Flameless combustion with liquid fuel: A review focusing on fundamentals and gas turbine application

DOI:
10.1016/j.apenergy.2017.02.010

Document Version
Accepted author manuscript

Citation for published version (APA):
Xing, F., Kumar, A., Huang, Y., Chan, S., Ruan, C., Gu, S., & Fan, X. (2017). Flameless combustion with liquid fuel: A review focusing on fundamentals and gas turbine application. *Applied Energy*, *193*, 28–51. https://doi.org/10.1016/j.apenergy.2017.02.010

Published in:
Applied Energy

Flameless Combustion with Liquid Fuel: A Review Focusing on Fundamentals and Gas Turbine Application

Fei XING[a,*], Arvind KUMAR[b], Yue HUANG[a], Sai GU[c], Xiaolei FAN[d]

[a] School of Aerospace Engineering, Xiamen University, Xiamen, 361005, P.R. China
[b] Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India
[c] Department of Chemical and Process Engineering, University of Surrey, Guildford, GU2 7XH, UK
[d] School of Chemical Engineering and Analytical Science, The University of Manchester,
Manchester, M13 9PL, UK

Abstract: Flameless combustion has been developed to reduce emissions whilst retaining thermal efficiencies in combustion systems. It is characterized with its distinguished features, such as suppressed pollutant emission, homogeneous temperature distribution, reduced noise and thermal stress for burners and less restriction on fuels (since no flame stability is required). Recent research has shown the potential of flameless combustion in the power generation industry such as gas turbines. In spite of its potential, this technology needs further research and development to improve its versatility in using liquid fuels as a source of energy. In this review, progress toward application of the flameless technique is presented with emphasis on gas turbine engines. A systematic analysis of the state-of-the-art and the major technical and physical challenges in operating gas turbines with liquid fuels in a flameless combustion mode is presented. Combustion characteristics of flameless combustion are explained along with a thorough review of modelling and simulation of the liquid fuel fed flameless combustion. A special focus is given to the relevant research on applications to the inner turbine burners. The paper is concluded by highlighting recent findings and pointing out several further research directions to improve the flameless combustion application in gas turbines, including in-depth flow and combustion mechanisms, advanced modelling, developed experimental technology and comprehensive design methods aiming at gas turbine flameless combustors.

1. Introduction

Fossil fuels have been used by the society since thousands of years. With rapid expansion and development of technology, the society rapidly reached a point of overconsumption of any kind of natural resources. The facts that these resources are exhaustible, and our utilization rate is high, lead to the concern that in a very near future the fossil fuels will run out.

---

[*] Corresponding author. Tel.: +8613063039116; e-mail address: f.xing@xmu.edu.cn

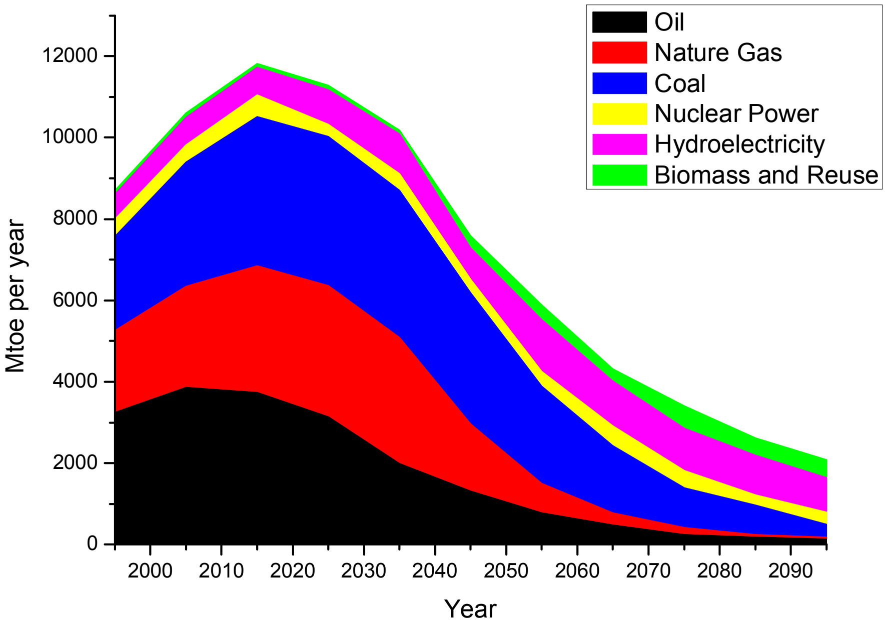


Fig.1 Global energy consumption by source in 2012 and in future [1]

The concerns about energy first surfaced during the energy crisis of the seventies. This leads to development of nuclear and solar energy. As can be seen in figure 1, fossil fuels still account for over 3/4th of the world's total energy supply today (Mtoe in Y axis label means million tonnes of oil per year) [1]. Although nuclear and solar energy may provide more promise for the future, fossil fuel cannot be quickly replaced for all applications, at least in the near future because of their several advantages including non-radioactivity, safety, matured utilization technologies, high conversion efficiency and cost (the data is from http://www.bp.com/).

However, when one considers the negative impact of fossil fuels, besides the limited reserves, concerns over environmental issues turn out to be quite serious. In 1992, the United Nation Conference on Environment and Development provided global efforts to protect our environment. Then, at the Kyoto protocol in 1997, many developed countries discussed the possibility and requirement of reducing the actual carbon emissions by 7% below the 90’s level over the next 10 years [2]. During the end of the last century more and more attention was given to the utilization of fossil fuels. Indeed, many problems are directly related to their consumption as fuel, and the pollutant, such as CO, CO_2, hydrocarbon, soot and NOx, that they produce during their combustion [3].

At present, gas turbines are a principal source of new power-generating capacity throughout the world, and the dominant source for air-breathing flight vehicles as well. Gas turbines will continue to be an important combustion-based energy conversion device for many decades to come, for example, for air craft propulsion, ground-based power generation, and mechanical-drive applications [4]. Large aerospace companies continue to push gas turbine engines to new limits, for example, Pratt & Whitney plans to produce future engines with 15-25% lower CO_2, 70-85% lower NOx, CO, and UHC, and have 15-25% lower fuel burn while providing reductions in noise, improved thrust-to-weight ratio, etc [5].

The impact of the emissions, such as NOx, CO and UHC on the environment is critical now. The gas turbines always work at high operation temperature which leads to the formation of NOx. In this way, the gas turbines are one of the main sources of pollutant in the lower layers of atmosphere [4]. Thermodynamically improvement of combustion efficiency and power output suggests the higher flame temperature (see figure 2). However, the long residence time of molecular nitrogen at peak temperature zone with high availability of oxygen (for few seconds above 1800 K or for only milliseconds above 2300 K) will lead to the formation of NOx. They are formed from the oxidation of the free nitrogen in the combustion air or fuel, and are called "thermal NOx." They are mainly a function of the stoichiometric adiabatic flame temperature of the fuel, which is the temperature reached by burning a theoretically correct mixture of fuel and air in an insulated vessel.

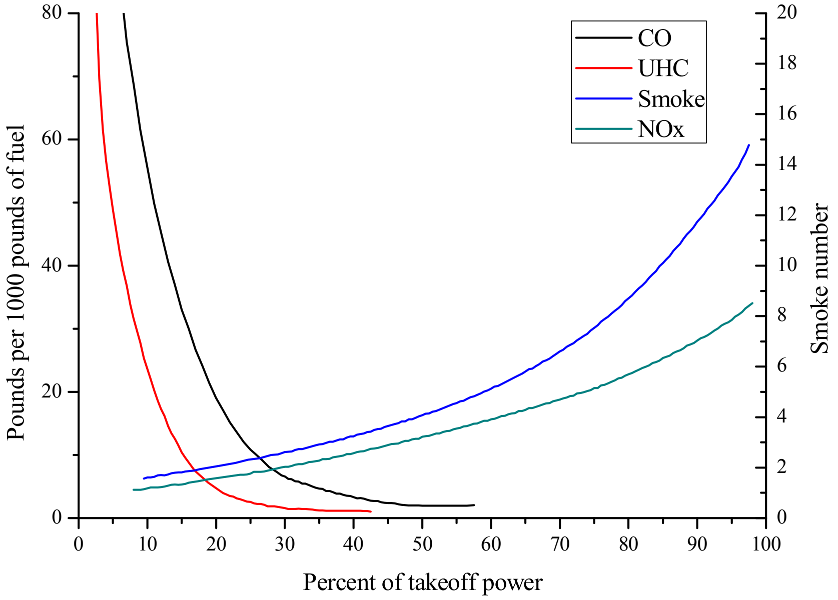


Fig. 2 Relation between the powers output of gas turbine and the amount of emissions [4]

With this big background, besides the high energy demand, every gas turbine designer is looking forward to converting the natural form of energy (gaseous fuels and liquid fuels) to useful work in a green manner with high efficiency. Therefore, many new techniques and new types of gas turbine combustors were developed for reducing the peak temperature and availability of oxygen in order to reduce the NOx and CO. For example, stage combustor, rich-quench-lean (RQL), lean direct injection (LDI), lean premixed pre-vaporized (LPP), etc [4]. In this paper, we will discuss another technique called flameless combustion and its application in gas turbine area.

In 1971, an interesting phenomenon was observed at high furnace temperature above auto ignition temperature of the mixture, that with exhaust gas recirculation, no flame could be seen and no UV-signal could be detected. Despite that, the combustion was stable and smooth, the fuel was burned completely and the NOx emissions were close to zero. This is called flameless combustion [6]. Its acronyms are usually related to the inlet air, such as: Excess Enthalpy Combustion (EEC), High Temperature Air Combustion (HiTAC) in Japan, or Moderate and Intense Low oxygen Diffusion (MILD) Combustion in Italy, Flameless Oxidation (FLOX) in Germany, and Low NOx Injection (LNI) in the USA. No matter how it is called, it implies hot oxidizers with exhaust gas recirculation at high turbulence level, and under typical conditions, it occurs with no flame, very lean and stable.

Developments in gas turbine engines are primarily focused on improving stability, emission and noise reduction. The aerospace industry continues to strive for higher compression ratios to increase engine efficiency, while burning at leaner conditions to reduce fuel consumption and lower NOx production. The new combustion technology is needed to meet the demands of higher pressure, leaner fuel combustion while meeting increasingly more strict emission standards. So far many topics have been reviewed to develop fundamental knowledge and understanding of combustion in gas turbine engines and how modern technologies are changing the way in which these engines operate. The uniform temperature distribution characteristics and low rate of emissions of flameless combustion are desirable in gas turbine engines. Since most of the aircraft engines and industrial combustors are operated with liquid fuels and research on flameless combustion with liquid fuel is limited with only few on-going laboratory works, it is important to review flameless combustion with liquid fuels. Such review should help to understand the role of flameless combustion on the improvement of gas turbine performance.

The technical review report presented here will first discuss major technical and physical challenges in liquid flameless combustion. Secondly, review of studies on flameless combustion of selective liquid fuels will be presented. Thereafter, flameless combustion studies related with the gas turbine engines all over the world will be discussed. The authors will also discuss some basic research areas in flameless combustion application in gas turbine engines that need improvement. The discussion will focus on future directions, flameless combustion, and inner turbine burner.

2. Fundamentals and Challenges in Flameless Combustion Research

2.1 Fundamentals of Flameless Combustion

Flameless combustion is based on exhaust gas recirculation in which NOx formation is suppressed without compromising the thermal efficiency. In flameless combustion, the re-circulated exhaust gas is defined as the exhaust gas that is re-circulated and mixed into combustion air before the reaction. The peak temperature of reaction can be reduced with increased inserts but beyond certain limits it leads to unstable combustion and blow off. Because of distinct benefits of flameless combustion, various efforts have been made to define the condition boundaries for flameless combustion in different systems.

The relationship between the exhaust gas recirculation rate and the furnace temperature in diffusion combustion is established by Wünning & Wünningin 1997 [7] for the non-premixed flameless combustion of methane in a laboratory furnace system, in which the relative internal recirculation rate (K_V) was defined as in Eq. (1):

$$K_V = \frac{\dot{M}_E}{\dot{M}_F + \dot{M}_A} \tag{1}$$

where $\dot{M}_E$, $\dot{M}_F$ and $\dot{M}_A$ are mass flow-rates of internal recirculation gas, initial fuel and air jet, respectively. Accordingly, a stability limit diagram was mapped as seen in Figure 3 showing the boundaries of different combustion modes. Stable combustion (zone A) is achievable over the whole range of operating temperature with a narrow recirculation rate window. For the higher relative recirculation rate, if the operating temperature is lower than the self-ignition temperature, the flame becomes unstable leading to the extinguishment as seen the 'No Reaction' zone in Figure 3. However, the combination of high temperature (above the self-ignition temperature), and high exhaust gas recirculation rate (greater than 3) can result in steady and stable reactions without flame (flameless zone C).

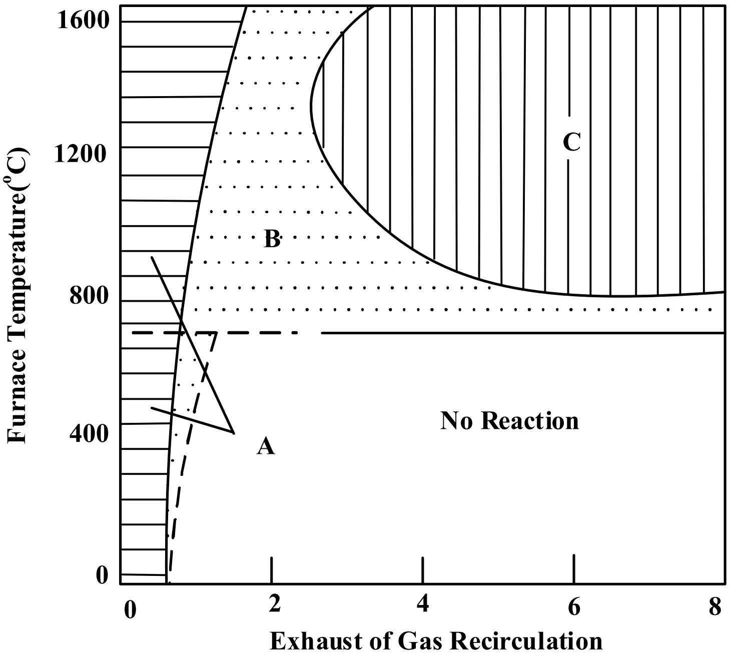


Fig. 3 Stability limits diagram as functions of furnace temperature and relative internal recirculation rate: zone A - stable combustion, zone B - unstable combustion, zone C-flameless zone [7]

At a high recirculation rate, the re-circulated exhaust gas dilutes oxygen concentration in the air stream and preheats the air stream leading to an increase in chemical reaction time and hence a smaller Damköhler number, which is an essential prerequisite for achieving flameless combustion. The uniform thermal field is one of the main characteristics of flameless combustion. The temperature rise in flameless combustion is moderate and dispersed due to distributed heat release during the combustion. In addition, it was observed that the effect of air preheating on NOx emission becomes insignificant with high recirculation rate of exhaust gas.

The map of different combustion regimes based on the inlet temperature (T_{in}) and temperature increase (ΔT) coordinate was measured for a methane combustion system (molar fractions: $CH_4/O_2/N_2$ = 0.1/0.05/0.85), as seen in Figure 4 [8]. The self-ignition temperature (T_{si}) of 1000 K, which is estimated based on a numerical computation, is used as the boundaries to map different combustion zones. For regions with higher ΔT, *i.e.* feedback and high temperature combustion, the required temperature for sustaining the flame is guaranteed, hence known as the traditional combustion process. When conditions satisfy $T_{in}>T_{si}$ and $\Delta T<T_{si}$, flameless combustion was identified (marked as the Mild Combustion in Fig. 4). The mild combustion process cannot be sustained without preheating the reactants. Though in results shown in Fig. 4 efforts were made to map the boundaries of flameless combustion for specific systems, it is difficult to develop a generic criterion to define flameless combustion for various combustion systems with different fuels. Therefore, the conclusions from the identification of the operating boundaries for flameless combustion are still restricted to the specific fuel, and flame observation is still the most common approach for research on such identification.

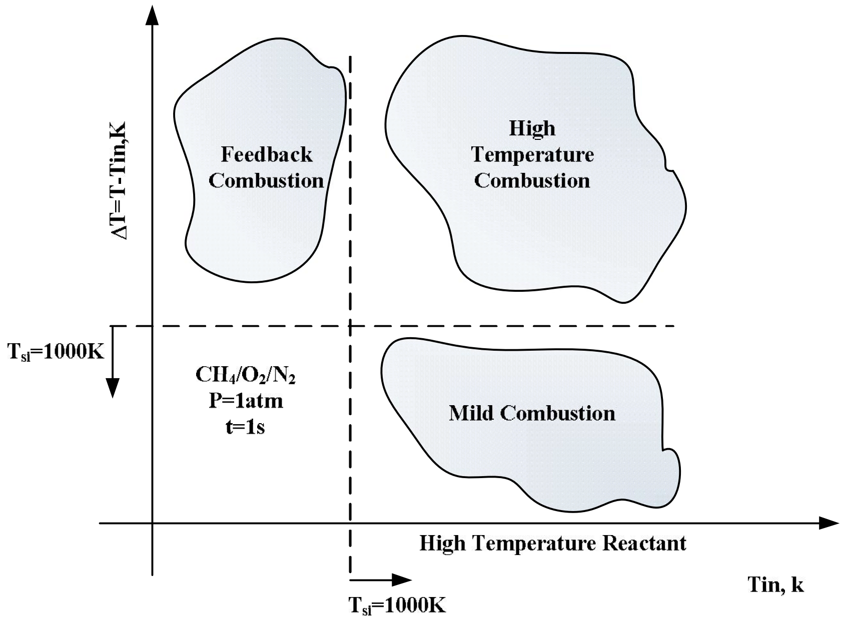


Fig. 4 Distinguished combustion state with inlet temperature and temperature raise (residence time =1s, atmospheric pressure) [8]

Flame is a product of self-propagating exothermic reaction that usually has a luminous reaction zone, in which the temperature increases from the minimum to the maximum, and accordingly the intermediate and product concentration increases. The high temperature in the reaction zone promotes decomposition of fuel molecules leading to the formation of free radicals. Reactions between reactive radical species are extremely exothermic for the product to be formed in excited electronic state with high energy level.

As seen in Figure 5, when the temperature of the mixture is higher than the self-ignition temperature, as the recirculation rate increases gradually, there is no flame front, no visible flame, no UV or ionization detection, and no noise or roar. A transparent flame combustion called flameless combustion forms. In this case, homogeneous combustion occurs, the reaction zone temperature increases only few hundred degrees, and CO and NOx are abated to very small residual values.

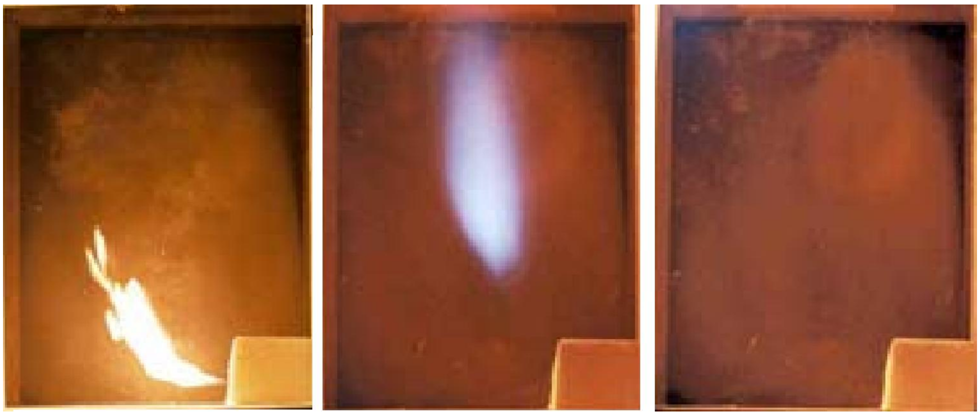


Fig. 5 Transition of acetylene flame from visible flame to flameless by decreasing the oxygen concentration from 21% to 2% [9]

2.2 Technical and Physical Challenges

According to Li et al. [10] and Noor at al. [11], technical challenges of gas flameless combustion can be summarized with the help of following issues: the way to judge flameless phenomena; physics of flow and combustion including high turbulence intensity, fuel injection momentum and temperature demand of the oxidant; experimental facilities and test methods; combustor design methods; combustion testing; and technology development tracking. In addition, from the authors' point of view, flameless combustion with liquid fuel is different from the one with gas fuel, therefore, the physical challenges may also include: atomization and evaporation of different liquid fuel; fuel injection and interaction with the high temperature gas; reaction mechanism of flameless combustion with liquid fuels; flow control of gas recirculation; gas entrainment; turbulence and reaction interactions, etc.

Overall, in order to develop a practical flameless combustor, each of these aspects must be addressed by either modelling or experimental approaches or combining both.

As previously stated, the design of flameless combustion systems depends largely on accurate estimation of similarity between the liquid fuel and the gas fuel systems, which requires proper understanding of the mechanism of flameless formation. For example, from 2006 to 2009, the researchers from University of Cincinnati [12-17] modified the old version of the EU burner leading to the development of a new burner with high turbulence intensity. The new combustion system uses fuel injectors with air jet flows into the recirculation zone [17]. The design is made such that a very high swirl forms and creates a very strong recirculation zone by turbulent processes. The fuel is then injected directly into the recirculation zone, and mixed with re-circulated exhausted gas to reduce the reaction rate. Chemiluminescence measurements were employed to provide data of species concentrations. Results showed that the reaction mechanism of flameless combustion is still unclear and a multi-pronged approach (e.g., when and how to realize flameless combustion) is needed to address this challenge. It was hoped that the new, more advanced "physics–based" methods and the theory for flameless can be applied correctly to this kind of problem.

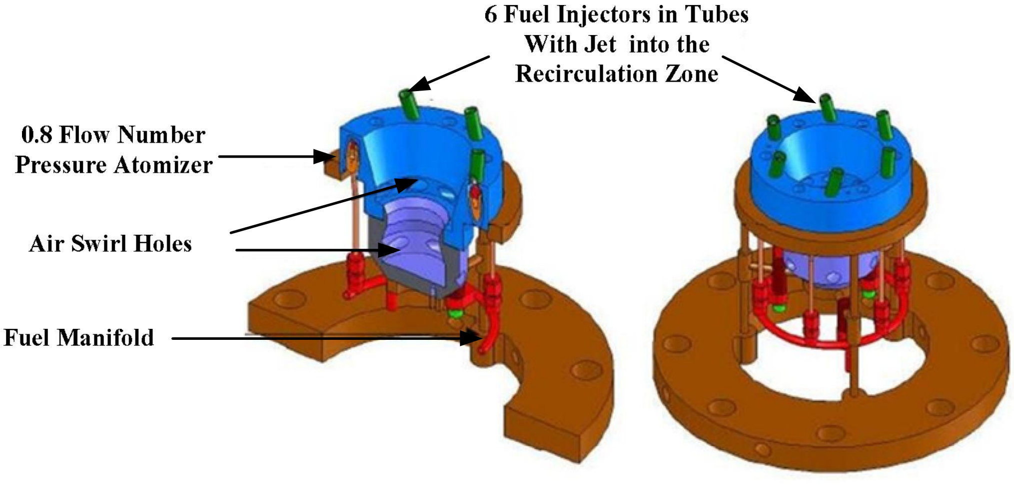


Fig. 6 Flameless burner design based on swirl stabilized combustion [17]

The flameless combustion occurs when both high levels of turbulence and oxidizer temperature exist for an evenly distributed fuel/air mixture. This kind of combustion has several advantages for application in gas turbine combustors, such as:

- stable operation at low equivalence ratios
- producing low concentrations of NOx and CO
- significant noise reduction
- evenly distributed temperature pattern in the reaction zone and at the outlet

What mentioned above suggest flameless combustion as a desirable mode of combustion for gas turbine engines, as lean instabilities become more of a problem for higher pressure ratio engines. The implementation of flameless combustion has been successfully demonstrated in non-adiabatic type combustion systems, such as industrial furnaces [10, 18]. However, operational parameters for gas turbine combustors are very different from those of industrial furnaces, which possess several major challenges to applying flameless combustion to gas turbine as follows.

Firstly, the operational range of flameless combustion combustors is narrow, and hence cannot satisfy the dynamic requirements for a gas turbine engine, especially that of an aircraft. The stable flameless combustion can be achieved only when the specific operating conditions are maintained. However, the operation of gas turbine combustors is dynamic and difficult to maintain at the specific conditions. For example, when the aircrafts climb or take maneuverable flights, the air flow and fuel injection often change dramatically, leading to the interruption of flameless combustion. Secondly, the O_2 concentration and pressure in a gas turbine is higher than in an industrial burner, hence a harsher environment exists in a gas turbine. The gas turbine cycle efficiency increases with Turbine Inlet Temperature (TIT), producing high average operational temperature that is beneficial to the flameless combustion. However, gas turbine combustors operate at a low overall equivalence ratio, i.e., very high O_2 concentration in the combustor. Since flameless combustion is a low O_2 concentration combustion phenomenon, creating a suitable operational zone may be difficult. Thirdly, the volume required by flameless combustors is large as compared to the conventional combustors, which is an important constraint for aircraft applications. A large amount of combustion gases need to be circulated within the combustor to decrease the concentration of O_2. This also results in lower volumetric heat densities as compared to existing conventional gas turbine combustors. Finally, it is also challenging to develop sufficient gas recirculation for flameless combustion without adding a mechanical system for creating recirculation. The difficulty remains in controlling the reaction rate in a way in which sufficient mixing is achieved before completion of the reaction.

Closely associated with liquid fuel flameless combustion for gas turbine, an important near term challenge for flameless combustion is to determine the suitable conditions for specific application using various fuels. Systematic fundamental studies will provide optimum design guidelines for a specific application. A few technical objectives are as follows:

- Fundamental understanding of effects of fuel types, high pressure, initial air temperature and exhaust gas recirculation ratio on flameless combustion using liquid fuel.
- Design of flameless combustors, considering geometry, liquid droplet breakup and evaporation, fuel supply and gas matching, control of the equivalence ratio in the combustion zone.
- Development of numerical models for the simulation of flameless phenomena in gas turbines at working conditions.
- Development correlations between numerical models and ground tests, and validation.

3. State of the Art of Flameless Combustion with Liquid Fuel

Based on the previous flameless combustion investigations with gas fuels [10], the consensus for this type of combustion appears to be:

- Preheating of combustion air with high temperature exhaust recirculation and high-speed injections of air and fuel are the main requirements for achieving flameless combustion.
- Strong entrainment of high-temperature exhaust gases, diluting fuel and air jets, is the key to maintaining flameless combustion.
- Essential environment conditions for the establishment of flameless combustion are: local oxygen concentration < 5% - 10%, and local temperature > the fuel self-ignition temperature in the reaction zone. Such conditions can be achieved by high dilution of the reactants with the flue gas (N_2 and CO_2-rich exhaust gas).
- In comparison with conventional combustion, the thermal efficiency of flameless combustion can be increased by more than 30% but the NOx emission can be reduced by more than 70%, when a regenerator is used to recycle the waste heat of flue gases [19].

Flameless combustion has been extensively investigated for systems using gaseous fuels~~,~~ such as hydrogen, methane, ethanol etc. However, to the best of the authors' knowledge, there is no pilot scale or large-scale investigation of flameless combustion using liquid fuels although liquid fuels are essential to gas turbine engines. Therefore, it becomes imperative to understand the characteristics of flameless combustion with liquid fuels to increase the engine efficiency and reduce NOx and CO emissions. In the following sections of this contribution, the focus is on reviewing the available work ~~conducted~~ on the flameless combustion with liquid fuels.

3.1 Bio Fuels

Biomass-derived fuels have assumed an ever-increasing role in the projected sustainable energy supply system of the future, considering the fossil fuel supplies vary with the increasing world energy demand. Some researchers published considerable interest in bio fuels in the flameless combustion systems in order to significantly lower the emission levels.

Flameless combustion with biomass fuel was first investigated with gaseous biomass fuels because of the similar physical properties and combustion mechanisms of gaseous fossil and biomass fuels. Kaneko lab at the University of Tokyo developed a MGT (micro gas turbine) system that use biomass gas as fuel. A trial combustor with three combustion zones and one dilution zone was designed for the MGT system. In this combustor, premixed gases are injected vertically into the main flow and mixed with the burned gas supplied from previous stage. At this moment, flameless combustion takes place and achieved the lower emissions

[20]. Thereafter, effort was made to use liquid bio-ethanol as the fuel for the flameless combustion in micro gas turbine [21, 22]. A comprehensive analysis is presented for the possibilities that are offered by a bio-fuel supplied to a micro-gas turbine, together with the attempt to a nearly zero-emission operation. It was also found that the efficiency of flameless combustion is close to that of conventional combustion with kerosene fuel if the fuel/air ratio is maintained as the same. The emission levels can be further decreased by selecting a different location of the pilot injector. All the research works mentioned above are based on CFD without experiments validation. Meanwhile, the lack of species concentration and temperature in the combustors makes it difficult to understand the mechanism of the flameless combustion.

Ellis et al. [23] investigated the combustion process within a Power, Water Extraction, and Refrigeration system, known as PoWER (Figure 7). Four liquid bio-fuels were tested for exhaust emission and soot behaviour in the PoWER gas turbine system as see in Figure 8. The exhaust gas recirculation was applied to the system through a semi-closed cycle gas turbine system called the High-Pressure Regenerative Turbine Engine (HPRTE). The major objective in the development of this system is long-term operation on liquid biofuels flameless combustion, in order to demonstrate the potential for coupling such systems in a distributed generation mode to relatively small biofuel processing plants needed to take advantage of biomass resources. It is the first but important step for the liquid bio fuel.

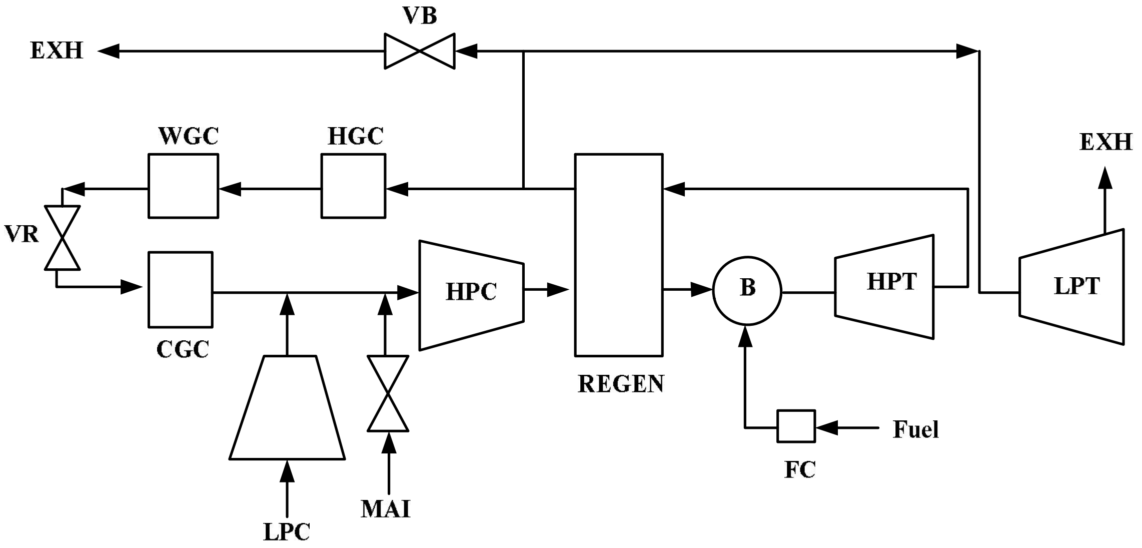


Fig. 7 PoWER System Diagram [23]

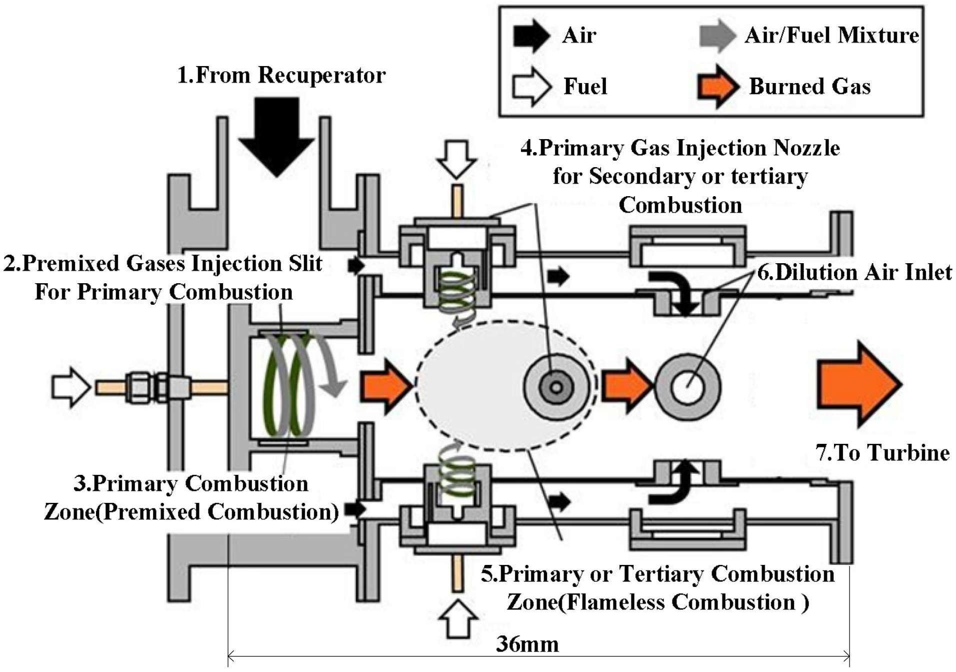


Fig. 8 Schematic view of combustor in PoWER System [23]

3.2 Diesel Oil

Torresi et al. [24] designed an aerodynamic ally staged swirled burner using the diesel oil as the fuel. The burner has been experimentally tested and numerically simulated under diluted and highly preheated inlet flow conditions. The staged injection is realised through a double coaxial air inlet with the same swirl orientation. The diesel oil is injected through a central atomizing nozzle characterized by very high range ability. The air was heated to 673 K and diluted by CO_2 and H_2O, and the concentration of O_2 is 12.59 %. It may be noted that there is no information about the diesel oil atomization and evaporation. The numerical simulation was in a good agreement with experimental results, confirming that the burner, under properly operating conditions, is able to burn the fuel completely without a flame front and with a very uniform temperature field, as seen in Fig. 9.

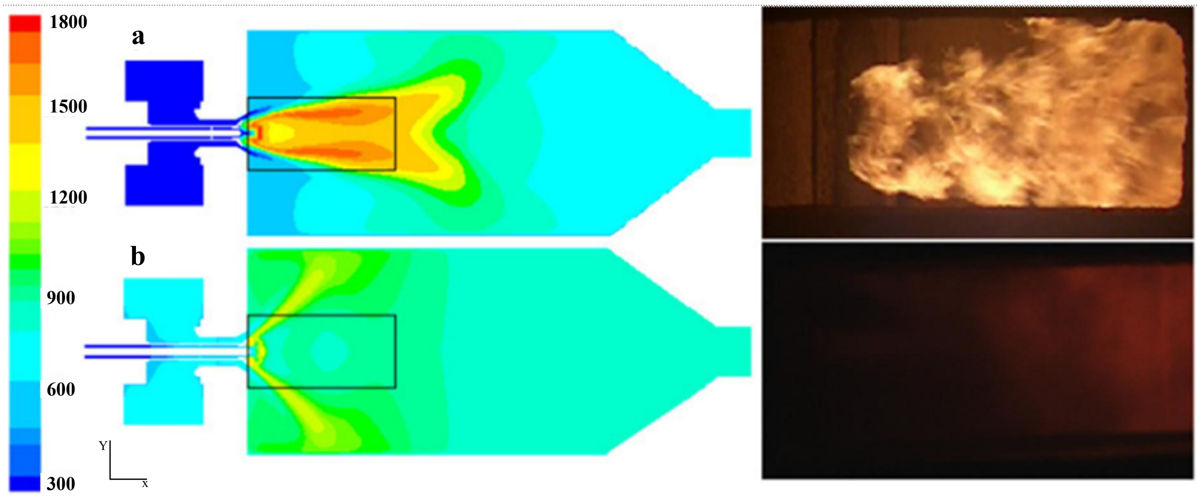


Fig. 9 Contours of temperature for flame (a) and flameless (b) conditions with the relative experimental images [24]

In China, Professor Lin's research team also realized the flameless combustion of liquid diesel in 2012 [25, 26]. After Li et al. [10] realized that flameless combustion occurred not only in high temperature low oxidant concentration but also in high temperature high oxidant concentration, Qizhao Lin [25, 26] also believes that air preheating is not an essential condition to attain flameless mode and that the air injection speed is more important to lower the whole reaction rate.

A cubical combustor was designed with a recirculation structure, as shown in Fig.10, and flameless combustion experiments were carried out by using 0# diesel. It has been observed that with the increase of the injection momentum of the reactants, the combustion mode is converted from flame to flameless while the recirculation structure does not change. The liquid diesel was supplied by air blast atomizer, however, the performance of the atomizer was not mentioned. It can be concluded from the analysis in the works [25, 26] that the air injection velocity and the entrainment and mixing with the high temperature exhaust gas are considered as the most important factors in controlling the reaction rate and changing the combustion mode, and that the appropriate preheating of the combustion air is an effective way to enhance the combustion stability. The effect of the high temperature was not emphasized, which would reduce the cost of the experiment remarkably. Otherwise, the conclusions are very important and useful.

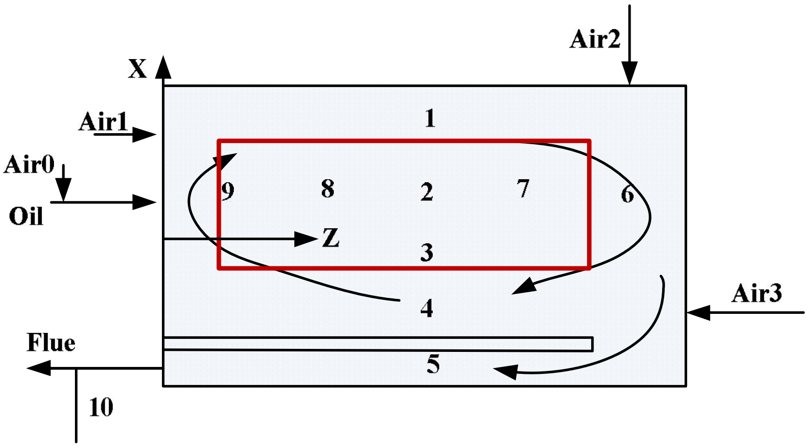


Fig. 10 Combustor configuration and thermocouples layout [25]

3.3 Other Liquid Hydrocarbons

To avoid the complex mixture of real liquid hydrocarbon fuels, surrogate fuels are commonly used with two purposes, for designing better reproducible experimental tests, and for obtaining physical insights from well-controlled fundamental and kinetic studies. Since 2006, Gutmark's research team has been focusing on the flameless combustion and the use of gas fuel [12-16]. In 2009, they published a paper about the flameless combustion with several kinds of liquid hydrocarbons [17].

In a collaborative work between Goodrich Aerospace and the University of Cincinnati, a flameless burner was designed and tested [12]. In the first design, the burner was composed of a circle of premixed air/fuel jets directed to mix with the combustion products. The results were globally unsuccessful [12,13]. The burner demonstrated the usual premixed flame instabilities when combustion transits out of steady flameless mode. Therefore, it was found that it is a key factor to achieve the necessarily high turbulence intensity.

Take with the above paragraph, then the burner was modified to form a very strong recirculation zone and to operate at the conditions typical to gas turbine engines. In particular, the emphasis was placed on achieving high mixing rate while maintaining a low pressure drop across the fuel inject (see the Fig.7). A low-noise high-sensitivity microphone and thermocouples were used to determine temperature uniformity of the flameless model.

The research work has shown that operating the burner at high oxidizer temperature (from 325 °C to 525 °C) and relatively low pressure drop (from 3 % to 5 %) allows flameless combustion to occur while running very lean (equivalence ratio is from 0.7 to near LBO). Different fuels including propane (liquid), n-butane (liquid), n-pentane, n-hexane, toluene, jet-A and a blend of alkanes/alkenes centered around C9 were tested. All fuels, with the exception of n-butane, showed very similar characteristics [17].

Derudi et al. [27] from Italy also focused on the investigation of the sustainability of flameless combustion for liquid hydrocarbons using a dual-nozzle laboratory-scale burner. Air and gaseous fuel are fed through the bottom of the combustion chamber, as shown in Fig.11a. After finding that configuration is not suitable for liquid fuels, the apparatus has been modified by implementing the double-nozzle (DN) inlet configuration as shown in Fig.11c, where the preheated air enters the combustion chamber through the bottom nozzle, while the liquid fuel is injected as a well-dispersed and homogeneous spray througha water-cooled plain jet airblast atomizer. The two jets interact perpendicularly and mix with each other in a high turbulence region. The research has shown that the DN configuration allows to sustain flameless combustion by directly injecting different liquid hydrocarbons under the conditions that are previously established using a gaseous fuel as shown in Fig.11b. DN configuration provides different results for liquid hydrocarbons, suggesting that the flameless combustion characteristics are probably more influenced by the physical state of fuels than the chain length of the hydrocarbon. For example, the flameless combustion region in terms of the window T_{avg} (average combustion chamber temperature) $-K_v$ (gas recirculation rate) space was found enlargeed with the liquid hydrocarbons in comparison with the gaseous ones.

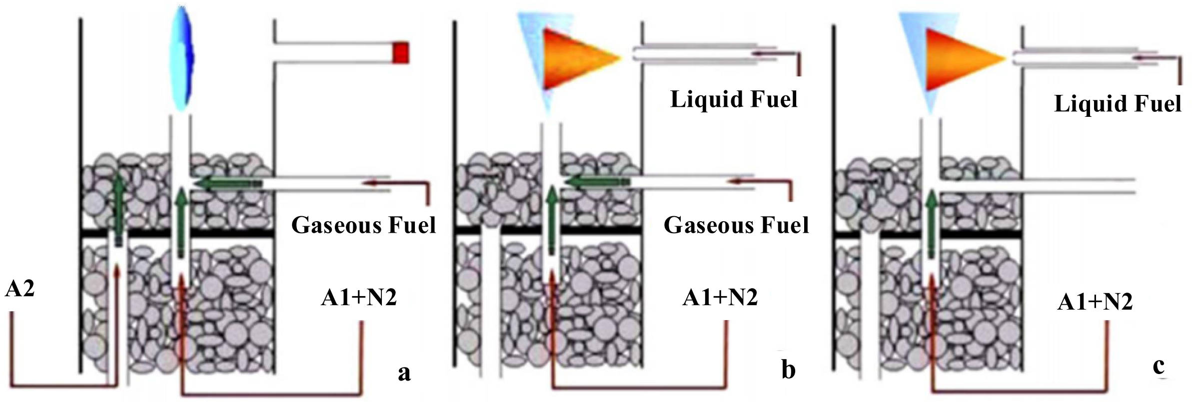


Fig. 11 Reactants feeding system: (a) SN gas-fuel feed; (b) DN liquid- and gas-fuels feed; (c) DN liquid-fuel feed. A1: primary air; A2: secondary air [27]

Though the chemical reaction mechanism involved in such flameless combustion burner remains unknown and numerical or experimental approaches are required to reveal this, such work does corroborate its potential for flameless combustion applications with liquid fuel.

3.4 Kerosene

Since kerosene is a complex mixture of hydrocarbons, effort has been made to achieve flameless combustion using liquid kerosene after several attempts on achieving flameless combustion with the liquid hydrocarbons [18-33].

Experimental and numerical research has been carried out to use a two-stage combustor to investigate characteristics of flameless combustion with kerosene. The design of the combustor is based on the injection of fuel and air at ambient conditions, as seen in Fig. 12a. The fuel injection and air injection schemes are believed to have an impact on fuel spray, increasing shear force and resulting in enhancing mixing and evaporation of droplets. The latest research published in 2014 [30] shows that the two-stage combustor was not ideal for establishing flameless combustion. Therefore, a swirl-based combustor with a chamfer ~~provided~~ at the top of the combustor (see Fig. 12b) was considered, aiming at improving the droplet residence times and the recirculation rate. Observations from this study are summarized [30]. Firstly, flameless combustion was stabilized in the base combustor. However, for higher fuel flow rates flameless combustion was not achieved and unburned fuel accumulated in the combustor. Secondly, a chamfer near the exit in the modified combustor configuration helped increase the circulation rate and residence time. The outstanding performance of the burner with very low chemical and acoustic emissions at high heat release rates indicates the potential for various industrial and gas turbine applications.

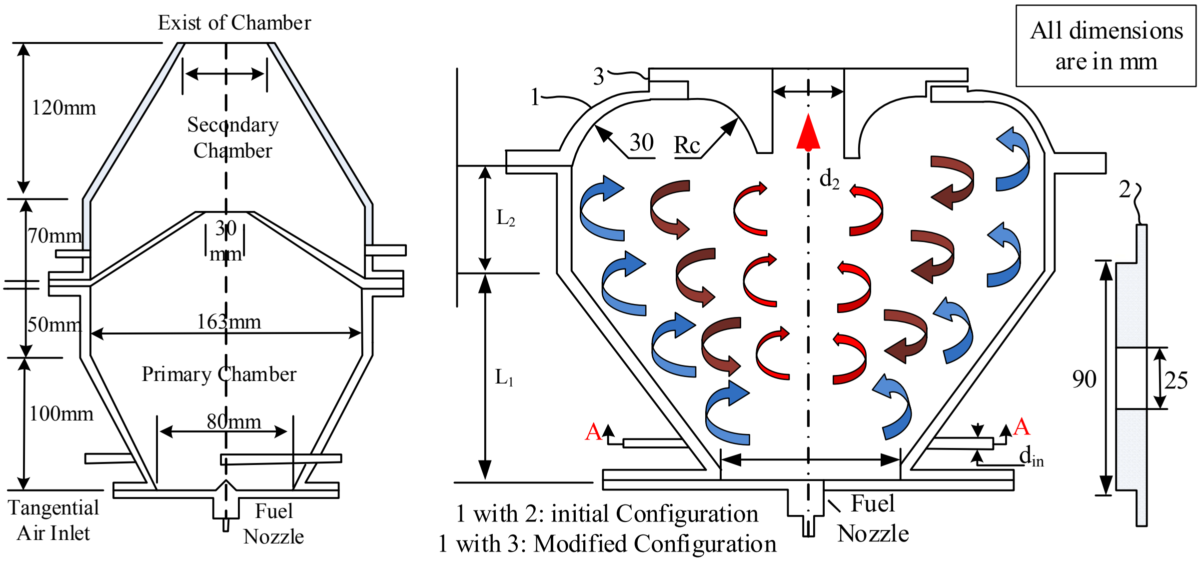


Fig. 12 Schematic diagrams of the combustors:
two stage combustor [28,29] and swirl based combustor [30]

Simulation and experimental research on flameless combustor based on trapped-vortex [31, 32] were also carried out with kerosene. The zero dimensional and three dimensional numerical simulation was performed first. The emissions and temperature profile of the outlet are in good agreements with the cavity configuration. In the experimental work, the emphasis was to analyze the influences of the inlet air temperature, air flow-rate and equivalent ratio. The fuel is supplied by air atomization injectors, when the inlet temperature is above 550 K, and the reference velocity is higher than 10 m/s. The authors considered that the flameless combustion was stabilized by the trapped vortex.

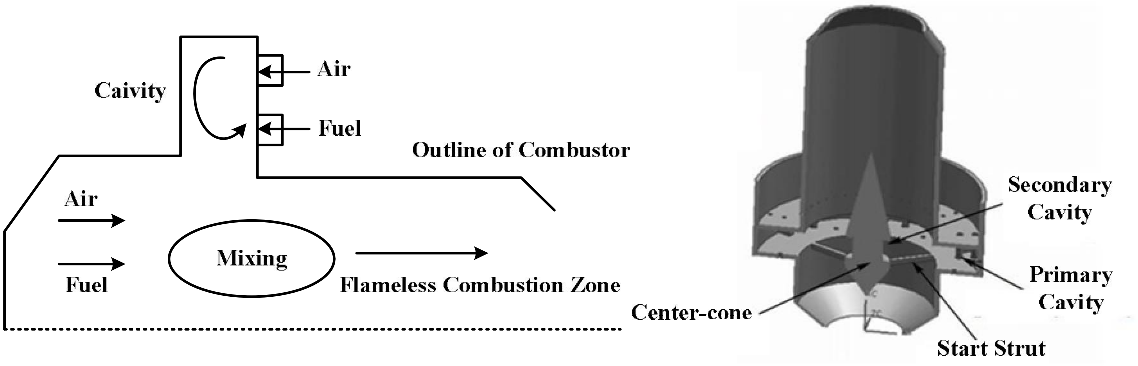


Fig. 13 Schematic diagram of the flameless combustor [31, 32]

4. Flameless Combustion for Gas Turbine

The application described in this section is exploratory since many examples from gas turbines can be reported in which partial fulfillment of the flameless condition occurs, though most of them use the gaseous fuel. Very few gas turbine systems have been built with the purpose to satisfy flameless combustion conditions, especially with liquid fuels. Nevertheless some of them deserve mention, because they partially fulfill flameless combustion conditions and they are of interest to foresee possible potentials and problems.

4.1 FLOX Combustor from Europe

Flameless oxidation (FLOX) based on high internal flue gas recirculation was investigated using gas turbines [34-42]. Several liquid fuels were tested under atmospheric conditions [34] and similar results were obtained. Natural gas, as well as mixtures of natural gas and H_2 were used as fuel at the second stage of the project [35, 36]. The NOx and CO emissions were monitored under different operating conditions and at two air preheat temperatures of 703 K and 873 K, and 20 bar pressure with a maximum thermal power of 475 kW. The imaging of OH* chemiluminescence and planar laser-induced fluorescence (PLIF) of OH were applied in order to characterize the influence of various parameters, such as mixture composition, degree of premixing, velocities on the pollutant emissions, flame zone, the relative temperature distributions etc.

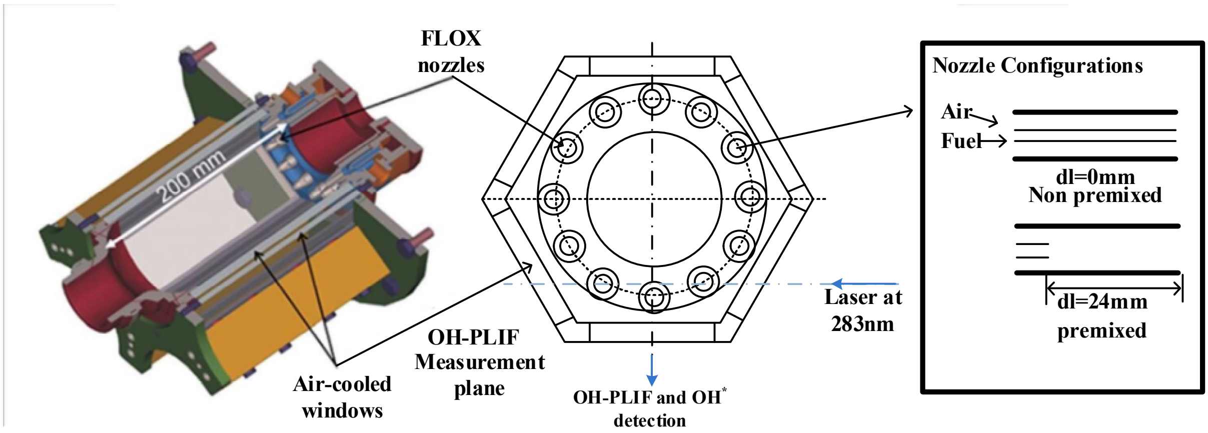


Fig. 14 3D drawing of the combustion chamber with the FLOX burner (left) and the schematic of the FLOX burner with the OH-PLIF measurement planes marked (right) [36]

Successful operation of the FLOX® combustor with low emissions was demonstrated at high pressure as well. It was shown that the jet exit velocity of the fuel/air mixtures had a strong influence on the mixing process within the combustion chamber, and that the low emission operating range is increased with the increase in jet exit velocity. With adding H_2 to the natural gas, the range of stable operation could be extended; however, the NOx emissions are also increased, probably due to inhomogeneities in the temperature distribution.

A reversed flow combustor for small and medium size gas turbine engines, called optional schemes for an adiabatic flameless oxidation combustor (FLOXCOM) [38, 39], was studied. A procedure for calculating the thermodynamic parameters and the gas properties, at every stage of the combustion process, was developed in 2004 [38]. It is shown that the oxygen concentration at the end of the combustion zone increases when the difference between combustion and air inlet temperatures decreases. It is believed that the key to ~~have~~ a low NOx flameless gas turbine combustor is to keep a low O_2 concentration within the combustion zone and a relatively even temperature distribution within the combustion chamber. In order to meet the above-mentioned stringent demands, the schematic of the combustion methodology is presented as in Fig. 15 [39].

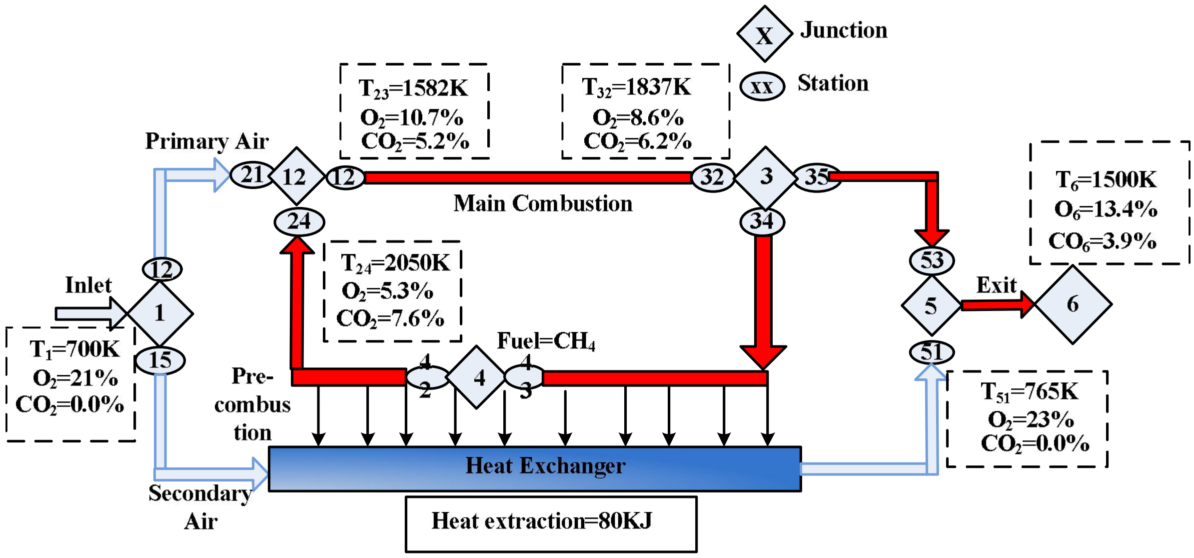


Fig. 15 Schematic of the proposed new flameless combustion methodology [39]

A schematic of the conceptual gas turbine combustor operating on the proposed combustion methodology is illustrated in Fig. 16a. The various junctions and stations described in the thermodynamic model (Fig. 15) are also depicted in the Fig. 16b for better understanding. Salient features of this concept as compared to other proposed combustors for gas turbines are:

- Fuel (CH_4) is injected into the deficient O_2 and high CO_2, H_2O concentration recirculation zone, to make sure that the fuel is injected in an optimum environment where flameless combustion can take place.
- Certain amount of energy is transferred from primary combustion zone to the secondary cooling air, thus reducing combustion temperature and hence limiting the NOx formation.
- Energy is added in two steps, partially in the pre-combustion region (between “4” and “2”) of the recirculation zone and partially in the main combustion zone (between “2” and “3”). Thus, it limits the maximum temperature rise below the temperature above which NO formation would have increased exponentially ($\cong$ 2000 K).

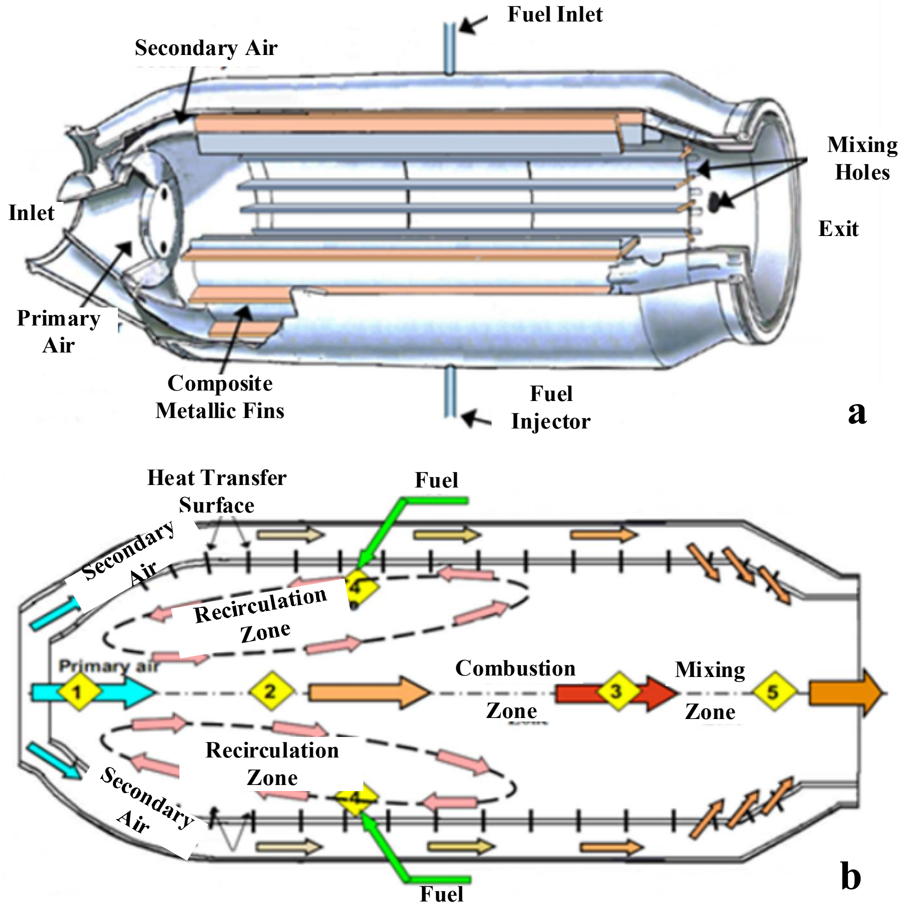


Fig. 16 Schematic of a Gas Turbine Combustor Operating on the Newly Proposed Cycle [39]

In 2011, Levy cooperated with Melo et al. from Technical University of Lisbon and developed the schematic of a gas turbine combustor operating on the new cycle mentioned in Figs. 15 and 16 [40]. The main characteristic of such design is the formation of a large recirculation vortex, stimulated by the momentum of the incoming air jets and aided by the specific geometry of the combustion chamber, as seen Fig. 17. The air from the compressor enters at station 1 and is split into two streams with identical flow rates. One stream is entrained and its oxygen concentration is diluted by the recirculated combustion products and directed toward point 2. At that point the fuel (methane) is injected and mixed. The combustible mixture ignites at station 3 after a certain ignition delay time. Combustion occurs between points 3 and 4, and thereafter the combustion products are split, partially recirculating with fresh air and partially exiting the combustor while diluting with fresh air (point 5). The two streams mix and exit the combustor at point 6, at the required combustor's exit temperature, typically determined by the performance of the turbine located immediately downstream.

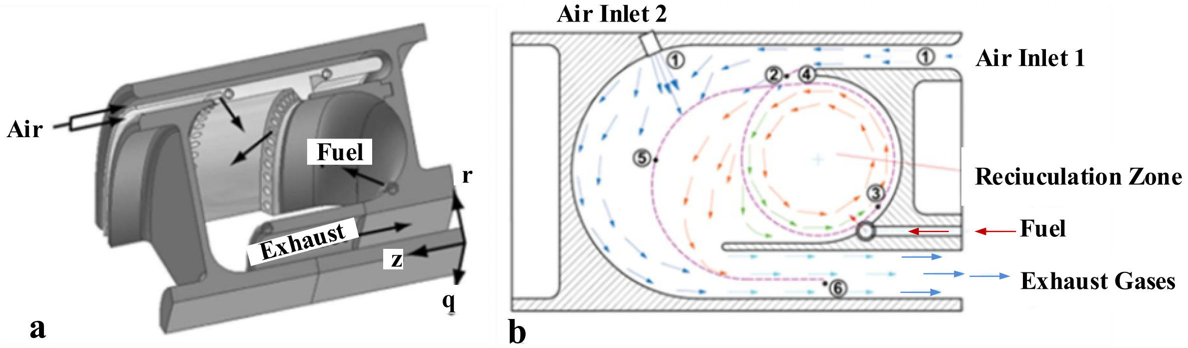
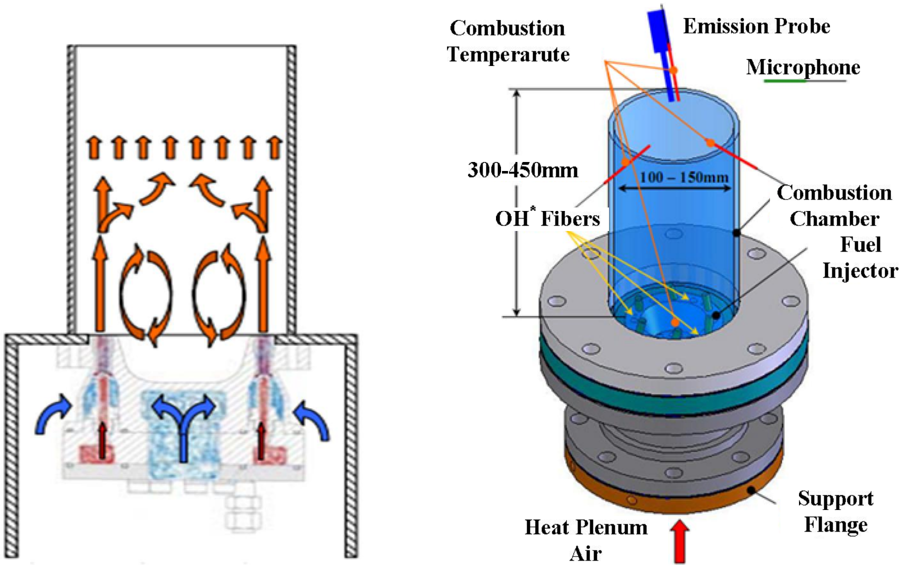


Fig. 17 Schematic of internal aerodynamics of the combustor [40]

The new combustor was experimentally investigated and found as stable over a relatively wide range of operating conditions. At specific conditions, i.e., air inlet temperature = 425 K, equivalent ratio: 0.24 - 0.28, the NOx level was measured as lower than 10 ppm. However, the CO level was measured as relatively high, about 700-1200 ppm, showing that there was still space for improving the design to increase combustion efficiency without hampering the combustor performance. The authors thought that the flameless combustion did not happen in the recent design theme.

4.2 Flameless Combustor from America

As previously stated, from 2006 to 2009, the research team from University of Cincinnati [12-17] modified the old version of the EU burner, and developed a new concept combustion using the swirl method to achieve the necessary high turbulence intensity. In the first approach, the burner was tested unsuccessful [12, 13]. The new burner was designed to form a very strong recirculation zone and to operate at conditions typical to gas turbine engine. In particular, the emphasis was placed on achieving high mixing rate while maintaining a low pressure drop across the fuel inject (see Fig. 7 and Fig. 18b). Inlet temperature, pressure drop and combustor geometry were varied to determine the boundaries of flameless combustion within the constraints acceptable to current and future aircraft engines. Data were collected starting at equivalence ratio of 0.7 and decreasing to lean-blow-out (LBO) to determine the flammability limits of the flameless burner. Important aspects of flameless combustion include uniform temperature distribution, low emissions, and decoupling between heat transfer, fluid dynamics, and acoustics.



a b

Fig. 18 Schematic of EU burner (a) and modified combustor (b) [12, 17]

The research work considered the high turbulence intensity, maximized the residence time, and assisted fast fuel/air/combustion product mixing, and suggested high inlet temperatures as the most important aspects for the flameless combustor design. The points above are common points as other researchers have also proposed. Except those points, the research work using the gaseous propane as the fuel has also shown that:

- The transition to flameless mode from regular combustion is gradual and a definite transition point cannot be defined clearly.
- High air mass flow rates promote evenly distributed flame, resulting in good mixing, strong reaction, and less NOx formation.
- The increase of the inlet temperature reduces the LBO limit, and expands the range of equivalence ratios where the flameless mode occurs.

4.3 Model Flameless Combustor from China

In 2010, researchers from Chinese Academy of Sciences focused on the dynamic characteristics of a flameless model combustor [43-45]. The model combustor is a can-type reverse flow combustor (Fig. 19) with two parts: head and chamber. The head of the combustor comprises the air and the fuel distribution units. All the air is injected into the chamber by co-flow injection through the twelve main nozzles. There is a concave recirculation structure at the head of combustion chamber in which the burned gas recirculates and mixes with fresh reactants. The positional relationship between the nozzles and the concave structure raises the mixture's temperature above the fuel self-ignition temperature, and dilutes the air to reduce the concentration of O_2, thereby achieving flameless combustion. Additionally, there is a pilot nozzle fixed in the center of the concave recirculation structure, which is designed for ignition and maintaining combustion in case that the equivalence ratio is low. Therefore, in the combustor's mixed mode, the fuel is partially premixed. The pure methane and nitrogen-diluted methane (volume ratio of CH4:N2=1.0) were used as the main fuel, and propane was used for the pilot.

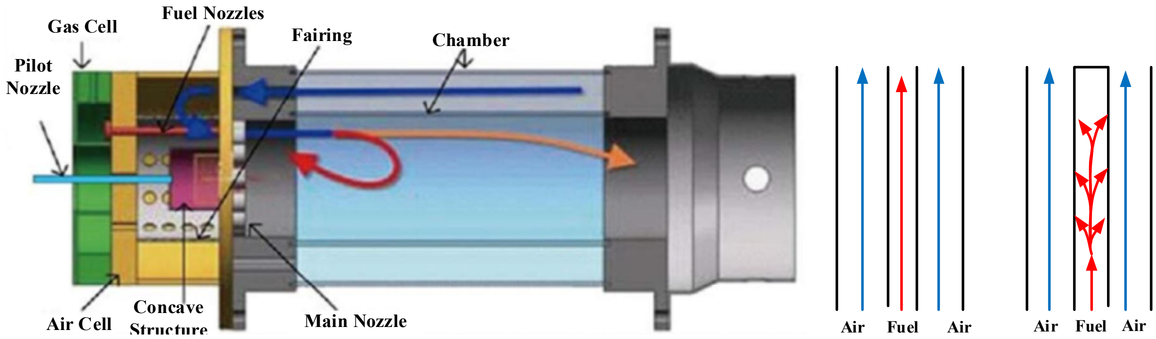


Fig. 19 Cross-section view of flameless combustion model combustor and fuel nozzle [43]

In this model combustor, there are three working modes (see Fig.20). These are Pilot-only mode, Mixed mode (the pilot and main nozzles work together), and Flameless mode. The pilot nozzle is closed, while the main nozzles continue to supply fuel, attaining flameless combustion.

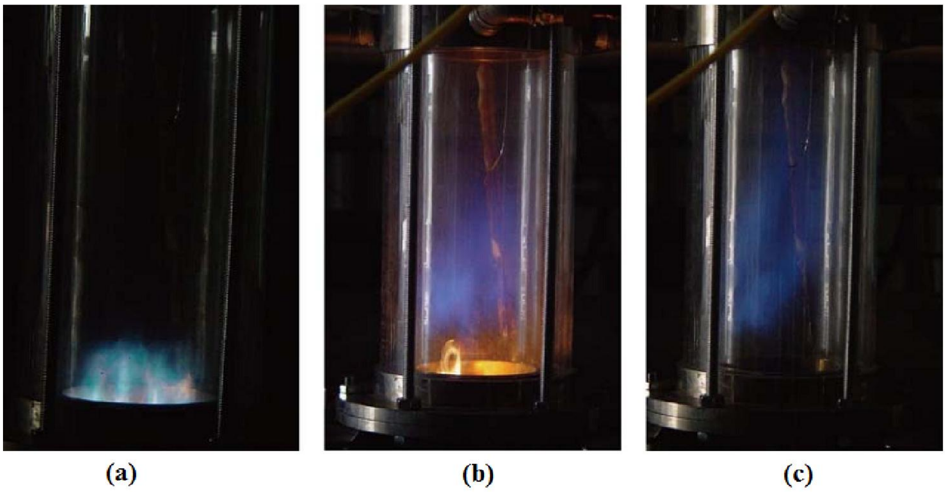

(a) (b) (c)

Fig. 20 The combustor ignition sequence (a) Mode I: pilot nozzle only; (b) Mode II: pilot and main nozzles; (c) Mode III: main nozzles only [43, 44]

The highlight of the research is the use of the dynamic pressure sensors to detect the dynamic pressure signal. An autoregressive (AR) model was used to estimate the power spectrum. Furthermore, there was no dominant oscillation amplitude in flameless combustion. The flameless combustion mode showed lower combustion noise and no thermal-acoustic oscillation problems while achieving ultra-low NOx and CO emissions. However, when the pilot flame coexisted with the main combustion flame, instability was excited at certain equivalence ratios. The experimental method is very helpful to identify the transformation from the conventional combustion to the flameless model.

4.4 Flameless Combustion Based on Trapped Vortex

The trapped vortex is a design concept for the gas turbine combustor. It is currently being developed for the low-emission and high-performance combustion systems in aircrafts and ground power gas turbine engines [46]. The trapped vortex combustor (TVC) design is based on a fast mixing process of hot combustion products and reactants, and can function appropriately when a vortex is "trapped" within a cavity where reactants are injected and efficiently mixed. Since part of the combustion occurs within the recirculating (vortex) zone, the reactants mix with the products in a "typical" flameless regime, thereby, the flameless combustion process may occur in this zone.

Netherlands and Italy

The first group who combines flameless combustion and trapped vortex combustor (TVC) is the research team from Delft University of Technology and University of Rome in 2006 [47]. They agreed that reactants are mixed at high temperature in a TVC by means of a vortex and burn at a low oxidizer concentration and at high recirculation factors like a flameless burner. However, they also pointed out that the amounts of the mainstream flow from these two types of combustion, which were involved in the combustion process, were different.

The first configuration (see Figure 21a) was proposed as the solution for low-power and single-cavity combustion chambers. In order to stabilize the vortex, the mass flow rate of the primary air injected should be lower than the rate of the main air stream. But the simulation results showed that the combustion primarily occurs next to the primary air injectors and downstream the cavity along the outlet pathway. It means that the combustion is incomplete because of inefficient mixing. The next design of geometry contains the diffuser (see Figure 21b) which is capable of supplying sufficient oxidizer to the secondary cavity, thus providing a more stable vortex. The second design was found ~~to be~~ able to generate two independent vortices, each trapped within its cavity, by means of two (almost) independent air streams.

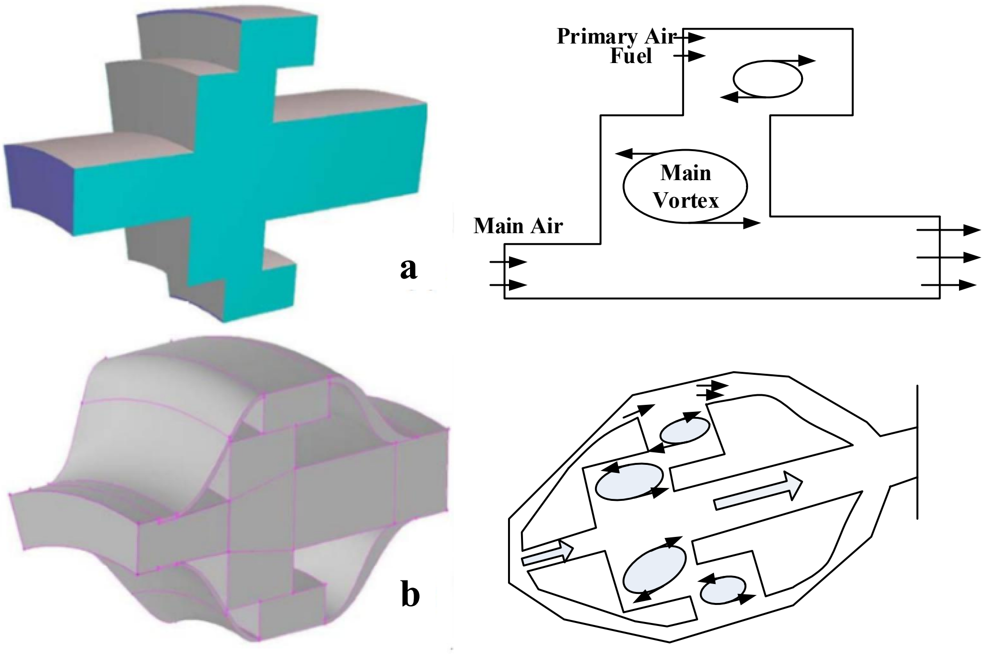


Fig. 21 Sketches of TVC geometry with and without diffuser and their injection strategy [47]

A novel double cavity TVC geometry has been numerically investigated. Critical issues highlighted in this work are the vortex stability and the combination of these two kinds of geometry as shown in Fig.21. The emissions and pressure drop are well predicted, but the Outlet Temperature Distribution Factor (OTDF) parameter is still too high. The outflow temperature is found non-uniform, hence the characteristics of flameless are not identified clearly. Therefore, geometry modification was proposed for further improvement.

From 2010 to 2012, Di Nardo et al. developed a burner prototype which promotes flows in cavities to stabilize the flame [48, 49]. The right combination of the cavity design and the fluid dynamics inside the cavity enhances the formation of stable vortex, so that it promotes the heat and mass transfer processes with the incoming flow and hence establishes the appropriate conditions for flameless combustion.

TVC is chosen for the annular combustion chamber, which is made up of a single cavity with air introduced tangentially (Fig. 22). The tangential air flow creates a vortex that fills the entire chamber to realize a flameless combustion relying only on internal mixing of reagents and exhaust gases. Use of the high speed jets helps to recycle more products, while the depression recalls a larger quantity of products and accelerates the vortex. It is found that even for fast rotating vortices, mixing is not fast enough to prevent the production of NOx in large amount.

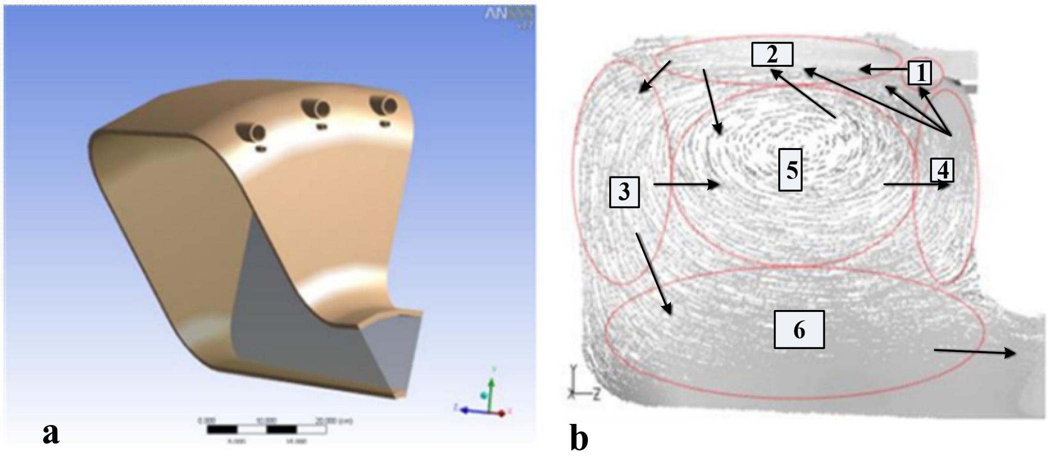


Fig. 22 The 60° sector of the proposed prototype and the flow field in the cavity [48].

After the first unsatisfactory attempt, Di Nardo et al developed the new prototype as shown in Fig. 23 [49]. The new design was simplified with a linearized sector of the annular chamber (square section of 190 × 190mm). The vortex in such a combustion chamber is created by two flows, while other streams of air and syngas fuel are distributed among the tangential flows, feeding the "vortex heart". The air stream, which is introduced in the middle, provides primary oxidant to the combustion reaction, while the tangential flows provide the excess air~~,~~ ~~which~~ to cool the walls and the combustion products.

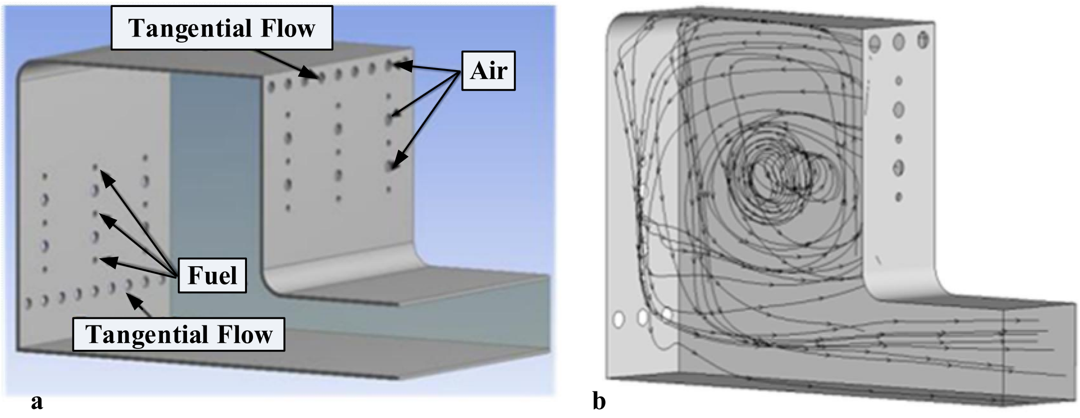


Fig. 23 Burner geometry and path lines from LES simulation [49].

The optimization principle of the prototype geometry is to balance different flows to establish the vortex that can fill the entire combustion chamber. The large exhaust recirculation and the good mixing is able to assure satisfying the fundamental prerequisites for a flameless combustion regime. A sensitivity analysis allowed determining the optimal operating conditions for which the contemporary reduction of the major pollutants species was achieved.

Germany and USA

In 2007, the cooperation on the combustion noise characteristics of a Flameless Trapped-Vortex Reheat Burner (FTVRB) between University of Technology Berlin and University of Cincinnati [15, 50] were published. In Fig. 24 schematics of the FTVRB combustor test rig (left) and the combustor cavity (right) are depicted. In FTVRB burner, a small part of the main flow is deflected into the cavity to establish the cavity circumferential vortex. The vortex is strengthened by axial injection of the secondary cavity air through six circumferential holes (see Fig. 24 right). Additionally, the combination of the axial and tangential air injection with the cavity vortices forms a spiral vortex. The spiral vortex enhances mixing and provides an important controlling factor for the cavity combustion process. The cavity is fuelled in the middle of the cavity depth. The stabilizing effect of the cavity pilot flame may also amplify the burner's combustion noise. Strong axial air jets stabilized the flame deep within the cavity, intensified the combustion process by enhancing the recirculation of hot combustion products, and thus caused a reduction in CO emissions. For strong tangential air injection, the pilot flame was located in the interaction zone of main and cavity flow, reducing the cavity temperature and the NOx emission.

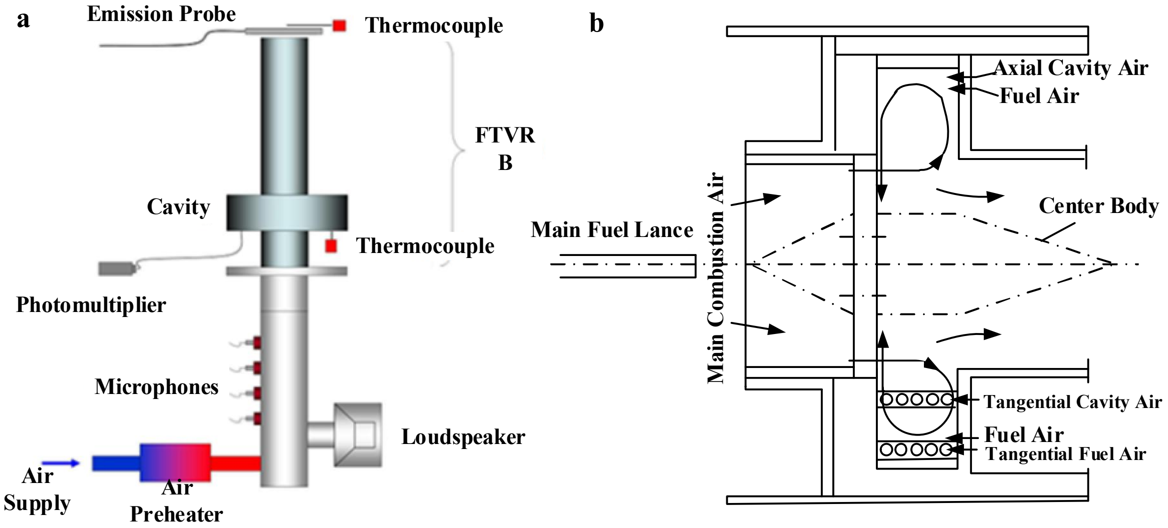


Fig. 24 FTVRB set-up [15, 50]

The researcher [50] obtained much information through the tests with pressure sensors, PIV, thermocouples and flame photos. The results showed that flameless combustion in the cavity could not be ensured over its entire working range. The combination of the local heat release at the flame front and the mixing dynamics, which also includes coherent structures in the cavity, leaded to local oscillation of the heat release. The cavity air injection pattern and the cavity equivalence ratio were identified as major parameters for controlling and optimizing the FTVRB performance with respect to pollutants and combustion noise. A relation between the noise and heat releases was presented, however, there was still need for digging the mechanism of coupling of heat release and acoustic characteristics in flameless combustion.

Some key issues that can be concluded from the analyses presented above are that the air injection velocity (high turbulence intensity), the entrainment and mixing with high temperature exhaust gas are considered to be the most important factors. While some Chinese researchers think that the air preheating is not the essential condition to attain flameless model [10, 25, 26]. The summary of some important information from the two groups of researchers are shown in Table 1. From ~~the~~ Table 1, it can be concluded that further progress is needed in the flameless combustion technology area. Several of possible aspects of further progress are as following:

- Majority of the reported work on flameless combustion is based on CFD simulation. However, such CFD models need experimental validation. Furthermore, there are still challenges in terms of simulating droplets evaporation, distribution and coupling detailed reaction mechanism for flameless combustion in commercial CFD codes. In-house codes and specialized UDF should be encouraged.
- The experimental techniques for measuring the species concentration and the temperature in the combustors are needed. All the information in the combustion field is very critical for diagnostic and understanding the mechanism of switching in the flame model and validating the simulation results.
- The effects of atomization and evaporation of the droplets on the combustion performance are neglected. Droplets' atomization and evaporation are the most noticeable characteristics of the liquid fuels, and it is also the key factor for realizing the flameless combustion model.
- In most of the experiments, the velocity of the air in the flameless combustors is too slow, even considering the small size of the combustors. The similarity theory should be used to draw the conclusive working parameters to make the experimental results more beneficial to understand the mechanism of the flameless combustion.

With these viewpoints, in the following section, future research directions are suggested for improving the understanding of flameless combustion for the gas turbine engines with liquid fuels.

Table 1 Summary of the flameless combustion for gas turbines

Fuel Type	**Combustion Type**	**Working Conditions**	**Atomization**	**Research Methods**	**Additional Remark**	**Year/ Reference**
Butane and propane	Partial premix	O_2 mass fraction 6.7 -7.3% Oxidant pressure 200 kPa Oxidant temperature>1300 K Oxidant mass rate70-102 g/s (Φ 160 mm) air excess factor 0.95-1.5	No need	House CFD code ($k-\varepsilon$ model, laminar flame let joint PDF), Experiments	Validated and supplied CFD code from the Mechanical Engineering Department at Imperial College London	2006 /Ref. 41
Propane	Premix	Air temperature 523-823 K Air mass flowrate10-35 g/s (Φ 100 mm) Equivalence ratio 0.3-0.55	No need	Experiments with PIV, ICCD for flame images, emissions measurement	The transition to flameless mode from regular combustion was gradual and cannot be well defined	2006 /Ref. 12
Liquid kerosene and Methane	Non premixed	Velocity of fuel 20 m/s Velocity of inlet air 40-100 m/s Inlet air pressure 30 atm Equivalence ratio 0.5-0.69	No mention	Fluent (RANS and LES, EDM and EBU)	The outflow temperature is not uniform, therefore, the characteristics of flameless are not obvious	2006 /Ref. 47
Gaseous fuel	Partial premix	Tangential airflow rate 0-12 g/s Axial airflow rate 0-12 g/s Main airflow rate 47.2 g/s Air temperature 298 K Equivalence ratio0.59-0.78	No need	Experiments with PIV, pressure spectra, flame images, and emissions measurement	The cavity air injection pattern and the cavity equivalence ratio were identified as the major parameters for flameless combustion controlling	2007 /Ref. 50
Methane	Non premixed	Air temperature 425 K Airflow rate 0.01-0.025 m^3/s Fuel flow rate 0.2-0.43 g/s Equivalence ratio 0.24-0.28	No need	Chemkin (Chemical Reactor Modeling). Experiments with LDV, gas temperature, and emissions measurement	The flameless combustor is experimented and exhibits stable operation over a relatively wide range of operating conditions	2007, 2011 /Ref. 38-40

Fuel Type	**Combustion Type**	**Working Conditions**	**Atomization**	**Research Methods**	**Additional Remark**	**Year/ Reference**
Biomass gas	Partial premix	O_2 mass fraction 0.17-0.23 Oxidant pressure 270 kPa Oxidant temperature 723 K Oxidant rate 90 g/s (Φ 110 mm) Equivalence ratio 0-1	No need	Chemkin and Experiments (without further information)	A 3 staged combustor for micro-gas turbine	2007 /Ref. 20
Liquid bio-diesel	Non premixed	Reference from Rover IS/60 gas turbine	No mention	Experiments with outlet gas analyzer	Flame spectra to measure soot volume fraction in combustion zone	2008 /Ref. 23
Natural gas and H_2	Non premixed	Inlet air pressure 20 bar Inlet air temperature 600-735K Inlet air velocity 40-160 m/s	No need	Experiment with PLIF, temperature, pressure and emissions measurement	A successful operation of the FLOX® combustor with low emissions could be the first time at high pressure	2008, 2011 /Ref. 35, 36
Liquid hydrocarbons	Non premixed	Oxidant temperature >600 K Oxidant flow rate 355 g/s Equivalence ratio 0.25-0.75	Pressure atomizer with 0.8 Flow Number	Experiment with SPIV, PLIF, temperature, and noise and emissions measurement	All fuels with the exception of n-butane showed very similar combustion characteristics	2009 /Ref. 17
Methane	Non premixed	Inlet air pressure 2.5 atm Inlet air temperature 530 K Inlet air velocity 25-35 m/s Equivalence ratio 0.46	No need	Experiments with PIV, pressure spectra, flame images, and emissions measurement	In flameless model, the emissions are extreme low and without the thermoacoustic problems	2010 /Ref. 43
Syngasfuel	Premixed	Inlet air pressure 20 bar Inlet air temperature 700K Inlet air velocity 62-75 m/s Equivalence ratio 0.2-1.4	No need	Chemkin and Fluent (Realize k-ε, LES and P1, EDC)	The preliminary optimization of geometry causes different flows in perfect balance and a vortex filling the entire volume	2010, 2012 /Ref.48, 49

Fuel Type	**Combustor Type**	**Working Conditions**	**Atomization**	**Research Methods**	**Additional Remark**	**Year/Reference**
Liquid bio-fuels	Lean premixed	O_2 mass fraction 0.17-0.23 Oxidant temperature 905 K Oxidant flow rate 0.808 kg/s Fuel mass flow rate 0.0065 kg/s	No mention	Fluent (Realize k-ε and EDC)	Building the relation between the emissions and recirculation ratio	2011 /Ref. 22
Liquid diesel	Non premixed	O_2 mass fraction 0.23 Oxidant temperature 323 K Oxidant flow rate 0.5 m^3/h Equivalence ratio 0.25-0.5	The SMD is between 30-60 μm	Fluent (Realize k-ε). Experiments with outlet gas analyzer, thermocouples	There is a critical injection momentum from the air blast atomizer for the combustion mode is converting	2012 /Ref.25, 26
Liquid Kerosene	Non premixed	Reference Velocity 12-22 m/s Oxidant temperature >560 K Equivalence ratio 0.2-0.36	No mention	Chemkin and Fluent (Realize k-ε& DO & PDF).	Trapped-vortex is used as the gas generator and flame stabilizer	2012, 2014 /Ref. 31, 32
Liquid Kerosene	Non premixed	Reactants dilution ratio >2.71 Fuel mass flow rate 28.67 g/s at 9 bar injection pressure Equivalence ratio 0.6-1	A pressure swirl fuel injector provides SMD 17-23 μm	Fluent (RSM and P1 and PDF). Experiments with outlet gas analyzer, thermocouples	The outstanding performance of the burner with very low chemical and acoustic emissions at high heat release rates	2013, 2014 /Ref. 28-30
Methane	Partial premix	The initial temperature 1000 K The initial pressure 1 bar Reference Velocity 12 m/s Combustor diameter 10 mm Equivalence ratio 0.57-0.8	No need	Experiments with PIV, OH* chemiluminescence images, pressure pulsating, emissions measurement	Both frequency and amplitude of the pulsation are specific for each equivalence ratios, which have a strong impact on NOx emissions	2014 /Ref. 37

5. Future Research Directions

5.1 Flow Dynamics

Prediction of flow patterns in a combustor is one of the most challenging tasks. Variations in the gas flow, thermodynamic and chemical state can significantly impact the flow and heat transfer properties in the primary combustion zone and to the interacting scales of various phenomena, including droplets deformation, atomization and evaporation. Understanding the fluid dynamics and the associated chemical and thermodynamic state of the species in the flow helps to find the details and evaluate the performance of the combustors.

From the former gas flameless combustion research, a series of characteristics on the mechanisms have been drawn. Appropriate momentum of the injection and the entrainment of the gases have significant effects on the gas recirculation rate, strengthen the swirling air injection into the combustion chamber, and thus enhance the distributed combustion reactions and the flow field in the chamber. The flow field in the combustion chamber plays a decisive role in the flameless formation. A great advantage of the recirculation structure is to entrain and circulate the high temperature exhaust gas in a small combustion chamber with the high speed air jet. This entrainment and circulation increase the residence time of reactants and products, and thus complete a series of coupled processes which reflect the concept of flameless combustion, including endothermic evaporation/heat release, mixing and slow reaction.

The key parameter in the interaction between the combustion and the turbulence is Damköhler number, which is described by two characteristic~~s~~ time scales and can determine the flameless phenomena. Hence, existing turbulence and combustion models for flameless combustion need to be considered in a combined manner in numerical studies ~~in order~~ to determine the value of Damköhler number.

5.2 Multiphase System and Atomization

Droplet evaporation involving heat and mass transfer processes in a turbulent environment is of great importance for engineering applications, such as atomization, evaporation and combustion performance of the flameless combustors. From a practical point of view, deformation and vaporization of droplets are very important in understanding spray flows that are used commonly in liquid-fuelled combustion systems. The knowledge gained from these relatively ‘simple’ phenomena may be used to advance the understanding of the complex mechanisms of the two-phase spray combustion phenomenon encountered in liquid-fuelled flameless combustion systems. There are considerable experimental, theoretical and numerical data in the open literatures on the vaporization and burning of single droplets that are subjected to isolated and/or coupled conditions such as, gas ambient pressure, gas ambient temperature, liquid properties, and droplet spacing.

To the authors' knowledge, additional experiments under ambient turbulent hot environment, as well as over a wider range of turbulent integral length scale and Reynolds number are needed for assessing the effect of turbulence on droplets deformation and evaporation in forced convective turbulent flows. In all published studies, the suspended droplet technique has been utilized only at ambient room temperature and atmospheric pressure conditions, which is not satisfactory for the development of new correlations for the deformation and evaporation of the droplets. Meanwhile, the new numerical methods such as Lattice Boltzmann Methods and Moving Particle Semi-implicit Method for simulation work should be improved to meet the high resolution requirement in the interface between the gas and the liquid droplets.

5.3 Chemical Reaction Mechanisms

Developing chemical-kinetic models that describe combustion of kerosene are of practical importance for developing realistic models for simulation of flameless combustion. Due to the complex nature of kerosene combustion and the difficulty to reveal such reaction mechanism through experimental investigation, recent research is focusing on the surrogate fuels, such as KERO (C10H20), which have similar physical and chemical properties as the commercial kerosene. Its reference-state thermodynamic properties are obtained by a linear combination of the properties of $C_{10}H_{22}$, C_9H_{12} and C_9H_{18} species which are described by NASA polynomial parameterization. The general form of the molar specific heat at constant pressure in J/(kmol·K) is written with five coefficients, and also used by CHEMKIN, COSILAB and CANTERA software, which would be helpful to perform the simulation work.

5.4 Laser Diagnosis Technology

There have been many laser diagnosis techniques for measuring the flow field and species concentration in the combustors, such as Mie Scattering (MS), Rayleigh Scattering (RS), Spontaneous Vibrational Raman Scattering (VRS), Laser Induced Fluorescence (LIF), Molecular Tagging Velocimetry (MTV), etc. Combination of these methods is beneficial. For example, one might use RS and LIF to take simultaneous images of temperature profiles and NO densities, RS, VRS, and LIF to image a number of species and temperature simultaneously, or MTV and VRS to measure flow velocities, species and temperature simultaneously. Such combined methods are easy to realize because each method uses the same hardware arrangement. The changes required to alter a method are often simply those of the excitation wavelength of the laser and of a filter that alters the selected range of emission wavelengths. Such combined methods can give extensive information about the progress of flameless combustion phenomena.

5.5 Design Methods

Current modem gas turbine combustor configurations do not exhibit sufficient flow performance to attain the desired global performance for the whole engine. High resolution design and optimization methodologies can be employed to accelerate the closure of gas turbine combustor design and to increase/enhance the capture of complex flow field and species concentration effects on new flameless combustion concepts. The following technical challenges need to be addressed:

- Numerical algorithms are needed to efficiently resolve computational fluid dynamics for the flow field and the species concentration in the complex flow fields and thus to guide the design of new concept combustors.
- Rapid design methodologies will be needed to couple modelling of aerodynamics, thermodynamics, and chemical phenomenology in reactive gas flows of flameless combustor in the gas turbine operational environments.

Furthermore, it is also very important to establish a new design procedure for novel combustors, considering that the working conditions are different from the conventional gas turbine combustors. Referring to Refs. [38-40], Fig. 25 shows the design map for a typical flameless combustor with relevant research tools and reference pictures.

Briefly, there are four stages in the flameless combustor design procedure: I -Thermodynamic Analysis Stage, II - Concept Design Stage, III - Preliminary Design Stage, and IV - Application Stage. In Thermodynamic Analysis Stage, principal schemes of the internal flow inside of the flameless combustor are considered by CHEMKIN for calculating chemical equilibrium temperature and specie concentrations. If the primary results indicate that the proposed cycle would reduce the formation of NOx and other parameters ~~will~~ meet the demand of the engines, the next stage would be proceeded. Stage II, the concept design stage, ~~which~~ is generated according to the results of stage I. It will be accomplished by commercial and in-house codes. Fine details of the flow field in the flameless combustors will be obtained through the turbulence, two phase, radiation and flame models. Those models will provide sufficient information for optimizing the conceptual design after being validated via experiments. The velocity, diameters of the droplets, temperature, pressure and specie concentrations in the flameless combustor will be measured in the experiments. Then, the designers would take several optimization rounds to finish stage III, the preliminary stage. In the final stage, the flameless combustor will be installed in the real engine to replace the conventional combustor, and the whole engine will be tested to get a satisfactory performance.

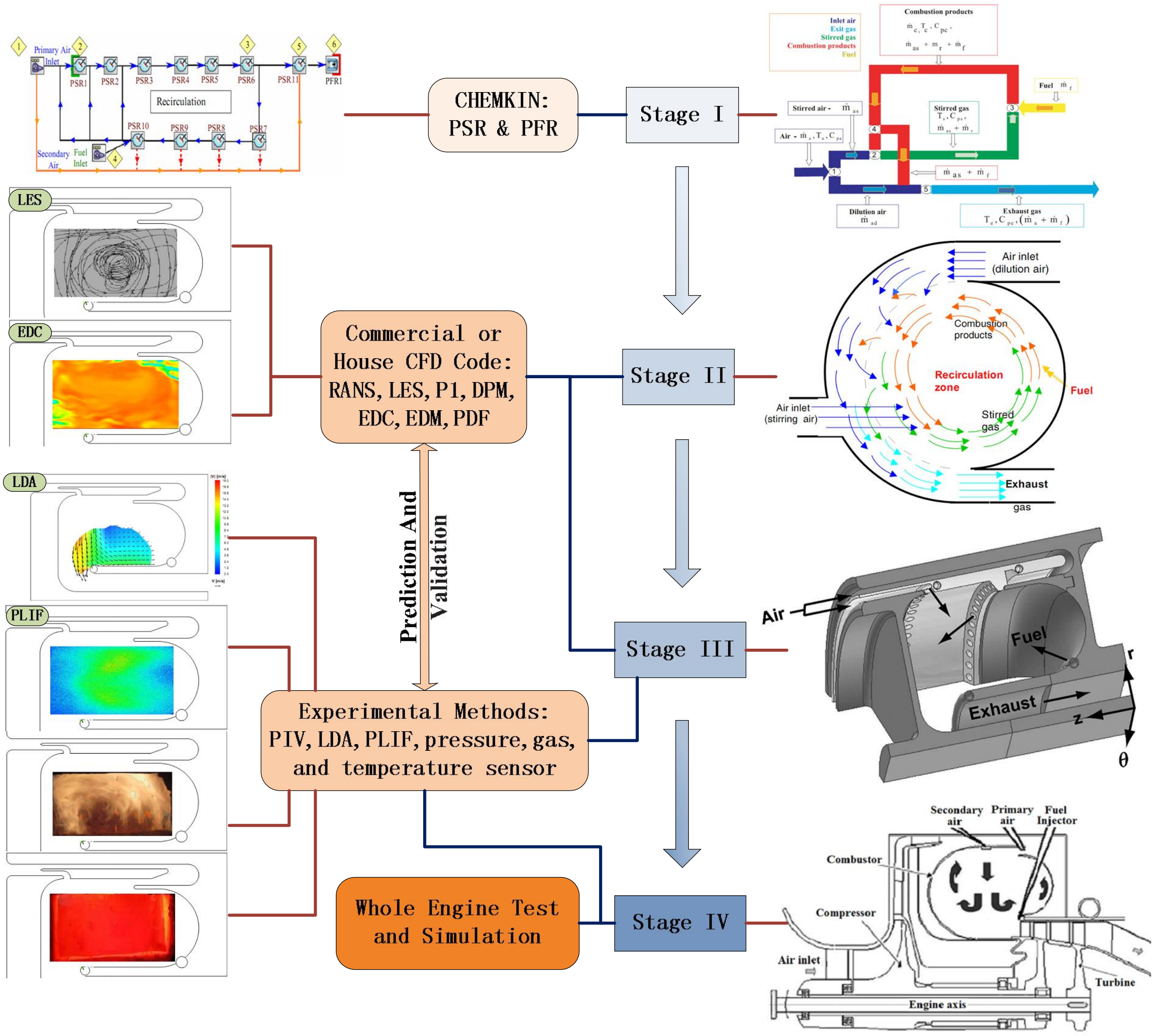


Fig. 25 Design map for the typical flameless combustor

6. Future Needs, Challenges and Perspectives

In this section, useful information is summarized to help to highlight the future needs, challenges, and perspectives for gas turbine applications of flameless combustion with liquid fuel.

For ground-based gas turbines, Wang et al. [51] investigated the techno-economic feasibility of applying the technology of flameless combustion to a simple gas turbine cycle, compared to that of conventional combustion technology. For flameless combustion, the main characteristic is to recirculate internal flue gas into the combustion zone for the dilution of combustion. Due to the high recirculation ratios, the maximum reaction temperature in flameless oxidation operation is much lower than in conventional combustion, thus reducing NOx formation considerably. This reduces the net power production by 5.38 % to 413 MW and lowers the heating valve efficiency from 33.5% to 32.7%. The main environmental change is the 92.3% reduction in NOx emissions from 112 to 8.6 mg/m^3 (5% O_2).

For aero gas turbines, the introduction of flameless combustion technology in gas turbines will be of great interest because it has been demonstrated as a stable form of combustion yielding simultaneously low concentrations of CO and NOx, intrinsic thermo acoustic stability and uniform temperature distribution within the limits of a gas turbine engine. Of course, there are still some restrictions of flameless combustion, such as the high inlet temperature, which in a gas turbine engine would be the compressor discharge temperature. However, there will be some other ways to use the flameless technology, such as ITB (inner-turbine burner) [52]. ITB is a new technology and developed especially for civil aero gas turbine combustors without an afterburner. Its target is to increase the thrust-to-weight ratio and to widen the range of engine operation. Combustion would extend from main combustors into the turbine passage, which is troublesome at first sight, because it can lead to an increase in heat transfer challenges. However, a significant benefit can result from augmented burning in the turbine. In Refs. [52, 53], the thermodynamic cycle analysis was performed to demonstrate the performance of aero-engines with and without the inter-stage turbine burners. Results showed that the inner-turbine burner produces extra thrust, but at the cost of increased fuel consumption for current compressor ratio values. A 10%–20% increase in efficiency can be achieved. At the higher compressor ratio values and high flight Ma number projected for the future, the turbine burner is superior in both thrust and fuel consumption.

The first and only published paper that mentioned the combination of ITB and flameless combustion is reported by Ochrymiuk and Badur in 2001 [54]. Flameless combustion is applied into the second SEV (Sequential En Vironmental) burner, which may be a perfect place for flameless combustion (see Fig. 26). Figure 26 shows several stages in the working process of GT 26.

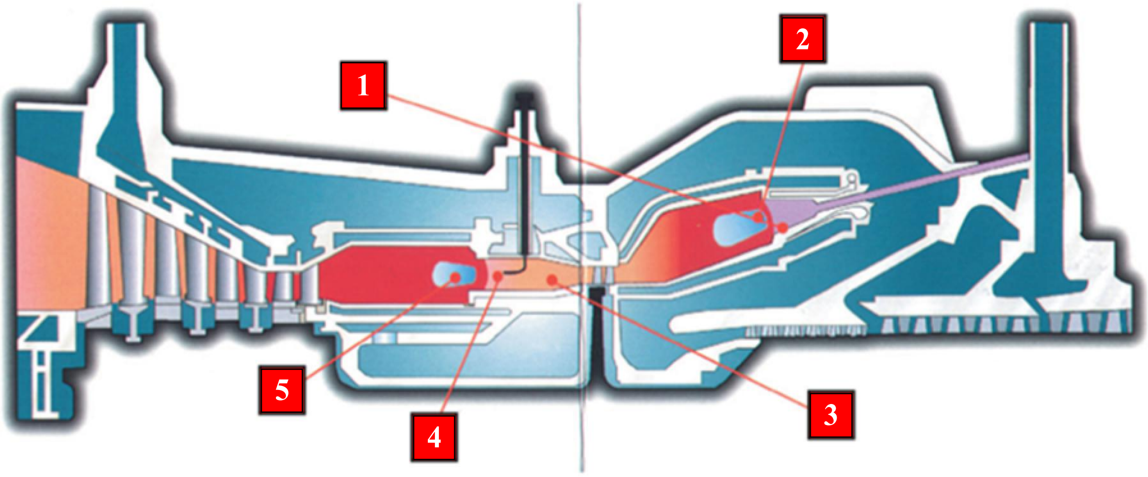


Fig. 26 GT26 gas turbine and key working stages [54]

Stage 1: The compressed air is fed into the first EV burner, creating a homogeneous, lean fuel/air mixture and the flow in the burner forming a recirculation zone.
Stage 2: The mixture ignites into a single, low temperature flame ring. The recirculation zone stabilizes the flame within the chamber, avoiding contact with the combustor wall.
Stage 3: The hot exhaust gas exits in this first EV chamber, moving through the high pressure turbine stage before entering the second SEV combustor.
Stage 4: Vortex generators in the SEV combustor enhance the SEV mixing process, while carrier air, injected with the fuel at the fuel lance, delays spontaneous ignition.
Stage 5: Ignition occurs when the fuel reaches self-ignition temperature in the free space of the SEV combustion chamber. The hot gas then continues its path into the low pressure turbine.

In stage 1, there is no demand on the inlet temperature from compressor since flameless combustion is not need. Stage 3 and 4 will provide the hot gas and enough recirculation gas (depending on the temperature raise and the stoichiometric ratio in the EV burner), which are the requirements for the realization of flameless combustion. So, in stage 5, when the self-ignition temperature of fuel is reached, flameless combustion will occur.

After summarizing the literature information and pointing out the future needs, some challenges and perspectives of flameless combustion are clear and encouraging. They are described as follows:

- *Mechanism of Flameless Combustion:* Flameless combustion is a new combustion regime, i.e. a super diluted explosion or a continuous auto-ignition/explosion. Therefore, the reaction mechanisms need to be addressed and established.
- *Modelling Combustion Model Transients:* Ability is essential to accurately estimate the combustion process transients from the conventional model to the flameless model. The modelling would use various geometric structures, fuels, initial air temperatures and exhaust gas recirculation ratios etc. to constrict or control the airflow and fuel supply in response to the requirements.
- *Mathematical Modelling for Flameless Combustion:* Although EDC (Eddy Dissipation Concept) and LES (Large Eddy Simulation) methods have been used for relatively satisfactory prediction, the detailed chemical kinetics schemas lack sufficient mathematical modelling. The precision of predictions need to be improved of the flameless region because of relative low O_2 concentration and of the NO emissions in complex configuration.
- *Atomization and Vaporization of Droplets:* Atomization and evaporation of liquid fuels in a flameless combustor are uniformly distributed throughout the combustor volume. New type of premixed and pre-heated fuel lance is needed to make liquid fuels more similar to gaseous ones. It produces partially premixed flame and hence may be easier for realizing the flameless combustion than diffusion flame.
- *Advanced Measurement Methods:* Use of advanced laser measurement methods to obtain more quantitative and qualitative information about the species concentration

and velocity field in the primary flameless combustion zones could provide a better understanding about the mechanism.

- *Flameless Burner Design Methods:* Though the mechanism of flameless combustion is not clear yet, and no standard design tools or methods exist for this type of phenomena, this behaviour has been relatively well understood through the last decade. There are still some rules and information about how to realize flameless combustion in special gas turbine conditions, which calls for new design methods.
- *Special Issues about ITB:* The novel ITB with flameless combustion yields several challenges: shortening the residence time at a low pressure lost with adequate vaporization of liquid fuel, mixing, and combustion; enhancing the flow dynamic stability of a stratified flow with a large turning acceleration; meeting the increased demands for cooling and aerodynamic-force loading on rotor and stator blades.

7. Conclusion Remarks

In spite of decades of research works devoted to flameless combustion, there are still many challenges to analyzing flameless phenomena and designing combustors. Therefore, many “unknowns” are in the field of flameless combustion that even our best experimental or numerical analysis cannot adequately predict. Current experimental approaches are not able to capture adequately the pressure, temperature, mass flow rate and high-enthalpy states in gas turbines leaving us to approximate and extrapolate our test data. Uncertainty in the ability to model chemical reactions in computational simulations, as well as adequately predict flow features, all these leave additional work to be done before CFD predictions will be fully trustworthy.

Still, many speculative considerations have been presented as follows in order to make the whole framework more consistent and rich with potential for practical gas turbine applications.

- Preliminary understanding about the mechanism of flameless is that O_2 concentration in the combustion air decreases quickly, leading to an increase of the characteristic reaction time that becomes comparable with the characteristic mixing time, which, on the contrary, is lowered by the high turbulence generated by the high-velocity reactants jets. Therefore, the reaction zone is uniformly distributed throughout the combustor volume with lower peak flame temperature than that of conventional mode.
- The key technique for gas turbine to realize flameless combustion is to organize the flow field in the combustor to form the high temperature gas recirculation and dilution of fresh reactants. There are three ways: the first outer recirculation, the gas flows outside the gaseous fuel jet, like FLOX Combustor; the second internal recirculation, the gas flows inside the fuel jet, like EU burner from Cincinnati; the third, cyclic periodical gas flows and mixes with fuels in the centre of the flow circle, like flameless combustion based on the trapped vortex.

- The way the fuel and air are injected into the furnace chamber is of primary importance for the distributions of furnace temperature, oxygen, and fuel that thus affects NOx emission and combustion efficiency. A group of parameters including fuel property, droplet distribution, evaporation, mixture formation and subsequent combustion with preheating and dilution of reactants need to be discussed and developed.
- The difficulty in designing a flameless prototype arises from the fact that there are no standard design tools. In spite of the innovative concept, its design and implementation involves the traditional issues of a gas turbine burner such as how to design a component with a suitable geometry taking into account the operating conditions, how to ensure the absence of thermo acoustic oscillations and the stability of the burner.
- It is not necessary to diffuse the compressed air to very low inlet velocities because high air inlet velocities can be used to enhance the recirculation ratio. Thermal radiation would form a substantial part of the total heat transfer between the recirculation gases and the secondary cooling air due to the distributed flame and uniform temperature. Alternative heat transfer techniques can be used to enhance the heat transfer between the cooling air and the combustor wall.
- Trapped vortex combustor is able for its intrinsic nature of improving mixing of hot combustion gases and fresh mixture that represents a prerequisite for a diluted combustion and at the most a flameless combustion regime. The trapped vortex technology offers several advantages as a gas turbines burner: burning low calorific value fuels, extremely low NOx emissions, and extension of the flammability limits.

A typical flameless combustor appears to have potential to substitute the conventional gas turbine combustor, avoiding the need for the very high adiabatic flame temperature values with their associated high-NO formation. Therefore, flameless combustion poses itself undoubtedly as a technology combining high efficiencies, and low pollutant emissions. All these aspects make flameless combustion worthy of further investigations and attention.

Acknowledgment

This review paper is written during the time when the author Fei XING has visited School of Engineering, Cranfield University, UK. The financial support from Cranfield University is kindly acknowledged. In addition, Fei XING would also like to thank Professor Sai Gu and his research team for their inspirational discussions on the presented topic and other research topics throughout the visiting period.

The authors are also grateful to National Natural Science Foundation of China (Grant No. 51406171), Natural Science Foundation of Fujian Province (Grant No. 2015J05111), and Fundamental Research Funds for the Central Universities of China (Grant No. 20720150180) for providing the funding support for the research.

References

[1] Chefurka P. World Energy and Population Trends to 2100. website: http://www.paulchefurka.ca/WEAP/WEAP.html.

[2] Gupta A K. Flame Characteristics and Challenges with High Temperature Air Combustion. Proceedings of the International Joint Power Generation Conference. Miami Beach Florida; 2000.

[3] Bee´r, J M. Combustion Technology Development in Power Generation in Response to Environmental Challenges. Progress in Energy and Combustion Science 2000; 26:301-327.

[4] Lieuwen, C T Yang V. Gas Turbine Emissions. Cambridge University Press; 2013.

[5] Schweitzer, Jerffrey K. Propulsion Technology Readiness for Next Generation Transport Systems. AIAA/ICAS International Air and Space Symposium and Exposition: The Next 100 Years. AIAA 2003; 2787.

[6] Weinberg F J. Combustion Temperature：The Future. Nature 1971; 233:239-241.

[7] Wünning J A, Wünning J G. Flameless oxidation to reduce thermal no-formation. Progress in Energy and Combustion Science 1997; 23(1):81-93.

[8] Cavaliere A, Joannon M. Mild Combustion. Progress in Energy and Combustion Science 2004; 30(4):329-366.

[9] Gupta A K. Developments in High Temperature Air Combustion (Flameless Oxidation) and Fuel Reforming.44th AIAA Aerospace Sciences Meeting and Exhibit. Reno, Nevada. AIAA 2006; 1498.

[10] Li P, Mi J, Dally B B, Wang F, Wang L, Liu Z, Chen S, Zheng C. Progress and recent trend in MILD combustion. Science China Technological Sciences 2011; 54(2):255-269.

[11] Noor M M, Wandel AP and Yusaf T. MILD Combustion: The Future for Lean and Clean Combustion Technology. International Review of Mechanical Engineering 2014; 8(1):251-257.

[12] Li G, Gutmark E J, Stankovic D, Overman N, Cornwell M, Fuchs L, Vladimir M. Experimental Study of Flameless Combustion in Gas Turbine Combustors. 44th AIAA Aerospace Sciences Meeting and Exhibit. AIAA 2006; 546. Reno, Nevada.

[13] Overman N, Cornwell M, Gutmark E J. Application of Flameless Combustion in Gas TurbineEngines. 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. AIAA 2006-4920. Sacramento, California.

[14] Overman N R. Flameless Combustion and Application for Gas Turbine Engines in the Aerospace Industry. Aerospace Engineering, University of Cincinnati. Master thesis; 2009.

[15] Gutmark E J, Paschereit C O, Guyot D, Lacarelle A, Moeck J, Schimek S, Faustmann T, Bothien M. Combustion Noise in a Flameless Trapped-Vortex Reheat Burner (FTVRB).13th AIAA/CEAS Aeroacoustics Conference. AIAA 2007-3697.

[16] Guillou E. Flame Characteristics and Application of flameless combustion. Aerospace Engineering, University of Cincinnati. Master thesis; 2009.

[17] Guillou E, Cornwell M, Gutmark E. Application of “Flameless” Combustion for Gas Turbine Engines. 47th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition. AIAA 2009; 225. Orlando, Florida.

[18] Abuelnuor A A A, Wahid M A, Mohammed MA, Saat A. Flameless combustion role in the mitigation of NOX emission: a review. International Journal of Energy Research 2004; 38(7):827-846.

[19] Tsuji H, Gupta A, Hasegawa T, Katsuki M, Kishimoto K, Morita M. High Temperature Air Combustion: From Energy Conservation to Pollution Reduction. Florida: CRC Press; 2003.

[20] Hiramatsu M, Nakashima Y, Adachi S, Yamasaki Y, Kaneko S. Combustion characteristics of small size gas turbine combustor fueled by biomass gas employing flameless combustion. Proceedings of GT2007, ASME Turbo Expo 2007; 463-469.

[21] Cameretti M C, Piazzesi R, Reale F, Tuccillo R. CFD ANALYSIS OF THE FLAMELESS COMBUSTION IN A MICRO-GAS TURBINE. Proceedings of ASME Turbo Expo 2009; 215-23.

[22] Cameretti M C, Tuccillo R, Reale F, Piazzesi R. LIQUID BIO-FUELS IN AN EGR EQUIPPED MICRO GAS TURBINE. Proceedings of ASME Turbo Expo 2011; 909-918.

[23] Ellis W, Lear W, Singh B, Srinivasan A, Crittenden J, Sherif S A. Flameless Combustion of Biofuels in a Semi-Closed Cycle Gas Turbine. 46th AIAA Aerospace Sciences Meeting and Exhibit. AIAA 2008; 1140.

Reno, Nevada.

[24] Torresi M, Camporeale S M, B Fortunato, S Ranaldo, M Mincuzzi, A Saponaro. Diluted combustion in a aerodynamically staged swirled burner fueled by diesel oil. Processes and Technologies for a Sustainable Energy 2010. Ischia.

[25] Cui Y J, Lin Q Z. Realization of Flameless Combustion of Liquid Fuel. Advanced Materials Research 2012; 512-515: 2088-2092.

[26] Cui Y, Ye T, Lin Q. Effect of fuel air equivalence ratio on the flameless combustion of liquid hydrocarbon. Jounal of University of Science and Technology of China 2012; 42(4): 325-334.

[27] Derudi M, R Rota. Experimental study of the mild combustion of liquid hydrocarbons. Proceedings of the Combustion Institute 2011; 33(2): 3325-3332.

[28] Reddy V M, Kumar S. Development of high intensity low emission combustor for achieving flameless combustion of liquid fuels. Propulsion and Power Research 2013; 2(2): 139-147.

[29] Reddy V M, Sawant D, Trivedi D, Kumar S. Studies on a liquid fuel based two stage flameless combustor. Proceedings of the Combustion Institute 2013; 34(2): 3319-3326.

[30] Reddy V M, Katoch A, Roberts WL, Kumar S. Experimental and numerical analysis for high intensity swirl based ultra-low emission flameless combustor operating with liquid fuels. Proceedings of the Combustion Institute 2014.(in press)

[31] Zang P, Zhang K, Cui Y, Nie C. Numerical Simulation of Flameless Combustor Based on Trapped-Vortex. Journal of Engineering Thermophysics 2012; 33(9): 1615-1618. (in Chinese)

[32] Wang K, Zang P, Xing S, Fang A, Cui Y, Nie C. Experimental Study of Flameless Combustor based On Trapped-Vortex. Gas Turbine Technology 2014; 27(3):14-19. (in Chinese)

[33] Wang L, Qi D, Sui X, Xie X. Analysis of Re Influence on MILD Combustion of Gas Turbine. Energy and Power Engineering 2013; 05(04): 92-96.

[34] Flamme M. New combustion systems for gas turbines (NGT). Applied Thermal Engineering 2004; 24(11-12): 1551-1559.

[35] Lückerath R, W Meier, Aigner M. FLOX® Combustion at High Pressure with Different Fuel Compositions. Journal of Engineering for Gas Turbines and Power 2008; 130(1): 011505-1-7.

[36] Sadanandan R, R Lückerath, Meier W, Wahl C. Flame Characteristics and Emissions in Flameless Combustion under Gas Turbine Relevant Conditions. Journal of Propulsion and Power 2011; 27(5): 970-980.

[37] Varea E, Kruse S, Pitsch H, Albin T, Abel D. Actuation Studies for Active Control of Mild Combustion for Gas Turbine Application. Proceedings of ASME Turbo Expo 2014: Turbine Technical Conference and Exposition 2014.Düsseldorf, Germany.

[38] Levy Y, Sherbaum V. Arfi P. Basic thermodynamics of FLOXCOM, the low-NOx gas turbines adiabatic combustor. Applied Thermal Engineering 2004; 24(11-12): 1593-1605.

[39] Levy Y, RaoG A, Sherbaum V. Chemical Kinetic and Thermodynamics of Flameless Combustion Methodology for Gas Turbine Combustors.43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit 2007; AIAA 2007-5629**.**

[40] Melo M J, Sousa J M M, Costa M, Levy Y. Flow and Combustion Characteristics of a Low-NOx Combustor Model for Gas Turbines. Journal of Propulsion and Power 2011; 27(6): 1212-1217. all authors in ref.

[41] Awosope I O, N H Kandamby, Lockwood F C. Flameless oxidation modelling: on application to gas turbine combustors. Journal of the Energy Institute 2006; 79(2): 75-83.

[42] Wang Y D, Y Huang, McIlveen-Wright D, Mcmullan J, Hewitt N, Eames P, Rezvani S. A techno-economic analysis of the application of continuous staged-combustion and flameless oxidation to the combustor design in gas turbines. Fuel Processing Technology 2006; 87(8): 727-736.

[43] Cui Y, Lü X, Xu G, Nie C Q. Dynamic analysis of a flameless combustion model combustor. Science China Technological Sciences 2010; 53(8): 2291-2298.

[44] Lü X. Investigation of Flameless Combustion Technology for Hydrogen-rich Fuels in Micro Gas Turbine. Engineering Thermo Physie, Chinese Academy of Sciences 2010. PhD thesis. (in Chinese)

[45] Mao Y H, Xu G, Fang A, Hou L. Advances in the Study of Gas Turbine Flameless Combustion Technology. Journal of Engineering for Thermal Energy & Power 2011; 26(5): 7. (in Chinese)

[46] Xing F, Wang P, Zhang S, Zou J F, Zheng Y, Zhang R, Fang W. Experiment and simulation study on lean blow-out of trapped vortex combustor with various aspect ratios. Aerospace Science and Technology

2012; 18(1): 48-55.

[47] Losurdo M, C Bruno. Numerical Simulations of Trapped Vortex Combustors Feasibility study of TVC integration in traditional GT combustion chambers. 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit 2006. AIAA 2006-5140. Sacramento, California.

[48] Di Nardo A, Galletti C, Giammartini S and etc. Design and analysis of a gas turbine trapped vortex combustion. Processes and Technologies for a Sustainable Energy 2010; 1-6.

[49] Di Nardo A, Calchetti G, Mongiello C. Non-premixed syngas MILD combustion: the trapped-vortex approach. Proceedings of the Seventh International Symposium on Turbulence, Heat and Mass Transfer 2012. Palermo, Italy.

[50] Guyot D, Bothien M R, Moeck J P, Schimek S, Lacarelle A, Paschereit O, Faustmann T, Gutmark E. Pollutant and Noise Emissions in a Flameless Trapped-Vortex Reheat Burner (FTVRB). 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit 2007.AIAA 2007-5630.

[51] Wang Y D, Huang Y, Mcllveen-Wright D, Mcmullan J, Hewitt N, Eames P, Rezvani S. A techno-economic analysis of the application of continuous staged-combustion and flameless oxidation to the combustor design in gas turbines. Fuel Processing Technology 2006; 87(8): 727-736.

[52] Sirignano W A, Dunn-Rankin D, Liu F, Colcord B, Puranam S. Turbine Burners: Performance Improvement and Challenge of Flame holding. AIAA Journal 2012; 50(8): 1645-1669.

[53] Fang X Y, Xing F, Xu L L, Xing P, Wang P Y. Performance Analysis of Three Kinds of Aero-Engine with Inter-Stage Turbine Burner. Journal of Propulsion Technology 2013; 34(11): 1513-1519.

[54] Ochrymiuk T, Badur J. Flameless Oxidation at the Gt26 Gas Turbine Numerical Study via Full Chemistry. Task Quarterly 2001; 5(2): 239-246.