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THE EFFECTS OF BURNING ALTERNATIVE LIQUID FUELS IN GAS TURBINE COMBUSTORS ON THE OVERALL OPERATING CONDITIONS AND PERFORMANCE

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Abstract. *Gas turbines are thermal machines with the great advantage of being capable of successfully burning a large variety of fuels in a continuous combustion process. Alternative liquid fuels are among possible fuels of interest, in addition to oil-derived fuels. Much research is being carried out in this field, aiming at the design and development of gas turbine combustors to successfully burn conventional and renewable fuels. A research to investigate the influence of alternative liquid fuels on the preliminary design, overall operating characteristics and performance of an industrial small size gas turbine combustor is reported. Design point and in-depth off-design analysis were performed to predict the operation parameters when burning alcohol fuels instead of diesel. The preliminary design, overall operating conditions and performance characteristics were calculated numerically using in-house developed computer codes, based on direct fuel injection, diffusion flames, stability loops and reaction mechanisms. Conclusions like air mass flow rate, fuel mass flow rate, pressure, combustion volume and type of used fuel have a marked effect on the stability of the combustion process and combustion advancement in the combustor zones, as well as the equivalence ratio in the primary zone, have important influence on the production rate of combustion products (CO, CO_2, NO_X and OH) at the combustor exit.*

Keywords: *Gas turbine combustor, alternative liquid fuels, combustion, reaction mechanisms, numerical simulation*

1. INTRODUCTION

A gas turbine combustor is the device responsible for the increase of the incoming airflow temperature through the addition of fuel and its subsequent combustion. The combustor should perform several requirements, among them the capacity to easily start the combustion and operate steadily on a wide range of conditions. In all operating points it should provide complete fuel combustion, while minimizing the formation of undesirable emissions. Many researches are being carried out in this field, aiming at the design and development of gas turbine combustors to successfully burning several types of fuels (Odgers and Kretschmer, 1986).

This manuscript contributes to the development of gas turbine combustors design technology using alternative fuels. This research is focused on the development of a methodology for sizing fuel flexible gas turbine combustors and analyzing the reacting flow in those combustors. As part of the work developed in the research for this paper, a numerical simulation for medium and high calorific value liquid fuels was accomplished and fuels such as ethanol and methanol were used.

Pressure, temperature and the equivalence ratio of the mixture were set and the chemical reactions for a stable equilibrium state were calculated. The chemical equilibrium was achieved when individual species, in the burned products, react to produce and remove each species at an equal rate. This is usually a good approximation in regard to the burnt products produced during the combustion of any fuel and air in gas turbine combustors (Stuttaford, 1997).

Among the scientific literature one can find much information related to topics such as flammability limits, fuel flexible combustor design, performance of combustion and emissions in combustion chambers. Nevertheless, these subjects were analyzed separately. It is necessary to emphasize that, in this work, all these topics are shown integrated into a global analysis using a computational tool developed for this special purpose.

The overall operating conditions are used to calculate flammability limits, the stability loops, the combustor geometric features, the performance of the designed fuel flexible combustor and characterization of emissions during the operation of the designed annular combustor. This study seeks qualitative information aiming at reaching an optimized design of the fuel flexible gas turbine combustor, for use as the starting point in other optimization studies related to the combustion chamber (Darby, 2001).

2. PHYSICAL AND MATHEMATICAL MODELLING

2.1 Alcohol fuels characterization

A great advantage of any thermal engine using a continuous combustion process is its capacity to burn with success a wide variety of fuels. Usually, the gas turbine combustors are developed for a specific single fuel (for instance, kerosene or synthetic fuels). The various types of liquid fuels that are available for gas turbines depend on various factors such as costs, availability, storage, handling, pollution and combustor type. In this study, for the numerical simulation, ethanol and methanol fuels were used. Table 1 shows some of their main characteristics (Lois, *et al*., 2002).

Table 1. Typical properties for ethanol and methanol fuels.

Property	Ethanol	Methanol	Unit
Formula	C_2H_5OH	CH_3OH	–
Enthalpy of vaporization	38.56	37.40	kJ/mol
Boiling point	351.2	337.7	K
Melting point	159	175.4	K
Flash point	286	285	K
Net Heating Value	27.2	22.7	MJ/kg
Critical temperature	514	513	K
Autoignition temperature	695	658	K
Critical pressure	6.3	8.07	MPa
Molecular weight	46.07	32.04	g/mol
Refractive index	1.36	1.33	–
Stoichiometric Air/Fuel	8.95	6.45	–
Specific gravity (15 ºC)	0.794	0.787	–
Energy density	21.6	15.6	MJ/l

In Brazil, anhydrous alcohol (C_2H_5OH) is a renewable fuel produced from sugar cane. It contains 35% oxygen by weight, boils at a temperature of 78 ºC and it has a high heat of vaporization due to its hydrogen bonding. These parameters are very important for fuel atomization and vaporization in the combustor. There are physical and chemical properties of ethanol that can be beneficially explored in gas turbine combustors, while other technical difficulties must be overcome (Hamelinck and Faaij, 2006).

Liquid methanol is an excellent motor fuel and fuel blending component. It may be used as fuel in diesel engines, gas turbines and fuel cells. It is a renewable fuel, with many uses. It can be produced from biomass and other energy sources. Methanol is an excellent fuel for gas turbines, but combustion turbines would have to be redesigned to make best use of its properties. Liquid methanol, in comparison with other conventional fuels has several differences that affect the operation of a combustion turbine. For example, methanol has a narrower flammability curve, featuring problems for transient operation (Specht and Bandi, 2012).

2.2 Performance predictions

General concepts can be used to define the layout, main component geometries and operational variables of a generic gas turbine combustor (O'Brien, 2002). Depending on the work requirements, these basic definitions may be extended to cover other combustor configurations and several types of components. The gas turbine combustor performance parameters that are most important for the overall engine performance presentation are pressure loss through the combustor, combustion stability and combustion efficiency (Mattingly, *et al*., 2002).

The pressure loss performance of a combustor is normally included in the diagram of the combustor loading and combustor intensity, which shows the corrected air mass flow rate through the combustion chamber for several fuel-air ratios. The stability loops and combustion efficiency of the gas turbine combustor can be shown as a plot of different fuel loading values for various fuel-air ratios (Visser and Kluiters, 1998).

Flammability limits in gas turbine combustors are related to many factors, including thermal energy losses from the flame due to conduction, convection and radiation to the combustor walls, instabilities in the flame and other causes. In this research, more attention was given towards studying the effects of parameters, such as combustor geometry, fuel mass flow, air mass flow, pressure, temperature and equivalence ratio (Odgers and Carrier, 1973).

The rate of the reaction between the vaporized fuel and air depends on both the total pressure and temperature at the combustor inlet. The flammability characteristics of any fuel provides a knowledge of the lower and the higher flammability limit for all operating conditions of the fuel flex combustor (Mattingly and von Ohain, 2006). One of the essential requirements of a gas turbine combustion chamber is that combustion must be stable under a wide range of fuel-air ratios. This is a measure of the maximum air velocity the combustion system can tolerate before flame extinction happens (Lefebvre and Ballal, 2010).

For the development of a new gas turbine combustor, it is necessary to calculate its stability performance to determine a series of predetermined levels of air mass flow, fuel mass flow, air temperature and pressure, where lean blowout and rich extinction occurs (Lefebvre and Ballal, 2010). If the stability loop must be calculated, an adequate approximation of the extinction limits may be obtained by using the Odgers-Carrier equations, solving the equations for the combustion efficiency and flammability limits for a given equivalence ratio (Odgers and Carrier, 1973).

Several items must be specified for each operational envelope: air mass flow rate, fuel mass flow rate, combustor inlet parameters (temperature, pressure and velocity), exit temperature, pressure losses, combustion efficiency, maximum allowable wall temperature, combustor type, weight and physical space (O'Brien, 2002).

Stability loops are affected by air loading or fuel loading parameters (air mass flow rate, pressure, fuel mass flow rate, reaction order and volume of the combustor). It is assumed that the attainable stability limit is dependent upon reaction-rate control. According to Odgers-Carrier, the performance curves of gas turbine combustors had similar characteristics to those yielded by simple equations based on reaction rate theory (Odgers and Carrier, 1973).

With the combustion efficiency calculated at any stable operating condition, it is possible to use the available data to find flammability limits using Eqs. (1), (2) and (3). There are two flammability loops for a fuel-air mixture. The weak fuel limit up to which the flame can propagate is denominated the lower flammability limit. The rich limit is denominated the upper flammability limit (Odgers and Carrier, 1973).

For lean mixtures:

$$0.911\left\{log\left(\frac{F\ \dot{m}_{fuel}}{V_{pz}\ p_3^{2\ \phi_{pz}}}\right)\right\} - log\left(log\left(\frac{1}{\eta_{pz}}\right)\right) + 8\left\{\phi_{pz}\right\} - 1.097 + D^*_{weak} = 0 \tag{1}$$

For rich mixtures:

$$0.911\left\{log\left(\frac{F\ \dot{m}_{fuel}}{V_{pz}\ p_3^{2/\phi_{pz}}}\right)\right\} - log\left(log\left(\frac{1}{\eta_{pz}}\right)\right) + \frac{8}{\phi_{pz}} - 1.097 + D^*_{rich} = 0 \tag{2}$$

$$\left\{\left(10^{-3.054\ \phi_{pz}^{-1.205}}\right)\left(T_3^{1.2327\ \phi_{pz}^{-1.205}}\right)\right\}^{-1} = F \tag{3}$$

where D^*_{rich} is a constant, dimensionless; D^*_{weak} another constant, dimensionless; F, the temperature factor, ratio $(\text{loading})_{Ti}/(\text{loading})_{300\ \text{deg K}}$; $\dot{m}_{fuel}$, the fuel mass flow at the combustor inlet, in kg/s; p_3, total pressure at the combustor inlet, in Pa; T_3, the total temperature at the combustor inlet, in K; V_{pz}, the specific volume at primary zone, in m^3/kg; ϕ_{pz} the equivalence ratio at primary zone, dimensionless and η_{pz}, the combustion efficiency at primary zone, dimensionless.

2.3 Prediction of temperature profile

To describe completely the combustion process in a gas turbine combustor, it is necessary a simultaneous resolution of the equations governing fluid mechanics and kinetics of chemical reactions. There are some methods used to describe the modeling of reacting flow in the combustion process of a gas turbine combustor; among them, we can mention the detailed flow simulation using simplified chemical kinetics (CFD), the simplified numerical flow simulation using detailed chemical kinetics (CRN), and hybrid numerical simulation combining the CFD method with nearly-global chemical kinetics mechanisms. In this study, the methodology of the reactor network was used (Drennan, 2008).

CRN's methodology is generally referred to as the chemical reactors network and is applied to the analysis of combustion products and temperature profile in preliminary designs of new combustion systems or existing systems. Therefore, it is the most suitable for the current purpose of this research: the development of a new gas turbine combustor (Hao, *et al*., 2012).

The different zones of a gas turbine combustor can be modeled using chemical reactors, like the perfectly stirred reactor (PSR) and the plug flow reactor (PFR). These reactors are interconnected forming a reactor network. In the numerical simulation of combustion in gas turbine combustors, the simultaneous integration of various chemical reactors is performed, in order to represent adequately the thermochemical parameters of each zone of the gas turbine combustor (Shakariyants, 2008). This can be seen in Fig. 1.

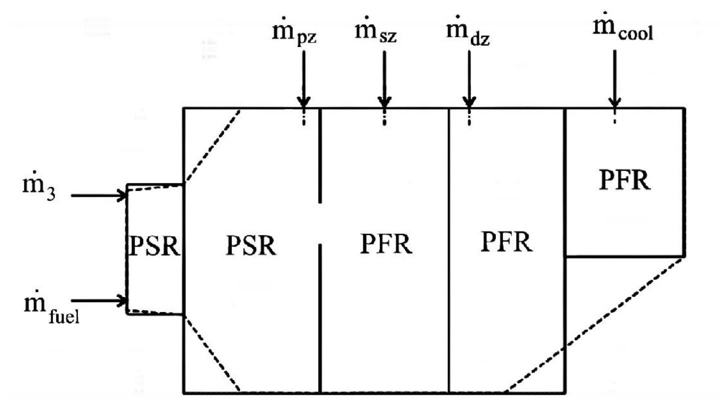

Figure 1. General reactor network sequence

The reactor network solution involves a series of simulations for each reactor at a time. For the reactor network, is assumed that the effluent of the preceding reactor is the input of the next reactor. These interconnected reactors include net generation of chemical species within each reactor volume (Goodwin, 2001).

The reactor network theory detailed above allows the designer to describe the detailed evolution of the reacting flow within the combustor and, based on the air and fuel flow to each zone and the geometric characteristics of each zone, it is possible to obtain the temperature profile of the interconnected reactors.

3. COMPUTATIONAL CODE

The undertaken research, the corresponding algorithms and the computer programs aim at

1. Calculating flammability curves.
2. The design of a combustion chamber for a specific application.
3. A performance analysis of the designed combustor.
4. Calculating the temperature profile in all the combustor zones.
5. Predicting the stability loops of the designed combustor for different fuels.

A computational code, written in Matlab, was developed to calculate the main characteristics of a gas turbine combustor burning fuels such as ethanol (C_2H_5OH) and liquid methanol (CH_3OH).

A main program calls several subroutines to perform specific sequential calculations. There are twenty subroutines. Some of these subroutines are described as follows:

a) A subroutine to input fuel, air and operating conditions data. In this subroutine the equivalence ratio, air mole fraction and fuel mole fraction for each work condition are calculated;
b) A subroutine to calculate the flammability curve for each fuel studied, based on thermokinetic equilibrium and reaction mechanism;
c) A subroutine to evaluate a few performance characteristics of the calculated combustor;
d) A subroutine to show the main results for the performance predictions.

The interaction among the computer codes for the calculation of the flammability curves, stability loops, design of a gas turbine combustion chamber and its performance analysis is schematically represented in Fig. 2.

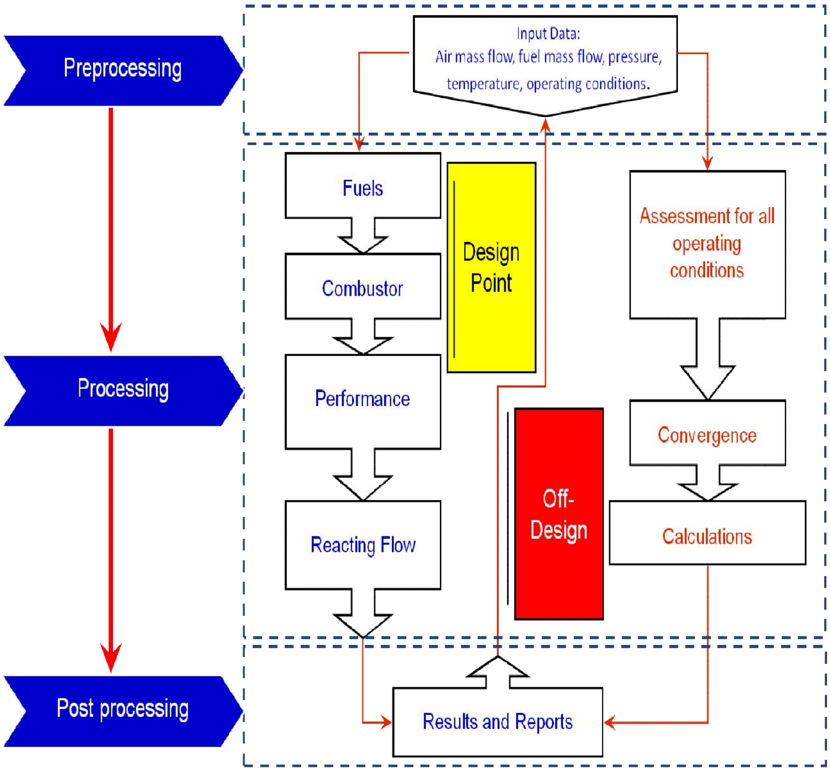

Figure 2. Schematic diagram of the interactions among computer codes

It is important to highlight that this is a brief description of the code developed – the main program and the subroutines. Selected reaction mechanisms, semi-empirical models and correlation available from the aeronautical industry and academia are synthesized and used during this research.

4. RESULTS ANALYSIS AND DISCUSSIONS

The combustor performance parameters on the operational envelope, for a gas turbine designed to burn ethanol and liquid methanol, were calculated using the methodology detailed above. The combustor inlet temperature varied from 340 K to 500 K; the combustor inlet pressure from 160 kPa to 500 kPa; and, the equivalence ratio from 0.1 to 2.8. Additionally, special attention was given to flammability limits and stability loops, having in mind the analysis of a newly designed combustor. These results are shown in Tab. 2 and 3, Fig. 3 and 4.

Table 2. Operational characteristics of the combustor for ethanol fuel.

Parameters	Maximum load	Minimum load	Base load	Idle
$\dot{m}_3$ (kg/s)	7.70	3.13	8.98	2.87
$\dot{m}_{fuel}$ (kg/s)	0.24	0.071	0.22	0.05
ϕ	0.27	0.20	0.22	0.15
η (%)	97.00	97.00	97.00	97.00
T_3 (K)	491.36	414.43	503.24	346.38
P_3 (kPa)	501.56	181.69	554.70	164.79
T_4 (K)	1170.00	950.86	1070.91	765.08
$\Delta P_{3\text{-}4}/P_3$	0.06	0.06	0.06	0.06
$\Delta P_{3\text{-}4}/q_{ref}$	20.00	20.00	20.00	20.00
Power (W)	2659.53	709.32	1968.09	303.19

Table 3. Operational characteristics of the combustor for methanol fuel.

Parameters	Maximum load	Minimum load	Base load	Idle
$\dot{m}_3$ (kg/s)	7.55	3.06	8.77	2.81
$\dot{m}_{fuel}$ (kg/s)	0.31	0.09	0.29	0.06
ϕ	0.26	0.19	0.22	0.15
η (%)	97.00	97.00	97.00	97.00
T_3 (K)	491.36	414.33	503.17	346.03
P_3 (kPa)	501.56	181.69	554.70	164.79
T_4 (K)	1173.00	950.10	1075.00	766.41
$\Delta P_{3-4}/P_3$	0.06	0.06	0.06	0.06
$\Delta P_{3-4}/q_{ref}$	20.00	20.00	20.00	20.00
Power (W)	2688.83	712.73	1987.82	301.58

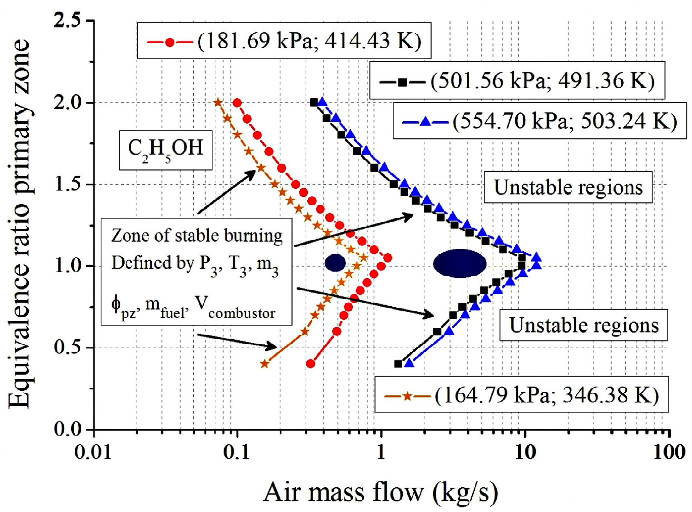

Figure 3. Stability loops for ethanol fuel

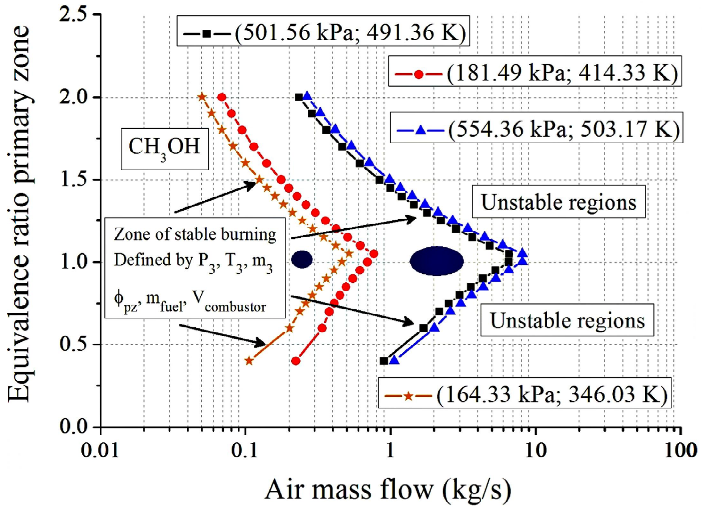

Figure 4. Stability loops for methanol fuel

The approach used in this study enables the calculation of temperature distribution in all combustor zones. These results are summarized in Fig. 5 and 6.

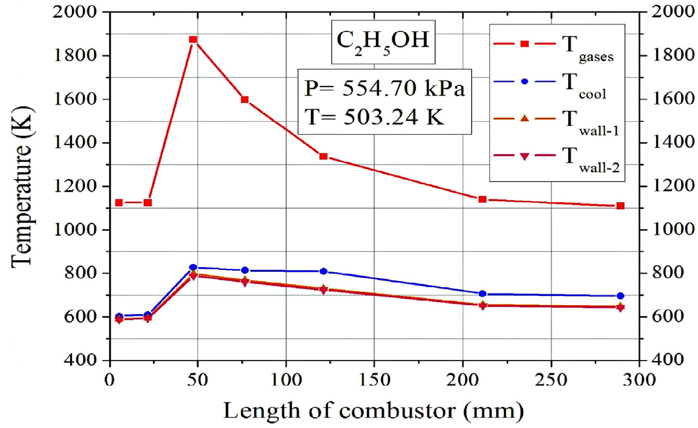

Figure 5. Temperature profile for combustor burning ethanol

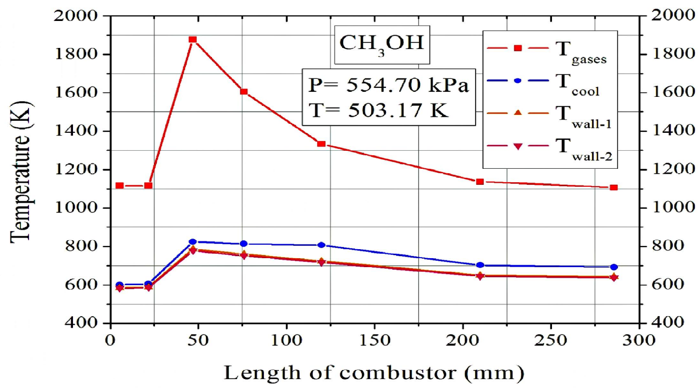

Figure 6. Temperature profile for combustor burning methanol

The combustor inlet temperature and pressure have a significant influence on the combustion stability, as reflected by the stability curves. In Figures 3 and 4, when the operating temperature is 346 K and the pressure is 164 kPa, it is seen that the stability zone is narrower. For the same operating conditions the air mass flow is less than what is obtained for an operating temperature of 503 K and a pressure of 554 kPa.

The increase of pressure and temperature at the combustor inlet has a double effect on the temperature of the combustor walls:

- It increases the heat transfer rate by radiation to the combustor walls, resulting in an increase of the cooling air temperature;
- The increase of cooling air temperature will produce a greater consumption of this flow to keep the temperatures of the combustor walls within the allowable range of temperature.

5. FINAL REMARKS

The major objective of this study is to develop a methodology applied to obtain the performance predictions of a fuel flexible annular gas turbine combustor and apply it systematically as a computational tool. The methodology used was implemented in a Matlab code. A gas turbine combustor was analyzed and the results of the simulations indicate the functionality and versatility of the model.

Although the results show the outcomes for only two fuels (ethanol and liquid methanol), the program is able to run any type of gas turbine fuel, requiring only the fuel chemical composition and the thermodynamic coefficients. The main parameters considered for implementing the fuels are: the heating value of the fuel, design of the diffuser, characteristic of the swirler, fuel mass flow rate, air mass flow rate and the air distribution in the combustor. From Figures 3 to 6, and according to Odgers and Kretschmer in similar conditions, it is concluded that the higher adiabatic flame temperature reached in the combustor the better combustion stability and greater combustion efficiency would be achieved.

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