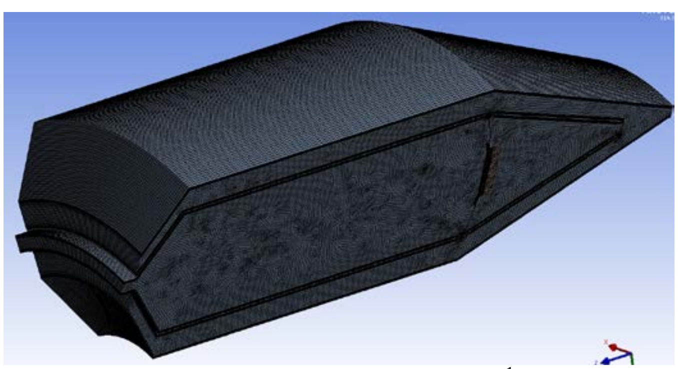

Fig. 2. Computational Domain and Grid – $^1/_8$ of EAC

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 κ-ϖ [7], based on the work of Mongia [8], Gobatto et al [9] and Rodrigues [20] 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 μm and average diameter of 37.8 μm, 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 Temperature 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.

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

The Non-Premixed Combustion approach allows significant computational savings since the scalar combustion such as density, temperature and fraction of species become functions only $\overline{f}$, $\overline{f'^2}$ e $\overline{H}$. 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 holes positions of the primary and secondary zone, keeping fixed the position of the dilution zone. Each row of holes positioning was allowed to be at 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 192 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 hard time consuming step of post-processing and mathematical treatment of the results, these might be condensed in the graphs of Fig. 3 and 4.

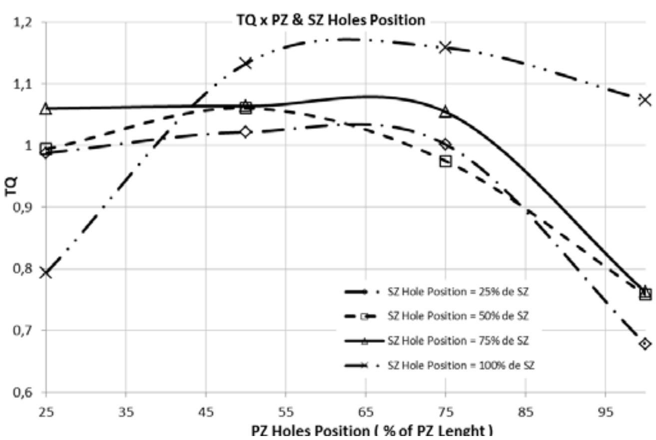

Fig. 3. TQ x PZ & SZ and SZ Holes Row Position (AEC)

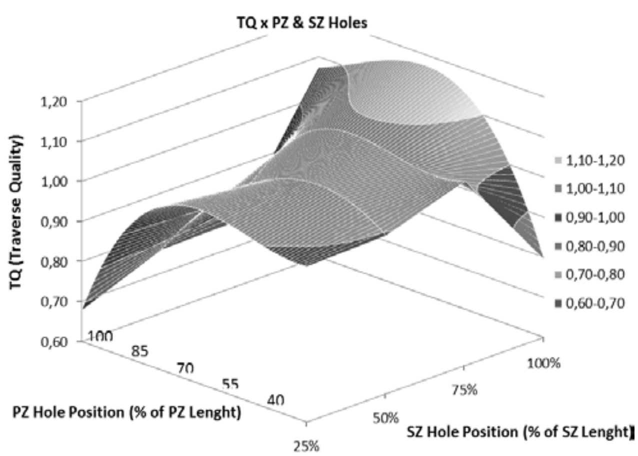

Fig. 4. 3D Map for TQ x PZ and SZ Holes Row Position for AEC

By Fig. 3 and 4, it can be concluded that the positioning of the PZ holes has a sharper influence on trend of TQ than the positioning of SZ holes, except for positions in the first half of the SZ length it also has significant influence.

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. Is remarkable a large portion of PZ occupied by gas at temperatures close to those of T_3, indicating inefficiency of this area to promote the combustion of fuel. Another aspect that draws attention is the large slope of the air jets from holes PZ, with respect to the radial direction, leading to penetration values jet lower and this is a cause for low intensity recirculation seen in Fig. 5.

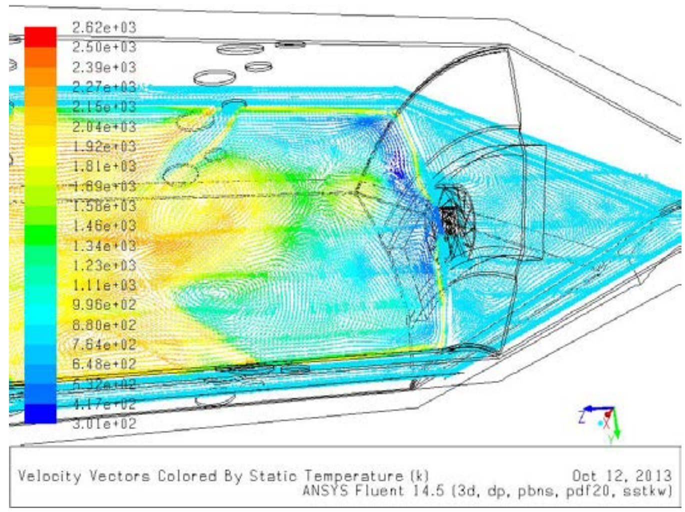

Fig. 5 Flow Vectors in RZ of the AEC for PZ Holes at 100% of PZ Length

For comparison, the Fig. 6 shows results over an ETC which has designed in a previous work [21], equivalent in power flow to eighth of the EAC in this article, both designed according to the same methodology and operating conditions. Is remarkable a significant worsening in TQ with AEC.

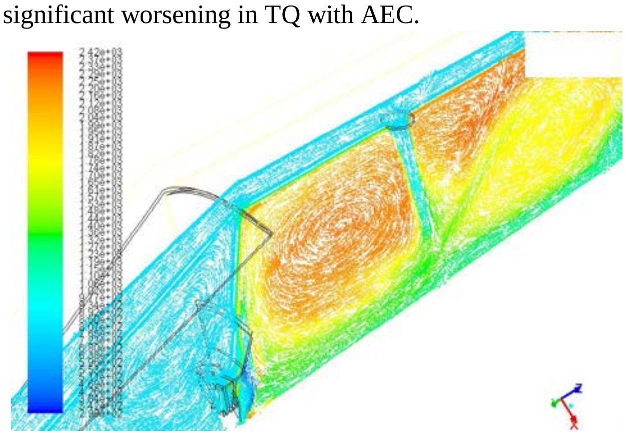

Fig. 6. Flow Vectors in RZ of the TEC for PZ Holes at ¾ of PZ Length (Vectors Colored by Static Temperature (K))

This indicates the need to adapt the default methodology for annular combustors design. Regardless, TQ proves still very sensitive to displacements of hole's rows in PZ. There is a recirculation zone – although partially – installed in the first three quarters the length of the PZ. It is remarkable that this recirculation zone is not shown as vigorous as that presented by its corresponding TEC [21]. This fact can be seen as another indication that the geometry dimensions obtained by default setup of the methodology for annular combustors, are below the required.

The more pronounced influence on TQ that has the row position of SZ holes on the first half of the length of this zone 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. On the map of Fig. 4, the increase in the values of TQ as a function of the position of the SZ holes's row depicts the contribution of these holes in the air supply to the recirculation zone, helping the combustion takes place in PZ. Its depart from PZ reduces this effect, unduly delaying the combustion of PZ and SZ to DZ even. However, this effect is also greatly reduced when compared to the TEC. As in the TEC case, has also been observed smaller TQ when positioning the PZ row downstream ¾ of the PZ length, albeit minimal TQ (PZ holes row @ 100% PZ length) for annular chamber remains above the maximum value found for TQ in the ETC. Melconian and Modak [2] 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 for tubular combustors; this was observed in the case of TEC. However, in the case of AEC, as there is no formed a recirculation zone well defined, this decline in TQ only occurs partially at the end of the length of PZ. For a given fixed position of the row of holes in SZ, there is no point of inflection in the curve TQ, as with TEC on which it is possible to easily identify a position for the holes in the PZ, as shown in Fig. 7.

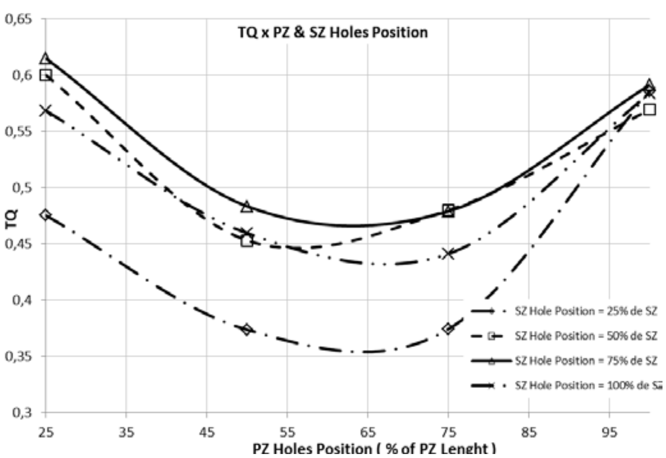

Fig. 7. TQ x PZ & SZ and SZ Holes Row Position (TEC)

In the AEC case, the curve on Fig. 4 informs that those points of minimum TQ would be in a position downstream of PZ length, in order to compensate for the negative effect caused by poor recirculation zone. The last indication that the flame tube is undersized, by adopting the default methodology is the fact that the values for CO obtained in mass fraction, in the best TQ condition, are larger than those obtained with some of the detailed kinetic mechanisms for methane combustion in the various conditions reported by Brewster et al. [16], as well as, with experimental data from actual combustors operating with conventional fuels, presented in Mongia et al. [8]. In the expectation that the assumptions above – about undersizing the AEC in relation to TEC – is the cause of their worst results with respect to TQ and CO, we've performed a CFD simulation with new dimensions obtained from GTCD, based on those TEC dimensioned successful. Seeking to increase the phenomenon of recirculation in the primary zone, the void area (space between flame tube and casing) was increased in order to reduce the annulus velocity and increase the annulus static pressure, thereby increasing the static pressure drop across the liner holes. This is desirable, since a high static pressure drop ensure that the air jets entering the liner have adequate penetration and sufficient turbulence intensity to promote rapid mixing with the combustion products. Unfortunately, for any fixed liner diameter, an increase in the annulus space can be obtained only at the expense of an increase area in annulus area. However, only for purpose of exploration, this was accepted. Additionally, the liner diameter has been raised approximately 30%. The result of this last attempt to improve the performance of the combustor is shown in Fig. 8.

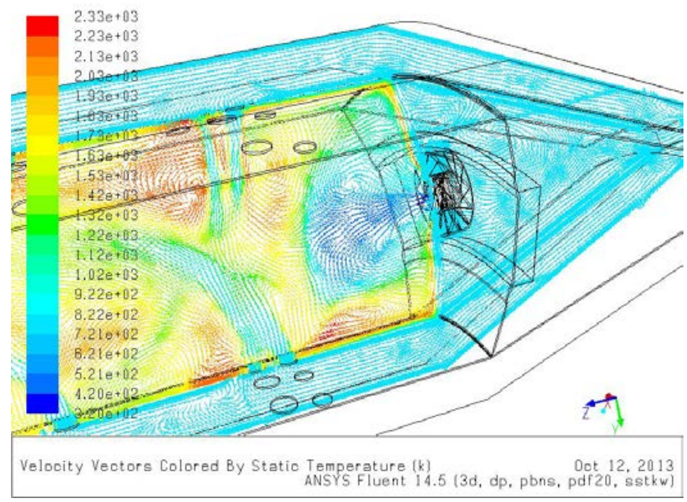

Fig. 8. Flow Vectors in RZ of the AEC Changes. PZ Holes at 100% of PZ Length

With this new configuration, where obtained for AEC TQ and CO emission values as satisfactory as those obtained for the TEC; even better. TQ obtained was close to 0.4. The average emission of CO has been reduced to a range of 0.025 g / kg of fuel, thus consistent with the experimental data in literature [8]

These new findings were obtained for PZ holes positioned at 100% of the PZ length and SZ and DZ holes positioned at 25% of the length of both zones. Besides the increase in the height of the annular space between the flame tube and the casing, to ensure greater penetration of air jets from the holes, another change that could intensify the recirculation RZ would be an increase in the angle of rotation of the blades swirler, β_{sw}. Lefebvre [1] indicates this parameter as a major influence on the amount of recirculated air in PZ. β_{sw} values near 65º are reported as a condition in which the flow of recirculated air in PZ is equal to that flow out of swirler. The changed

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dimensions for this modified configuration, obtained from the GTCD are shown in Table V.

TABLE V
RESULTS FROM GTCD OF AEC MODIFIED

Variable	Unit	Ethanol
$\%_{air,sw}$	%	8,20
$\Delta P_{3\text{-}4}/P_3$	%	11,62
D_{ft}	m	1,34E-01
L_{diff}	m	2,06E-01
L_{PZ}	m	1,19E-01
L_{SZ}	m	6,68E-02
L_{DZ}	m	1,90E-01
L_s	m	1,52E-01
L_{total}	m	5,89E-01
AR_{diff}		4,80
ψ_{diff}	°	23,17
ψ_s	°	21,41
ψ_d	°	75,00
$D_{sw,inner}$	m	2,09E-02
$D_{sw,outer}$	m	4,80E-02
S_N		1,33
$D_{h,PZ}$	m	9,53E-03
$D_{h,SZ}$	m	1,31E-02
$D_{h,DZ}$	m	1,21E-02
V_4	m/s	364,36

As foreseen in GTCD, increasing height in the annular space between liner and casing, the average angles values of the air jets from holes PZ, SZ and DZ relative to the central axis of the combustor went from close to 50 ° for 90º. As seen in Fig. 8, this contributes to the formation of a recirculation zone stronger than that seen in the combustor obtained from the default methodology.

The results of the modified annular combustor indicate the need to further explore the influence of others design parameters, beyond those originally proposed in this paper, that is, the positioning of PZ and SZ holes in the liner. Variations in the rotation angle of swirler blades, β_{sw}, at the time span between the liner and casing and the distance between the inner and outer walls of the flame tube, D_{ft} (equivalent to the tube diameter tubular flame burners) are objects of study already underway, highly demanding of computer resources, as well as, skills in programming, CAD, numerical mesh generating and CFD.

IV. CONCLUSION

The main objective of this study is to analyze the influence of the placement for PZ and SZ holes row in a gas turbine annular combustor operating with anhydrous ethanol, over the distribution of the gas temperature ("Traverse Quality") at the combustor outlet. A qualitative assessment of the CO emission is also made for different combustor configurations. Comparisons of results between an annular combustor and its equivalent tubular are made. For the study, is developed the concept of generic or equivalent combustors (TEC and AEC).

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 an annular equivalent combustor (EAC) 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 on primary and secondary zones is an important, factor in optimizing the distribution of temperature at the exit of the annular combustion chamber for ethanol, as well as combustion efficiency, as suggested by the results obtained for CO and TQ. However, other factors are also very important in a successful design of an annular combustor. In previous work [21], we have already seen that 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. However, for the case of annular chambers design, unlike what happens with the tubular, the adoption of the default parameters of the mathematical framework provided by the literature does not automatically lead to successful projects, requiring adjustments that can only be known through exploratory research in several settings, usually with the aid of CFD. For the generic annular combustor simulated in this work, corresponding to ethanol engines of typical medium power, the placement of the holes's row of PZ to get the lowest rates of CO and TQ is – likewise tubular combustors – best located downstream of the $^3/_4$ of the PZ length, regardless of the position of the SZ holes rows. It is necessary to assess the extent of this conclusion for a widened range of power that also covers ethanol engines for small and large power in accordance with classification Melconian and Modak [2]. This is an ongoing research.

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