COBEM UBERLÂNDIA 2019

ABCM Associação Brasileira de Engenharia e Ciências Mecânicas

25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COB-2019-0279 GEOMETRY INFLUENCE ON COMBUSTION INSTABILITIES IN DOUBLE-STAGE SWIRL NUMBER

Dener Silva de Almeida
1966, Maranhão Federal University, Portugueses Ave, Bacanga, São Luis, MA, Brazil
dener@ufma.br
Pedro Teixeira Lacava
50, Aeronautical Insitute of Technology, Marechal Eduardo Gomes Square, Acácia Village, São José dos Campos, SP, Brazil
placava@ita.br

Abstract. *This work presents a new Low-NOx combustor configuration to especial application in gas turbine. In this new concept, the combustion happens in two stages, being the first one rich in fuel (primary chamber) and the second with deficiency. Therefore, the occurrence of the unfavorable conditions for NOx formation is obtained through the dynamic control of the reactants flow. Five control combustion process parameters are analyzed: equivalence ratio, primary chamber length/diameter ratio (L/D), fuel jet Reynolds number, swirler blades angle and second chamber diameter. However, for some parameter combinations, it's observed the combustion acoustic instabilities phenomena. The results show that such instabilities can be attenuated and even suppressed by a better recirculation structure in the second stage, which in turn is achieved by proper selection of operating parameters and by increasing the diameter of the same stage.*

Keywords: *combustion, combustion instabilities, gas turbine*

1. INTRODUCTION

More and more stringent emission requirements indicate the importance of low emission and durable gas turbine combustors. Thus one of the main concerns in gas turbine applications is to achieve a stable flame and robust combustion. Diffusion flames could be applied in gas turbine combustors due to its relative high stability characteristics and better performance. However, due to the undesirable concentrations of NOx, such diffusion flames are not preferred (Zhang et al., 2019).

Lean premixed (LP) combustion of natural gas has been developed and successfully applied during the last few decades to achieve low NOx emissions (Taamallah et al., 2015). In this system, fuel and air are pre-mixed upstream of the combustor, thereby avoiding stoichiometric regions. The combustion region is operating with excess air to reduce the flame temperature and consequently occurs the virtual elimination of NOx. However, changes in the flow, related to the combustion or dynamic instability, often appear as a common problem and delay the LP system development (Huang and Yang, 2005b). Combustion instability is manifested by acoustic and heat release rate oscillations inside the combustor chamber. Heat release rate fluctuations add energy to the acoustic field, leading to acoustic pressure and velocity fluctuations that propagate throughout the combustor. These acoustic fluctuations then excite vortical structures and fuel/air ratio oscillations that, in turn, lead to further heat release fluctuations that close the feedback loop (O'Connor et al., 2015).

Another important contender in the ultralow NOX emissions field is the rich-burn/quick-quench/lean-burn (RQL) combustor. This concept employs a fuel-rich primary zone in which NOX formation rates are low because of the combined effects of low temperature and oxygen depletion. Downstream of the primary zone, the additional air required to complete the combustion process and reduce the gas temperature to the desired predilution zone level is injected in a manner that is designed to ensure uniform and rapid mixing with the primary-zone efflux. This mixing process must take place quickly, otherwise pockets of hot gas would survive long enough to produce appreciable amounts of NOX (Lefebvre and Ballal, 2010). Thus, combustion efficiency RQL is limited by the rate at which the air can be mixed with hot gases in the lean area (Brewster et al., 1999).

On the other hand, swirl combustion, the most employed technology in current gas turbine combustors, is important in promoting flame stability, increasing combustion efficiency and controlling emission of pollutants from combustion (Gupta et al., 1984). This is achieved by imparting a sufficient amount of rotation to the flow to establish a high adverse pressure gradient which induces a flow reversal and defines a Central Recirculation Zone (CRZ). Under reactive conditions, recirculation of burnt gases maintains a region of hot gases near the injector exhaust which serves to anchor the flame in a high speed flow even under lean conditions (Durox et al., 2013).

The model proposed here uses swirl flow and concepts of the LP and RQL, however without the pre-mixing that occurs in the LP combustors and the staged air addition of the RQL chambers. The combustion is developed in two stages, each one to a separate chamber. At first stage the fuel is injected through a central spear and the total air of the combustion process crosses a swirler, where acquire a tangential component of velocity (swirl flow). The air, which because of the tangential velocity component produced by swirler, flows concentrated near the wall of the combustion chamber and develop a film cooling from the wall of the chamber and flame. At the end of this primary zone, which is called transition zone, there is a sudden increase in the chamber diameter and the rotating air flow loses the wall effect, expanding itself radially. This causes the pressure decrease in the central region, which in turn allows the reversal of the air flow and consequently the creation of an intense recirculation zone mixing the remaining air with the combustion products of the primary zone. So that, in the secondary chamber a lean pre-mixed flame is established.

Despite the NOx reduction provided by this experimental assembly, it is observed for certain working conditions, the occurrence of acoustic combustion instabilities, being the objective of this work investigate experimentally the geometry influence on instabilities in this chamber model.

2. EXPERIMENTAL SETUP

The experiments were performed in an atmospheric pressure laboratorial scale combustor, made in stainless steel and without refrigeration. The air flow acts like a film cooling and the refrigeration is not necessary. The primary chamber diameter (D) is 10 cm and the length (L) may be 10, 20 or 30 cm (L/D ratio = 1, 2 or 3). The secondary chamber length is 50 cm, but two secondary chamber diameter (SCD) were used, 20 cm and 40 cm. The air, which comes from air blowers, is conducted axially to the swirler positioned at the primary chamber entry. The swirler diameter is the same of the primary chamber and it has eight blades whose angle with the axial direction may be set from 50° to 80°. So, it was possible to study the swirler blades angle influence on instabilities without changing the air flow passing through the swirler. The fuel (natural gas) was injected through the nozzle positioned in the center line of the primary chamber.

The mass flow rate of the natural gas was kept constant at 1 g/s for all experiments, and maximum air mass flow rate was 70 g/s. Both mass flow rates were measured by calibrated orifice plate systems and the maximum error is 3% of the measure. Three different nozzle diameters were utilized, 2.35, 3.20 and 7.8 mm, to provide the fuel jet Reynolds numbers of 50,000, 40,000 and 15,000, respectively. To detect the combustion instability, a Kistler 7261 piezoelectric pressure transducer was positioned at 3.0 cm above the swirler, at the primary chamber wall. The Figure 1 shows a schematic diagram of the experimental setup.

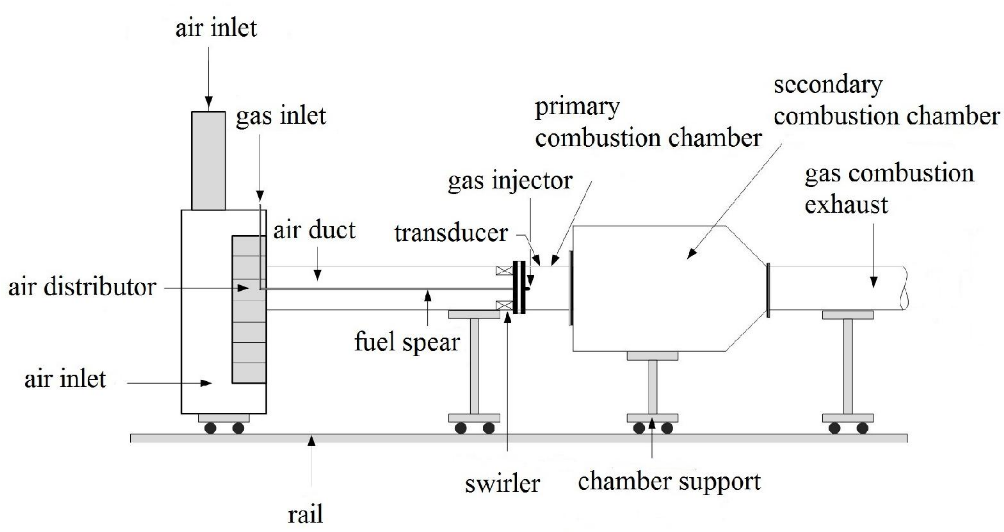

Figure 1. Schematic diagram of the experimental setup

The parameters changed during the experiments were: length/diameter ratio for the primary chamber (L/D), secondary chamber diameter (SCD), fuel jet Reynolds number (Re), swirler blades angle (α) and the global equivalence ratio (ϕ). Figure 2 shows a photo where the stainless steel primary chamber is substituted by a cylindrical glass chamber and the secondary chamber is not present. The operation conditions for the photo presented in Fig. 2 are: natural gas mass flow rate m_F = 1.0 g/s, air mass flow rate m_{air} = 50 g/s, swirler blades angle α = 80° and L/D = 1.

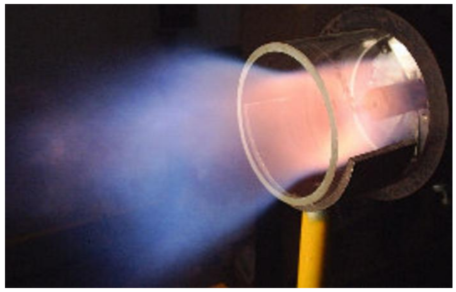

Figure 2. Double-stage swirl flame

3. RESULTS AND DISCUSSION

This section presents the results obtained through the tests developed, as well as the description and discussion of them. The presentation of the results follows the execution sequence of the experimental tests. For a given chamber length (fixed ratio L / D), a given second chamber diameter (fixed SCD), a given gas injector diameter (fixed Re) and a given swirler blade angle (α fixed) varied at the air flow rate (varied ϕ). Subsequently α, Re and L/D were varied, with combustion instabilities being obtained for each of these conditions.

Figures 3 to 5 show oscillation amplitudes results for the two secondary chambers as a function of the global equivalence ratio (Φ) and the angle between the swirler blades for different Reynolds numbers and L/D ratio.

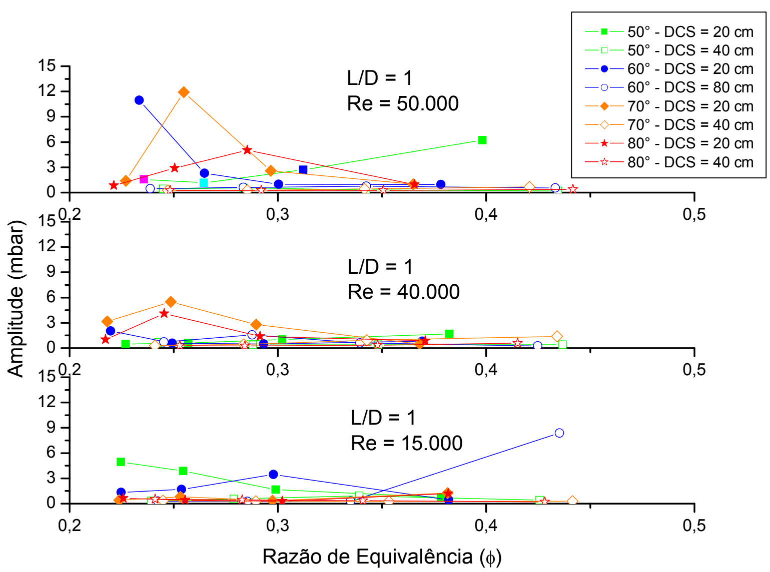

Figure 4. Equivalence ratio influence on amplitude of oscillation for L/D = 1, different Reynolds numbers, swirler blade angles and SCD = 20 and 40 cm

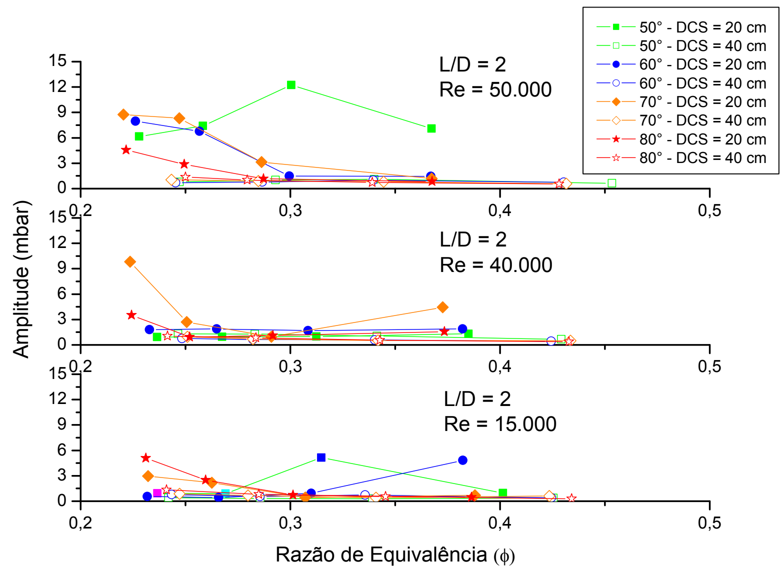

Figure 5. Equivalence ratio influence on amplitude of oscillation for L/D = 2, different Reynolds numbers, swirler blade angles and SCD = 20 and 40 cm

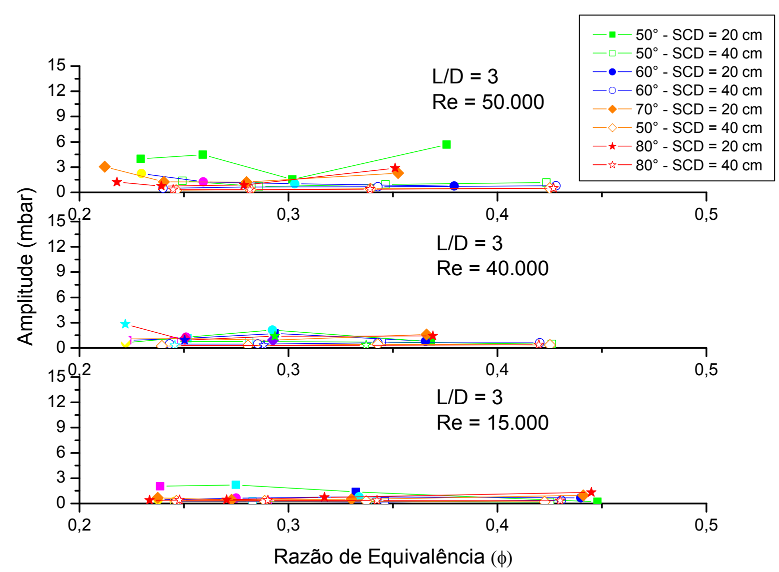

Figure 6. Equivalence ratio influence on amplitude of oscillation for L/D = 3, different Reynolds numbers, swirler blade angles and SCD = 20 and 40 cm

Before any analysis, it is important to emphasize that the combustion always has been on a lean regime, that is, with the equivalence ratio less than 0.5. Several studies have shown that combustion systems operating with low equivalence ratio are more likely to the combustion instability. Bradley et al. (1998) performed experiments with a flame formed by methane and air stabilized through swirler; the swirl number and the average axial entry speed were kept constant, while the equivalence ratio was reduced. It was observed that low-frequency acoustic instabilities appeared for equivalence ratio values less than 0.6. However, for ratios above this value, the combustion remained stable. Lieuwen et al. (1998) suggested that the deficient mixture between the reagents in a lean combustion condition causes equivalence ratio fluctuations, and they play an important role in the mechanism that induces the combustion instabilities onset.

Seo (2003) analyzed the combustion behavior in terms of stability in a model gas turbine combustor burning natural gas and air. This study identified the incompleteness of premixing as significant perturbation source for inducing unstable combustion. Seo and Lee (2010) studying experimentally the effects of the degree of premixing and swirl strength on combustion instabilities occurring in a lean premixed gas turbine combustion natural gas and air showed that combustion in lean conditions becomes more susceptible to instabilities as the degree of premixing becomes poor. In general, it has been shown that equivalence ratio small disturbances (pockets production) produce low-amplitude oscillations in stoichiometric mixtures, however, cause larger oscillations amplitudes in lean mixtures. In extremely lean combustion systems, fluctuations in the reagent mixture formation lead to energy release alternations, which can cause pressure fluctuations, especially if the flame is near its blowout limit. In the case of extremely lean mixtures, the flame propagation speed is very low, which does not allow an energy release recovery when fluctuations in the equivalence ratio are present (Stone and Menon, 2002), generate the instabilities.

In spite of ϕ, L/D, α and fuel jet Reynolds number, results show that the oscillations are always damped for the secondary chamber which larger diameter, 40 cm. According Huang and Yang (2009), combustor geometry is of crucial importance to the instability characteristics, because it not only determines the acoustic properties, but also exerts considerable influence on the flow and flame.

The proper combination of swirler blades angle (α = 70° and 80°), length/diameter ratio (L/D = 3), and fuel jet Reynolds number (Re = 15.000) improves the reactants mixing process and reduces the axial momentum in the transition region between the primary and secondary chambers. Higher swirler angle tends to attenuate the oscillations, due to the intensification of the recirculation zone, enhancing the reactants mixing process and, in addition, increasing the flame velocity due to the higher turbulence. The jet Reynolds number and the primary chamber length play an important role on the axial momentum in the transition region between the primary and secondary chambers. Higher axial momentum weakens the recirculation flow in the secondary chamber and increases the possibility of nonhomogeneous equivalence ratio in the reaction zone. By reducing the jet Reynolds number and increasing the primary chamber length the oscillations were attenuated (Almeida, 2009).

On the other hand, the increase of transverse section in the secondary chamber (SCD = 40 cm) generates two effects on the instabilities. The first effect is acoustic, because a larger secondary chamber volume tends to allow the oscillations damping. The second is related to the recirculation zone structure, which in turn depends on the "step" formed between the primary and secondary chambers. By passing through this “step”, the flow radial displacement generates low pressure in the central zone of the secondary chamber, forming a recirculation structure. Higher diameter differences in the “step” between the primary and secondary chambers enhance the air flow radial expansion, decreasing more intensely the pressure in the secondary chamber center line; as consequence, forcing more intense reverser flow to achieve the equilibrium condition of pressure.

Besides, increasing this difference to higher values contributes to a closer free wall situation with a stronger recirculation structure. According to Sawyer (1985), the chamber diameter must be 3 times larger than the swirler diameter to establish a strong recirculation zone and low permanence of a structure with a high tangential momentum. The strengthening of the recirculation zone promotes more homogeneous mixtures with less fluctuations in the rate of energy release, which is a factor that inhibits acoustic instabilities (Lieuwen and Zinn, 1998b; Liuewen et al., 1998).

In this kind of flow, i.e. swirl flow, there’s also the occurrence of coherent structures in the recirculation zone that causes unsteady motions, and, consequently, the instabilities onset. One of the most important is vortex breakdown, a phenomenon that manifests itself as an abrupt change in the core of a slender vortex and usually develops downstream into a recirculating bubble or a spiral pattern (Huang and Yang, 2009). It is also common in these flows the presence of precessing vortex core - PVC, i.e, spatial alternations of the core vortex. The PVC occurrence is usually associated to the vortex breakdown and the presence of a recirculation zone in a flow with high Reynolds number, and its behavior and occurrence are more complex during the combustion process, especially in case of lean combustion (Syred, 2006). Moreover, in developed flow, strong shear layers developed due to the speed difference between them and the fluid environment. Large-scale coherent structures are generated in regions of these shear layers and exert great influence on the combustion process by modulating the mixing process between fuel, air and hot combustion products (Paschereit et al., 1998).

Swirling flows can affect the occurrence of instabilities in two ways: by influencing the reactants mixing or by coupling between vortex ruptures and acoustic characteristics of the combustion chamber. In the first case, as discussed earlier, the increase in the secondary chamber diameter enhances the recirculation structure, which promotes more homogeneous mixtures and with less fluctuations in the energy release rates. Moreover, such intensification leads to speed reactions increase, which in the case of lean combustion can partly compensate for the reduction of speed due to the low temperature. Second, when large-scale unsteady motions arise not only from the shear layers instability but also the vortex breakdown, as well as the PVC may couple resonantly with acoustic waves in the combustor, and, consequently, cause combustion instabilities (Huang and Yang, 2005a).

It is possible that a larger secondary chamber volume allowed the modification of the large-scale vortices present in the secondary chamber in a way that has helped to minimize the instabilities onset, since these may be related to the formation or destruction of such structures. Fuel injection can also generate or modify oscillations in the chamber. Like large-scale movements, the fuel flow can be coupled resonantly with acoustic waves along the combustion chamber, resulting in high oscillations, and a larger volume may also have prevented this coupling.

Whether for attenuation of the unsteady effects of generated vortex or preventing the coupling between the structures described above with acoustic waves that develop along the combustor, the results showed that changes in flow structure that lead to the strengthening of the recirculation zone, as higher L / D ratio and swirler blades angle, lower Reynolds number and a larger secondary chamber diameter, tend to reduce the unsteady flow in the flame region, and, consequently, the instabilities onset.

4. CONCLUSIONS

The present paper investigated, experimentally, the geometry on the appearance of combustion instabilities in a laboratorial scale double stage swirl combustor for application in gas turbine. The parameters analyzed were: the global equivalence ratio, the swirler blade angle, the fuel jet Reynolds number, the primary chamber length/diameter ratio and the secondary chamber diameter.

This model incorporates features of two pre-existing and widely used combustion systems in gas turbines: RQL and LP. However, without the premixing inherent to the LP concept and without the staged addition of common air to the RQL combustors. This configuration allows the creation of distinct reaction environments, both in a lean overall combustion regime, and of a recirculation structure in the secondary region of the chamber. However, in this region the occurrence of combustion instabilities is observed, since this phenomenon is more susceptible in regimes that operate with low equivalence ratios.

Despite of the lean combustion, the results presented here showed that the instabilities attenuation or suppression is possible by choosing suitable values for the swirler angle, fuel jet Reynolds number, primary chamber length/diameter ratio and the relation between the primary and secondary chamber. A larger secondary diameter provided, in addition to a free wall condition, a low permanence of a structure with a high tangential momentum in the secondary zone, both contributing to the recirculation structure strengthening and, consequently, to the oscillations attenuation.

The results presented here have pointed some observations that may be taken into account for the design of double-stage swirl combustor for gas turbine applications. Additional numerical and experimental works must be done for better understanding about the flow dynamic inside the combustion chamber, for example, using laser techniques as PIV to observe the reagents and combustion gases flows. However, this work provided important informations to a deep analyse in future works.

5. ACKNOWLEDGEMENTS

This work was sponsored by the Brazilian National Research Council - CNPq (research resource and grant of Mr. Lacava) and by The State of Maranhão Research Foundation – FAPEMA (grant of Mr. Almeida). The tests were carried out at the Professor Feng Aeronautical Laboratory, Aeronautical Technology Institute.

6. REFERENCES

Almeida, D.S, Martins, C.A., Lacava, P.T., 2009. “Experimental Characterization of Combustion Instabilities in Double-Stage Swirl Chamber”. In: Proceedings of European Combustion Meeting, Vienna, Austria.

Brewster, B.S., Cannon, S. M., Farmer, J. R. and Meng, F., 1999. “Modeling of lean premixed combustion in stationary gas turbines”. *Progress in Energy and Combustion Science*, Vol. 25, pp. 353-385.

Durox, D., Moeck, J.P., Bourgouin, J.F., Moreton, P., Viallon, M., Schuller, T. and Candel, S., 2013.“Flame dynamics of a variable swirl number system and instability control”. *Combustion and Flame*, Vol. 160, pp. 1729-1742.

Gupta, A.K., Lilley, D.G. and Syred, N., 1984. *Swirl flows*. Tunbridge Wells, England, Abacus Press.

Huang, Y. and Yang, V., 2009. "Dynamics and Stability of Lean-Premixed Swirl-Stabilized Combustion". *Progress in Energy and Combustion Science*, Vol. 35, pp. 293-364.

Huang, Y., Yang, V., 2005a. "Effect of swirl on combustion dynamics in a lean-premixed swirl-stabilized combustor". *Proceedings of Combustion Institute*, Vol. 30, pp. 1775-1782.

Huang, Y., Yang, V., 2005b. "Modeling and Control of Combustion Dynamics in Lean Premixed Swirl-Stabilized Combustor". In *Proceedings of the 6th Symposium on Smart Control of Turbulence.* Tokyo, Japan.

Lefebvre, A.H. and Ballal, D.R., 2010. *Gas Turbine Combustion: Alternative Fuels and Emissions*. CRC Press, Taylor and Francis Group, 3rd edition.

Lieuwen, T. and Zinn, B.T. 1998. "The role of equivalence ratio oscillations in driving combustion instabilities in low NO_x gas turbines". In *27th Symposium International on Combustion*, pp. 1809-1816.

Lieuwen T., Neumeier, Y., Zinn, B.T. 1998. "The role of unmixedness and chemical kinetics in driving combustion instabilities in lean premixed combustors". *Combustion Science and Technology*, Vol. 135, pp. 193-211 .

O'Connor, J., Acharya, V. and Lieuwen, T., 2015. "Transverse combustion instabilities: acoustic fluid mechanic and flame processes". *Progress in Energy and Combustion Science*, Vol. 49, pp. 1-39.

Paschereit, C. O., Gutmark, E., Weisenstein, W., 1998. "Control of Thermoacoustic Instabilities and Emissions in an Industrial Type Gas Turbine Combustor". In Proceedings of 27th Symposium on Combustion**,** Vol. 27**,** pp. 1817-1824**.**

Sawyer, J.W., 1985. *Sawyer's Gas Turbine Engineering Handbook. Theory and Design*. v.1. Turbomachinery International Publ, Norwalk, CO, 3rd edition.

Seo, S., 2010. "Combustion Instability Mechanism of a Lean Premixed Gas Turbine Combustor". KSME International Journal, Vol. 17, pp. 906-913.

Seo, S. and Lee, S., 2010. "Effects of Unmixedness on Combustion Instabilities in a Lean-Premixed Gas Turbine Combustor". *Flow, Turbulence and Combustion*, Vol. 85, pp: 95-112.

Syred, N. A. 2006. "Review of Oscillation Mechanisms and the Role of the Precessing Vortex Core (PVC) in Swirl Combustion System". *Progress in Combustion and Energy Science*, Vol. 32, pp. 93-161.

Taamallah, S.,Vogiatzaki, K., Alzahrani, F.M., Mokheimer, E.M.A., Habib, M.A. and Ghoniem, A.F., 2015. "Fuel flexibility, stability and emissions in premixed hydrogen-rich gas turbine combustion: Technology, fundamentals, and numerical simulations". *Applied Energy*, Vol 54, pp.1020-1047.

Zhang, Z., Zhao, D., Siliang, N., Sun Y., Wang, B., Chen, Y., Li, G. and Li, S., 2019. "Experimental characterizing combustion emissions and thermodynamic properties of a thermoacoustic swirl combustor". *Applied Energy*, Vol. 235, pp. 463-472.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.