International Journal of Scientific Engineering and Applied Science (IJSEAS) – Volume-3, Issue-5,May 2017
ISSN: 2395-3470
www.ijseas.com

Development of a Combustion Chamber with Application to Gas Turbines

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Abstract

The present study proposes the preliminary construction of a combustion chamber which constitutes an important component in a gas turbine. This element has two applications: the first is to serve as an educational prototype that shows the components and their location, the second is to serve as an experimental prototype to study the combustion process. The operation of the combustion chamber and its behavior are analyzed using a visualization process, which determines the quality of combustion depending on the flame color. Such analysis is performed during an interval of 47 s, with a mass flow in the chamber of approximately 0.083 kg/s at an average pressure of 3.71 kg/cm^2. Experimental evidence indicates that under the conditions in which the experiment was carried out, the combustion efficiency can be above 60 percent.

Keywords: *Combustion chamber, Gas turbine, Combustion efficiency, Experimental prototype*

1. Introduction

In the last years great efforts have been made in order to implement methods for energy generation that do not harm the environment. Despite the recent consolidation in the use of renewable energy in some countries, the economy and the global energy production are still subordinated to the employment of fossil fuels. Nevertheless, these sources play an important role in the global energy balance in the immediate future and it is of great importance to develop efficient and clean production of electricity based on fossil fuel methods. Most of the energy production in the world is obtained from thermoelectric power plants. Among these plants, combined cycle power plants have wide acceptance because of their high efficiencies resulting from the combination of the best features of the cycles for gas and vapor turbines. Gas turbines employ natural gas and are one of the technologies that are used for power generation [1]. The thermal efficiency of a gas turbine is primarily affected by the maximum temperature of the cycle, which is limited by the thermal resistance of the materials. Different gas turbines operate with a limited maximum temperature of 1200 °C [2]. In the combined cycle technology, most of the energy supply occurs inside the combustion chamber, on the side of the gas turbine cycle. Because of this, controlling and optimizing the processes that occur inside these devices has become a priority.

Currently, the combustion efficiency of gas turbines at full working conditions is above 99.9% [3]. However, because of the complex processes that occur inside the combustion chamber, unwanted effects appear such as incomplete combustion, dissociation and other endothermic reactions. These unwanted effects decrease the chamber's efficiency and give rise to the formation of harmful substances like nitrogen oxides (NOx), carbon monoxide (CO), unburned hydrocarbons (UHC) and soot which are released with the exhaust gases. The NOx and CO are both mainly produced at the primary zone (or flame generation) and secondary zone (or intermediate) where the most extreme and diverse conditions exist for the temperature and for the composition of the mixture. There exist different techniques employed to reduce the rate of formation of these pollutants. Unfortunately, in general, it can be stated that any attempt oriented to reduce the fraction of NOx invariably tends to increase the fractions of CO and UHC, and vice versa [4]. In the same study, it was shown that flameless oxidation (a type of combustion technology based on fossil fuels) drastically reduce emissions of CO_2 and NOx producing greater efficiency in the combustion process. Among the benefits of this technology are: 1) Major efficiency in the combustion process, 2)

High flame temperature, 3) Improves the heat transfer, thus more efficiency and 4) Reduction of CO_2 and NOx.

The gas turbine cycle is very important to the combustion chamber and plays a decisive role in power generation standardized large-scale processes, and it is still being studied in order to make improvements. Levy *et al.* [5] investigated dilute products in the flame in a combustion testing device composed of a pre-combustor and a post-combustor. This device was specially built to study the NOx reduction potential of flameless oxidation on a proposed gas turbine combustor design. In the study [6], the same experimental combustor was used to model flameless oxidations and study their application on gas turbine combustors. The investigation proposed in [7], proposed an optimization of an open cycle intercooled gas turbine power plant with pressure drop irreversibilities adjusting the flow rate, the intercooling pressure ratio and the pressure losses distribution along the flow path.

All these above investigations concerns the design and improvement of combustion chamber technologies and help to improve the overall performance of gas turbines, increase efficiency, and reduce the amount of contaminant emissions. Following this trend, the aim of the present paper is to construct an experimental combustion chamber and compare it with another experimental combustor that operates similarly [6]. The combustor analyzed is intended to suit a cycle gas turbine for electricity generation and meet the needs of energy in the area of Poza Rica, Mexico. Table 1 shows the main conditions of the two combustion chambers analyzed.

The combustion chamber proposed in this work was built at the Faculty of Electrical and Mechanical Engineering of the University of Veracruz for two main purposes: First, to serve as a prototype for students of the faculties allowing the study of different combustion phenomena applied to gas turbines and second, to serve as a preliminary experimental prototype to investigate and analyze the parameters involved in a combustion process.

This paper is organized as follows. Section 2 shows the infrastructure and experimental components used. Section 3 presents the experimental parameters. Section 4 analyzes the results obtained.

Table 1: Combustion chambers analyzed

Chamber parameter	***Awosope et al. [6]***	***Poza Rica, Ver., Mexico***
Pressure	2.03 kgf/cm^2	3.71 kgf/cm^2
Fuel	LP gas	LP gas
Mass air flow	70-102 gr/s	15- 45 gr/s
Diameter	162 mm	170 mm
Lenght	1280 mm	2824 mm

2. Infrastructure and experimental components

The combustion chamber is constructed using the scheme presented in Fig. (1), which is based on the design presented in [3]. More information about the basis of the proposed infrastructure can be found, for example, in [8-10]. Fig. (2) shows the schematic diagram of the experimental setup along with the external components required for operation. For the final construction, the experimental combustor has been modified due to costs and some adjustments to apply materials found in the domestic market as shown in Fig. (3).

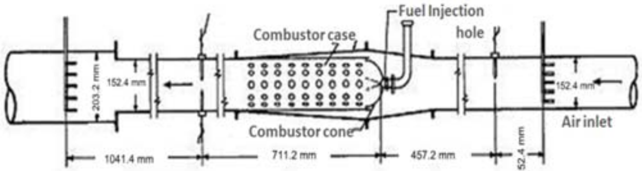

Fig. 1 Combustion chamber proposed (based on [2]).

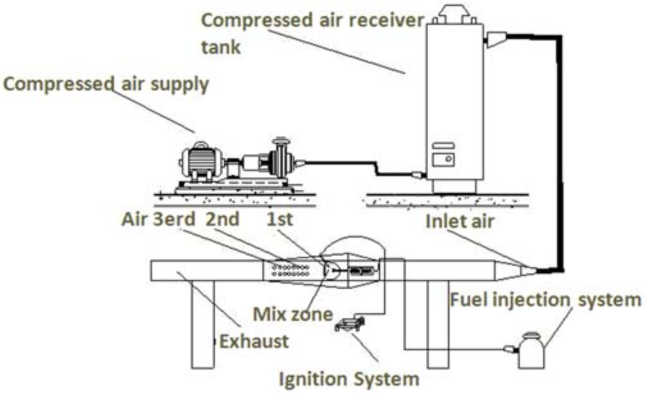

Fig. 2 Schematic diagram of components.

Fig. 3 Experimental combustion chamber.

The delivery system of the compressed air feeding the experimental combustion chamber is similar to the used in [11]. The intention is to analyze the transient flow in a transonic regime (as this experimental combustor operates) on very short time intervals. The experimental combustion chamber is annular type. Figure (4) shows the inner cylinder which contains an array of perforations in order to supply cooling air to the gases resulting from combustion in the primary zone.

Figure (5) shows the air and fuel supply pipe of compressed air to the primary combustion zone and its fuel pipe. Figure (6) illustrates idle jet injector needed for supplying the fuel.

Fig. 4 Combustor inner cylinder.

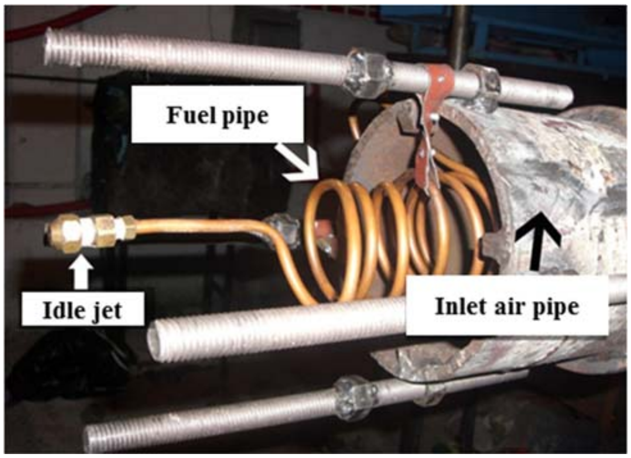

Fig. 5 Air and fuel supply pipes

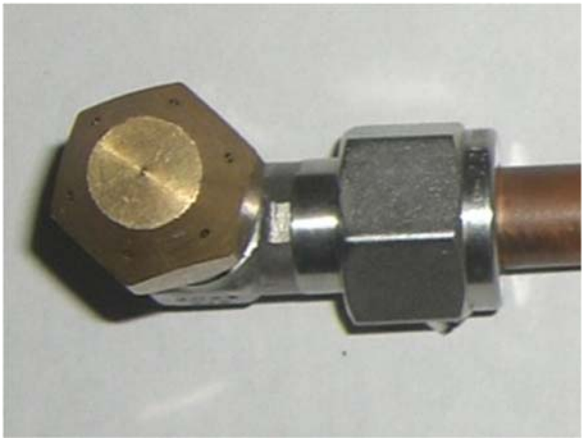

Fig. 6 Idle jet fuel injector.

The ignition system is adapted from an ignition system of a gasoline car and consists of a spark plug along with an ignition generator as shown in Fig. (7) and (8) respectively.

Fig. 7 Spark plug.

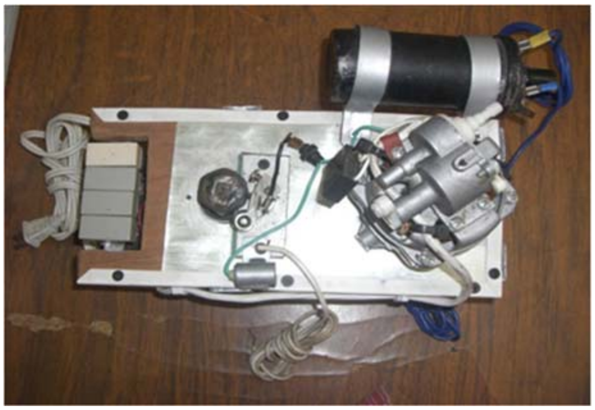

Fig. 8 Ignition generator.

When all the components of the combustion chamber and the infrastructure used in the experimental process are assembled according to the arrangements presented in Fig. (2) and (3), the next step is to operate the combustion chamber. The following subsection presents the experimental parameters necessary for operation.

3. Experimental parameters

In this investigation, the estimation of the mass flow that is introduced into the combustion chamber has two hypotheses, which limit the accuracy of the calculated results on the experimental tests:

- The first hypothesis focuses on the effect that during the time in which the test is performed, the total flow was not obtained using the air/fuel ratio but using the air flow only.

- The second hypothesis considers that the air stored in the receiver tank compressed air system behaves as an ideal gas. The behaviors of the pressure inside the tank and the combustion efficiency percentage versus time are shown in Fig. (9) and (10) respectively.

As can be seen, Fig. (10) shows that the time interval in which the camera is considered to operate with the best combustion behavior is between 18 s and 39 s after the combustion starting, within an average interval of 47 seconds comprising from ignition to shutdown time. This is based on a qualitative criteria analysis of the flame that will be mentioned later. From Fig. (9), the average pressure $\overline{P}$ is found to be 3.72 kg/cm^2. Under the hypothesis that the fluid that is injected into the combustion chamber behaves as an ideal gas, it can be established that:

$$P = \rho RT \tag{1}$$

where P is the absolute pressure in the air storage tank, ρ is the density, T is the temperature, R is the gas constant and m is the mass of air contained in a volume V of the tank. Since $\rho = m/v$, Eq. (1) can be expressed as:

$$P = \frac{m}{v} RT \tag{2}$$

The expression of differentiating Eq. (2) is:

$$dp = dm \frac{RT}{v} \tag{3}$$

Dividing Eq. (3) between dt, we obtain:

$$\frac{dp}{dt} = \frac{dm}{dt} \frac{RT}{v} \qquad 4)$$

Since $\frac{dm}{dt} = m$, Eq. (4) becomes:

$$m = \frac{dm}{dt} = \frac{V \, {}^{dp}\!/_{dt}}{RT} \tag{5}$$

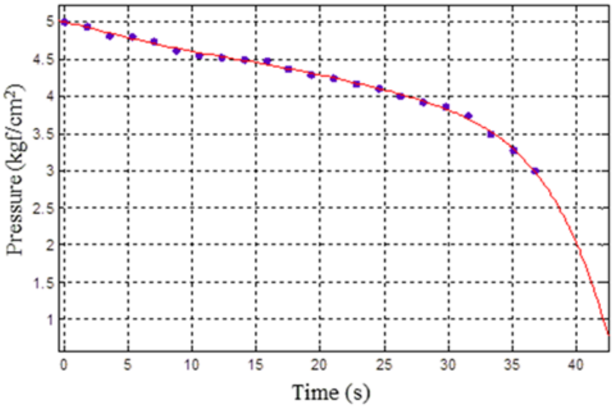

Fig. 9 Behavior of pressure vs. time within the receiver tank.

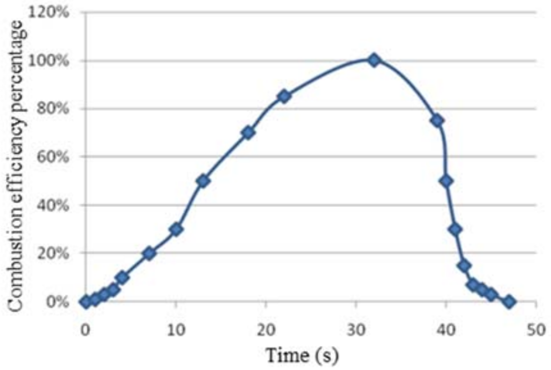

Fig. 10 Behavior of combustion efficiency over time.

If $R = 287\ l/KgK$, then T=303 K and V=0.034 m^3. The pressure behavior is presented in Appendix. This behavior is the same as shown in Fig. (10); however, a column that indicates the behavior of the derivative of pressure with respect to time is added. Figure (11) shows the curve describing the behavior of the mass flow versus time.

4. Results and discussion

In order to analyze the combustion process, some snapshots were taken during the performance of the experimental test in an average interval of 47 seconds. T=0 seconds in Fig. (12) is considered as the system ignition, when spark plugs are energized. Figure (13) shows 3 seconds after the system ignition. Here, a yellow flame (white light in the figure) indicates an excess of fuel with respect to the required stoichiometric mixture. This is because of a very poor mixture, which represents a combustion efficiency of about 3%. Figures (14)-(16) show the snapshots in which the combustion efficiencies have very high values, approximately 70% and 100%, according to the curve presented in Fig. (10). It can be seen that during this interval, there is a stable operation of the camera and the flame. This can be explained by the fact that during the interval of camera operation, the operating power peaks, decibels and frequencies produced by the camera match the typical values of a gas turbine combustor. In Figures (17) and (18), the shortage of air in the chamber causes a slightly oxidizing flame, i.e., a flame that is weakened as time passes, thus resulting in decreased combustion efficiencies. Figure (19) shows the flame extinction due to a reduced mass flow. At this time, a corresponding yellow flame is observed at the level of efficiency presented in Fig. (10).

The operation of the combustion chamber and its behavior are analyzed using a visualization process. In this case, the criterion proposed is based on the apparent power and quality of combustion depending on the flame color observed during the average period of 47 seconds, which is the interval used to complete the experiment. On the one hand, when an apparent maximum power of flame is observed, the rate of combustion can be considered as a percentage of 100%. This is based on the fact that the blue color means a self-sustained flame. On the other hand, when the flame is not burning or is still off, the rate of combustion can be considered as 0 %. As shown in Figs. (13) and (19), the color of the yellow flame means a poor power of the flame. The above criteria may resemble those used when gas welding equipment is operated. According to the visual analysis of Fig. (9)-(11) and Table 1, it can be inferred that the best operation for the combustor proposed is found to be in the time interval 25 ≤ t ≤ 35 seconds.

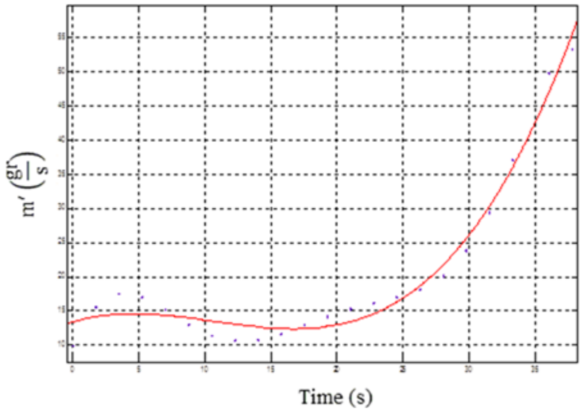

Fig. 11 Mass flow behavior against time.

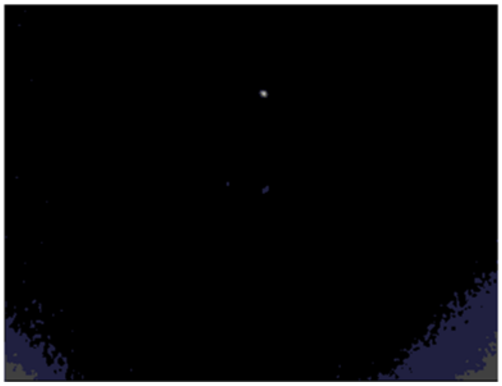

Fig. 12 Ignition of spark plug in t=0 s.

Fig. 13 Combustion in t=3 s.

Fig. 16 Combustion in t =32 s.

Fig. 14 Combustion in t=18 s.

Fig. 17 Combustion in t =42 s.

Fig. 15 Combustion in t=22 s.

Fig. 18 Combustion in t =43 s.

Fig. 19 Combustion in t =45 s.

5. Conclusion

Different efforts have been applied to develop new technologies and methodologies that allow the enhancement of gas turbine performances by increasing their efficiencies and reducing the emission of pollutants. This can be achieved by directly improving the combustor performance. The present experimental test was carried out with the intention of being a platform for the study and research of combustion phenomena in combustors with application to gas turbines. The results showed that the combustion chamber proposed had an optimal behavior in the range of $25 \leq t \leq 35$ seconds after starting the ignition, operating with a mass flow between 35 and 50 gr/s. However, it is important to mention that the hypothesis selected considered only air as the total flow. Thus, significant uncertainty can exist with respect to the air/fuel ratio during the time interval in which the experiment is performed. Due to the limited volume of supply air in the tank, the combustor behavior was only analyzed for a small time interval. Nevertheless, the experimental arrangement allows the study of transient conditions. With all this experimental evidence and under the conditions in which the experiment was carried out, it can be concluded that the combustion efficiency can be above 60 percent.

Acknowledgments

This work was carried out with the support of Instituto Politécnico Nacional and Universidad Veracruzana.

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Appendix

Table A.1 Pressure behavior with respect to time and its first derivative.

$P(Kg/cm^2)$	$t(s)$	$\frac{dP}{dt}\left(\frac{Kg/cm^2}{s}\right)$	$\frac{dP}{dt}\times 9.8\times 10^4\left(\frac{N/m^2}{s}\right)$	$m' = \frac{V}{RT}\times\frac{dP}{dt}\left(\frac{gr}{s}\right)$
5	0	-0.0258174	2530	9.86
4.95	1.75	-0.0408896	4007	15.62
4.83	3.5	-0.0460108	4505	17.58
4.80	5.25	-0.0445263	4363	17.01
4.75	7	-0.0397053	3891	15.17
4.62	8.75	-0.0342464	3356	13.08
4.56	10.5	-0.0300168	2941	11.46
4.53	12.25	-0.0279840	2742	10.69
4.5	14	-0.0282989	2773	10.81
4.48	15.75	-0.0304919	2988	11.65
4.37	17.5	-0.0337387	3306	12.89
4.30	19.25	-0.0371589	3641	14.20
4.25	21	-0.0401042	3930	15.32
4.18	22.75	-0.0423971	4155	16.20
4.12	24.5	-0.0444798	4359	17.00
4.0	26.25	-0.0474326	4648	18.12
3.93	28	-0.0528216	5176	20.18
3.86	29.75	-0.0623352	6105	23.82
3.75	31.5	-0.0771693	7562	29.49
3.50	33.25	-0.0971204	9517	37.11
3.78	35	-0.1305720	12796	49.90
3	36.75	-0.1397300	13693	53.40
2.53	38.5	-0.3006380	29462	114.84
1.91	40.25	-0.4199230	41152	160.41
1.04	42	-0.5809880	56936	221.94