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Review of the New Combustion Technologies in Modern Gas Turbines

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<http://dx.doi.org/10.5772/54403>

1. Introduction

The combustion chamber is the most critical part of a gas turbine. The chamber had to be designed so that the combustion process to sustain itself in a continuous manner and the temperature of the products is sufficiently below the maximum working temperature in the turbine. In the conventional industrial gas turbine combustion systems, the combustion chamber can be divided into two areas: the primary zone and the secondary zone. The primary zone is where the majority of the fuel combustion takes place. The fuel must be mixed with the correct amount of air so that a stoichiometric mixture is present. In the secondary zone, unburned air is mixed with the combustion products to cool the mixture before it enters the turbine. In some design, there is an intermediate zone where help secondary zone to eliminate the dissociation products and burn-out soot.

The majority of the combustors are developed base on diffusion flames as they are very stable and fuel flexibility option. In a diffusion flame, there will be always stoichiometric regions regardless of overall stoichiometry. The main disadvantage of diffusion-type combustor is the emission as high temperature of the primary zone produced larger than 70 ppm NO_x in burning natural gas and more than 100 ppm for liquid fuel [1]. Several techniques have been tried in order to reduce the amount of NO_x produced in conventional combustors. In general, it is difficult to reduce NO_x emissions while maintaining a high combustion efficiency as there is a tradeoff between NO_x production and CO/UHC production.

In some recent installations, the premixed type of combustion has been selected to reduce NO_x emissions bellow 10 ppm. Apart from the flame type change, there are some method such as “wet diffusion combustion”, FGR¹ and SCR². In an example of wet combustion, a nuzzle through which steam is injected is provided in the vicinity of the fuel injector. The level of NO_x emission is controlled by the amount of steam. However, there is a limit on the increas-

ing the steam flow rate as cause corresponding considerable CO emission. Furthermore, preparing pure steam in the required injection condition increases operational costs. Nowadays, wet combustion rarely applies due to water consumption and the penalty of reduced efficiency. Post Combustion treatments such as SCR are those which convert NO_x compounds to nitrogen or absorb them from flue gas. These methods are relatively inexpensive to install but does not achieve NO_x removal levels better than modern gas turbine combustor.

In this chapter, a short introduction of combustion process and then a description of some new pioneer combustor have been presented. As gas turbine manufacturers are looking for continuous operation or stable combustion, satisfactory emission level, minimum pressure loss and durability or life. Hence, the advanced combustor might include all of these criteria, so some of them are selected to discuss in details.

2. The combustion process

2.1. Type of combustion chamber

The diffusion and premixed flame are two main type of combustion, which are using in gas turbines. Apart from type of flame, there are two kind of combustor design, annular and tubular. The annular type mostly recommended in the propulsion of aircraft when small cross section and low weight are important parameters. Can or tubular combustors are cheaper and several of them can be adjusted for an industrial engine identically. Although there are different types of combustors, but generally, all combustion chambers have a diffuser, a casing, a liner, a fuel injector and a cooling arrangement. An entire common layout is visualized in figure 1.

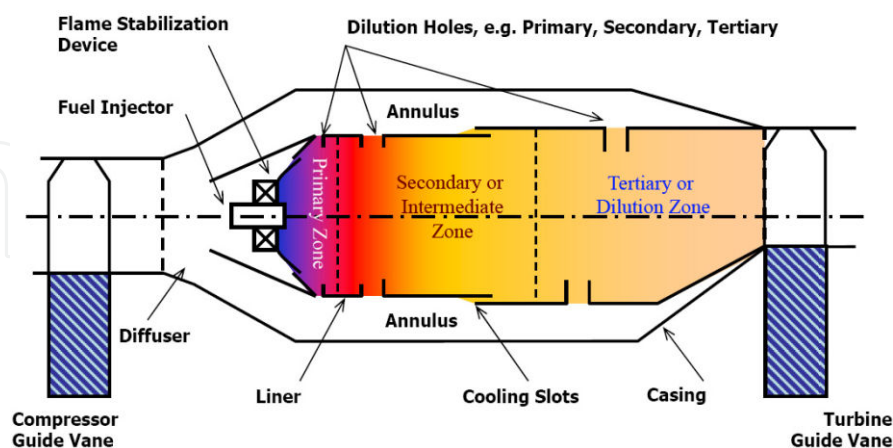


Figure 1. The layout of the combustion chamber.

1 Flue Gas Recirculation

2 Selective Catalytic Reduction

2.2. Flame stabilization

After the fuel has been injected into the air flow, the flow will enter the flame region. It does this with quite a high velocity, so to make sure the flame isn't blown away; suitable flame stabilization techniques must be applied. First, the high velocity of flow will be responsible for a pressure drop³. Secondly, the flame in the combustion chamber cannot survive if the air has a high velocity. So combustion chambers benefit from diffusers to slow down the air flow. There are two normal kinds of flame stabilizers: bluff-body flame holders and swirlers.

The shape of the bluff-body flame holder affects the flow stability characteristics through the influence on the size and shape of the wake region. Since the flame stabilization depends on size of the zone of recirculation behind the bluff-body, different geometries such as triangular, rectangular, circular and more complex shapes are being use. One of the basic problem of bluff-body flame holders is a considerable effect on pressure loss. Figure 2 shows a high speed image of three flame holders in atmospheric condition.



Figure 2. High speed images of the circular cylinder (top), square cylinder (middle) and V gutter (bottom) at $Re = 30,000$ and stoichiometric mixture [2].

Flow reversal can be applied in the primary zone. The best way to reverse the flow is to swirl it through using swirlers. The two most important types of swirlers are axial and radial. The advantage of flow reversal is that the flow speed varies a lot. So there will be a point at which the airflow velocity matches the flame speed where a flame could be stabilized. The degree of swirl in the flow is quantified by the dimensionless parameter, Sn known as the swirl number which is defined as:

³ This pressure drop is named the cold loss.

$$Sn = \frac{G_\theta}{G_x r} \quad (1)$$

Where:

$$G_\theta = \int_0^\infty (\rho u w + \overline{\rho u' w'}) r^2 dr$$

$$G_x = \int_0^\infty (\rho u^2 + \overline{\rho u'^2} + (p - p_\infty)) r dr$$

As this equation requires velocity and pressure profile of fluid, researchers proposed various expressions for calculating the swirl number. Indeed, the swirl number is a non-dimensional number representing the ratio of axial flux of angular momentum to the axial flux of axial momentum times the equivalent nozzle radius [3]. Tangential entry, guided vanes and direct rotation are three principal methods for generating swirl flow.

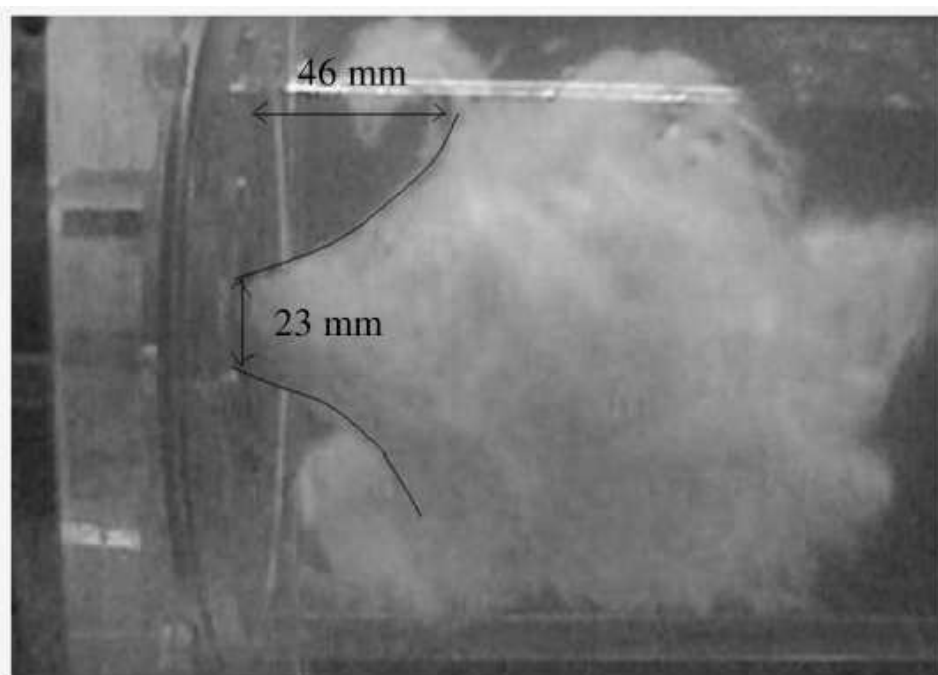


Figure 3. Photo of 60° flat guided vane swirler [4].

2.3. Type of flame

Most of the literatures divide combustible mixture into three categories as premixed, non-premixed and partially premixed combustion. If fuel and oxidizer are mixed prior ignition,

then premixed flame will propagate into the unburned reactants. If fuel and air mix at the same time and same place as they react, the diffusion or non-premixed combustion will appear. Partially premixed combustion systems are premixed flames with non-uniform fuel-oxidizer mixtures.

Gas turbines' manufacturers traditionally tend to use diffusion flame where fuel mixes with air by turbulent diffusion and the flame front stabilized in the locus of the stoichiometric mixture. The temperature of reactant is as high as 2000 °C, so the acceptable temperature at the combustor walls and turbine blades would be provide by diluted air. Although the non-premixed mixture in gas turbine combustors shows more stability in operation than premixed mixtures, but their shortcoming is high level of nitrogen oxide emission. Two most common ways of emission reduction are water injection and catalytic converter. However, the former technique is not capable of reducing NO_x to the expected level at many sites, while SCR adds complexity and expense to any project.

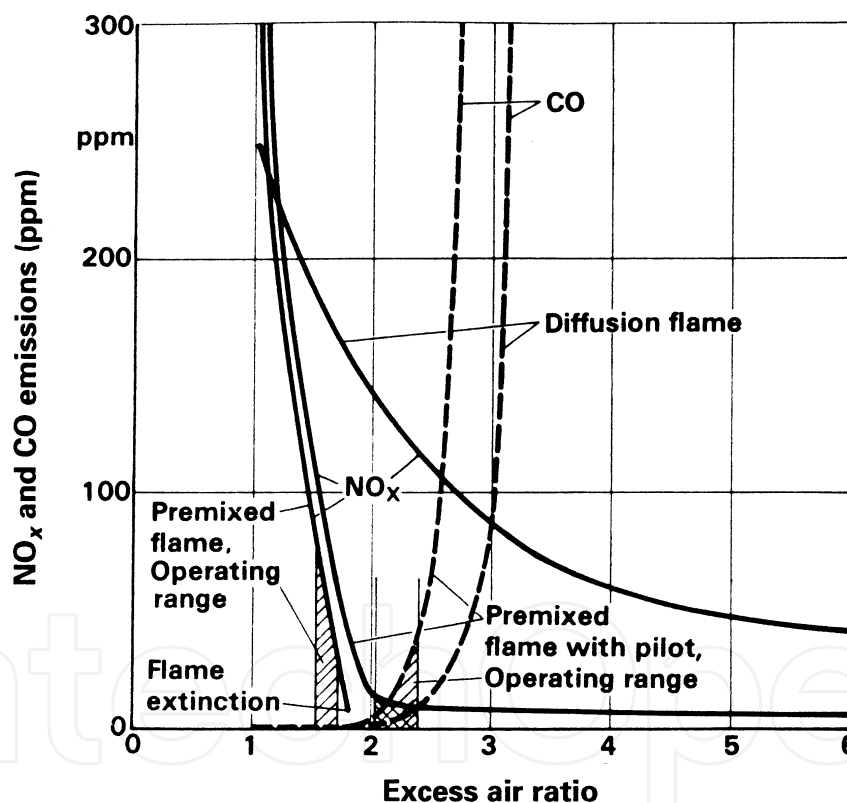


Figure 4. Operating range of premixed flames [5].

The idea of Dry Low NO_x (DLN) systems proposed base on lean premixed combustion to reduce flame temperature by a non-stoichiometric mixture. Premixed systems can be operated at a much lower equivalence ratio such that the flame temperature and thermal NO_x production throughout the system are decreased comparing with a diffusion system. The disadvantage of premixed systems is flame stability, especially at low equivalence ratios. Also, there is a tendency for the flame to flashback. Indeed, the current challenge of GT's de-

velopers is proposing a fuel flexible combustor for a stable combustion in all engine loads. The narrow range of fuel/air mixtures between the production of excessive NO_x and excessive CO is illustrated in figure 4. NO_x reduces by lowering flame temperature in a leaner mixture but CO, and unburned hydrocarbons (UHC) would increase contradictorily.

By increasing combustion residence time (volume) and preventing local quenching, CO and UHC will dissociate to CO₂ and the other products. CO burns away more slowly than the other radicals, so to obtain very low level emission such as 10 ppm; it requires over 4 ms. As shown in figure 5, below 1100 °C the CO reaction becomes too slow to effectively remove the CO in an improved combustion chamber. The residence time usually does not change much on part-load because the normalized flow approximately remains constant with a variable loading.

$$NF = \frac{\dot{m}\sqrt{T}}{P} \quad (2)$$

Where \dot{m} is the mass flow, T is combustion bulk temperature and P is combustor pressure. This will set a lower limit for the length of the primary zone in a DLN combustion system.

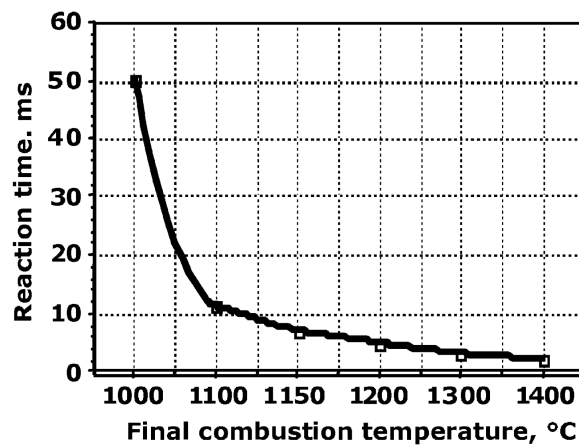


Figure 5. Calculated reaction time to achieve a CO concentration of 10 ppm in a commercial gas turbine exhaust [6].

2.4. Fuel

One of the features of heavy-duty gas turbines is a wide fuel capability. They can operate with vast series of commercial and process by-product fuels such as natural gas, petroleum distillates, gasified coal or biomass, gas condensates, alcohols, ash-forming fuels. In a review article, Molière offered essential aspects of fuel/machine interactions in thermodynamic performance, combustion and gaseous emission [7]. To sequester and store the CO₂ of fossil fuel, some new research projects aim to assess the combustion performances of alternative fuels for clean and efficient energy production by gas turbines. Another objective is to ex-

tend the capability of dry low emission gas turbine technologies to low heat value fuels produced by gasification of biomass and H₂ enriched fuels [8-10]. Significant quantity of hydrogen in fuel has the benefit of high calorific value, but the disadvantage of high flame speed and very fast chemical times. To classify gas turbine's fuels, a common way is to split them between gas and liquid fuels, and within the gaseous fuels, to split by their calorific value as shown in table 1.

	Typical composition	Lower Heating Value kJ/Nm ³	Typical specific fuels
Ultra/Low LHV gaseous fuels	H ₂ < 10% CH ₄ < 10% N ₂ +CO > 40%	< 11,200 (< 300)	Blast furnace gas (BFG), Air blown IGCC, Biomass gasification
High hydrogen gaseous fuels	H ₂ > 50% C _x H _y = 0-40%	5,500-11,200 (150-300)	Refinery gas, Petrochemical gas, Hydrogen power
Medium LHV gaseous fuels	CH ₄ < 60% N ₂ +CO ₂ = 30-50% H ₂ = 10-50%	11,200-30,000	Weak natural gas, Landfill gas, Coke oven gas, Corex gas
Natural gas	CH ₄ = 90% C _x H _y = 5% Inert = 5%	30,000-45,000	Natural gas Liquefied natural gas
High LHV gaseous fuels	CH ₄ and higher hydrocarbons C _x H _y > 10%	45,000-190,000	Liquid petroleum gas (butane, propane) Refinery off-gas
Liquid fuels	C _x H _y , with x > 6	32,000-45,000	Diesel oil, Naphtha Crude oils, Residual oils, Bio-liquids

Table 1. Classification of fuels [11].

3. New combustion systems for gas turbines

Next-generation gas turbines will operate at higher pressure ratios and hotter turbine inlet temperatures conditions that will tend to increase nitrogen oxide emissions. To conform to future air quality requirements, lower-emitting combustion technology will be required. In this section, a number of new combustion systems have been introduced where some of them could be found in the market, and the others are under development.

3.1. Trapped vortex combustion (TVC)

The trapped vortex combustor (TVC) may be considered as a promising technology for both pollutant emissions and pressure drop reduction. TVC is based on mixing hot combustion products and reactants at a high rate by a cavity stabilization concept. The trapped vortex

combustion concept has been under investigation since the early 1990's. The earlier studies of TVC have been concentrated on liquid fuel applications for aircraft combustors [12].

The trapped vortex technology offers several advantages as gas turbines burner:

- It is possible to burn a variety of fuels with medium and low calorific value.
- It is possible to operate at high excess air premixed regime, given the ability to support high-speed injections, which avoids flashback.
- NO_x emissions reach extremely low levels without dilution or post-combustion treatments.
- Produces the extension of the flammability limits and improves flame stability.

Flame stability is achieved through the use of recirculation zones to provide a continuous ignition source which facilitates the mixing of hot combustion products with the incoming fuel and air mixture [13]. Turbulence occurring in a TVC combustion chamber is “trapped” within a cavity where reactants are injected and efficiently mixed. Since part of the combustion occurs within the recirculation zone, a “typically” flameless regime can be achieved, while a trapped turbulent vortex may provide significant pressure drop reduction [14]. Besides this, TVC is having the capability of operating as a staged combustor if the fuel is injected into both the cavities and the main airflow. Generally, staged combustion systems are having the potential of achieving about 10 to 40% reduction in NO_x emissions [15]. It can also be operated as a rich-burn, quick-quench lean-burn (RQL) combustor when all of the fuel is injected into the cavities [16].

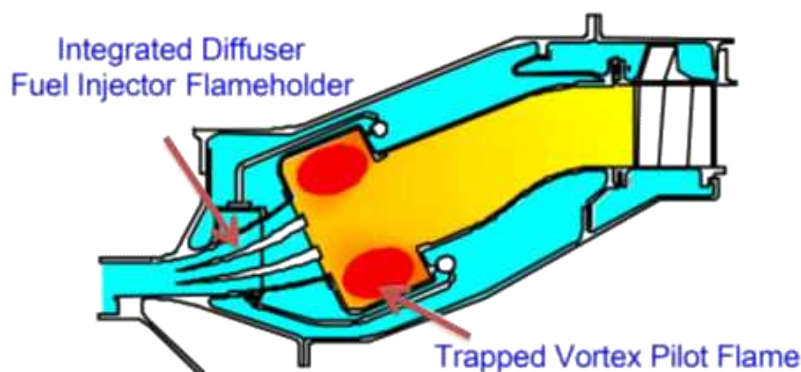


Figure 6. Trapped vortex combustor schematic.

An experiment in NASA with water injected TVC demonstrated a reduction in NO_x by a factor three in a natural gas fueled and up to two in a liquid JP-8 fueled over a range in water/fuel and fuel/air ratios [17]. Replacement of natural gas fuel with syngas and hydrogen fuels has been studied numerically by Ghenai et al. [18]. The effects of secondary air jet momentum on cavity flow structure of TVC have been studied recently by Kumar and Mishra [19]. Although the actual stabilization mechanism facilitated by the TVC is relatively simple,

a number of experiments and numerical simulations have been performed to enhance the stability of reacting flow inside trapped vortex. Xing et al. experimentally investigated lean blow-out of several combustors and the performance of slight temperature-raise in a single trapped vortex [20, 21]. In an experimental laboratory research, Bucher et al. proposed a new design for lean-premixed trapped vortex combustor [22].

3.2. Rich burn, quick- mix, lean burn (RQL)

Lean direct injection (LDI) and rich-burn/quick-quench/lean-burn (RQL) are two of the prominent low-emissions concepts for gas turbines. LDI operates the primary combustion region lean, hence, adequate flame stabilization has to be ensured; RQL is rich in the primary zone with a transition to lean combustion by rapid mixing with secondary air downstream. Hence, both concepts avoid stoichiometric combustion as much as possible, but flame stabilization and combustion in the main heat release region are entirely different. Relative to aviation engines, the need for reliability and safety has led to a focus on LDI of liquid fuels [23]. However, RQL combustor technology is of growing interest for stationary gas turbines due to the attributes of more effectively processing of fuels with complex composition. The concept of RQL was proposed in 1980 as a significant effort for reducing NO_x emission [24].

It is known that the primary zone of a gas turbine combustor operates most effectively with rich mixture ratios so, a “rich-burn” condition in the primary zone enhances the stability of the combustion reaction by producing and sustaining a high concentration of energetic hydrogen and hydrocarbon radical species. Secondly, rich burn conditions minimize the production of nitrogen oxides due to the relative low temperatures and low population of oxygen containing intermediate species. Critical factors of a RQL that need to be considered are careful tailoring of rich and lean equivalence ratios and very fast cooling rates. So the combustion regime shifts rapidly from rich to lean without going through the high NO_x route as shown in figure 7. The drawback of this technology is increased hardware and complexity of the system.

The mixing of the injected air takes the reaction to the lean-burn zone and rapidly reduces their temperature as well. On the other hand, the temperature must be high enough to burn CO and UHC. Thus, the equivalence ratio for the lean-burn zone must be carefully selected to satisfy all emissions requirements. Typically the equivalence ratio of fuel-rich primary zone is 1.2 to 1.6 and lean-burn combustion occurs between 0.5 and 0.7 [25].

Turbulent jet in a cross-flow is an important characteristic of RQL; so many researches have been conducted to improve it. The mixing limitation in a design of RQL/TVC combustion system addressed by Straub et al. [26]. Coaxial swirling air discussed experimentally by Cozzi and Coghe [27]. Furthermore, an experimental study of the effects of elevated pressure and temperature on jet mixing and emissions in an RQL reported by Jermakian et al. [28]. Fuel flexible combustion with RQL system is an interest of turbine manufacturer. GE reported results of a RQL test stand in their integrated gasification combined cycle (IGCC) power plants program [29, 30]. The test of Siemens-Westinghouse Multi-Annular Swirl Burner (MASB) was successfully performed at the University of

Tennessee Space Institute in Tullahoma [31]. Others, such as references [32-35] utilize CFD to investigate the performance of RQL combustor.

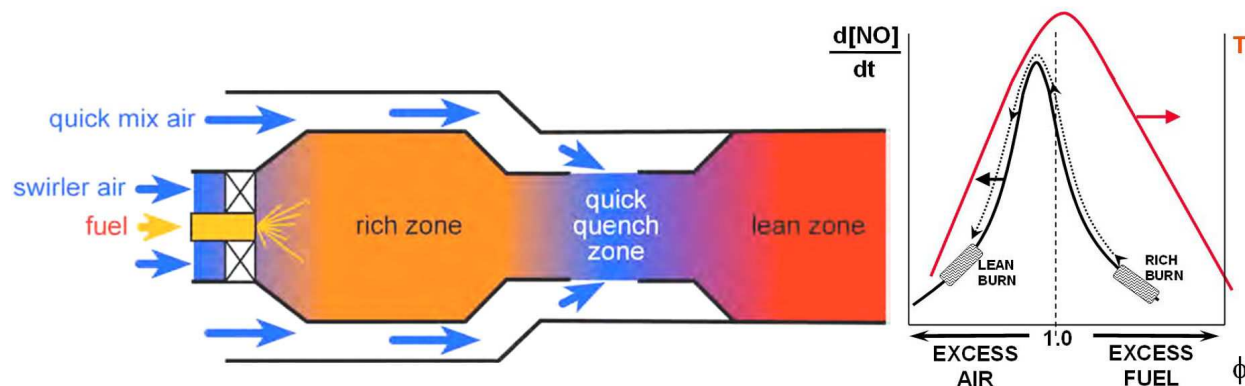


Figure 7. Rich-Burn, Quick-Mix, Lean-Burn combustor.

3.3. Staged air combustion

The COSTAIR⁴ combustion concept uses continuously staged air and internal recirculation within the combustion chamber to obtain a stable combustion with low NO_x and CO emissions. Research work on staged combustors started in the early 1970s under of the Energy Efficient Engine (E³) Program in the USA [36] and now widely used in industrial engines burning gaseous fuels, in both axial and radial configurations. The aero-derived GE LM6000 and CFM56-5B as well as RR211 DLE industrial engine employ staged combustion of premixed gaseous fuel/air mixtures. Recently, a research project proposed a COSTAIR burner system optimized for low calorific gases within a micro gas turbine [37].

The principle of staged air combustion is illustrated in Figure 8. It consists of a coaxial tube; the combustion air flows through the inner tube and the fuel through the outer cylinder ring. The combustion air is continually distributed throughout the combustion chamber by an air distributor with numerous openings on its contour, and fuel enters by several jets arranged around the air distributor.

The COSTAIR burner has the advantages of operating in full diffusion mode or in partially premixed mode. The heat is released more uniformly throughout the combustion chamber also the recirculated gas absorb some of the heat of combustion. It capable to work stable at cold combustor walls as well as high air ratio. Experimental measurements show that this combustion system allows clean exhaust. For instance, in an experimental research project of European Commission [39], NO_x emission values was in the range of 2-4 ppm at an air ratio of 2.5 over different loading. Furthermore, the corresponding CO emission was less than 7 ppm.

⁴ Continuous STaged Air

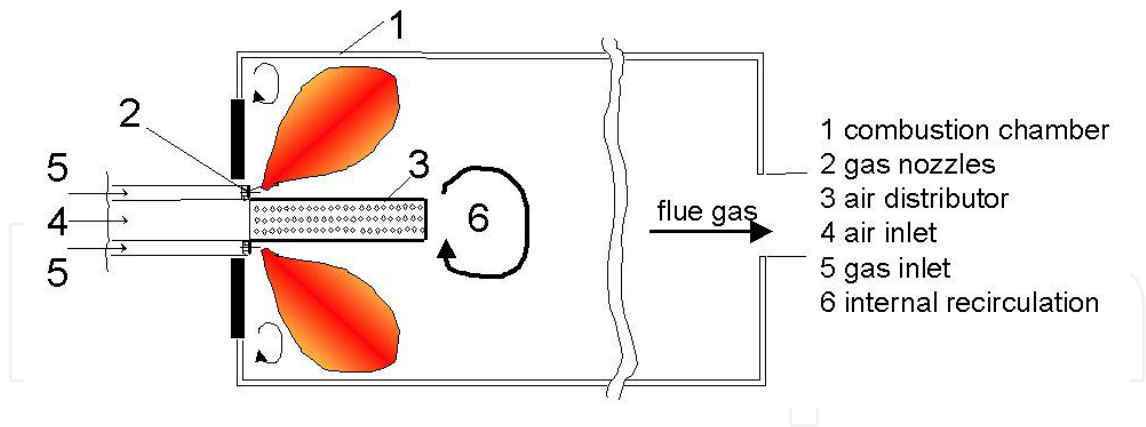


Figure 8. COSTAIR combustion concept [38].

Staged combustion can occur in either a radial or axial pattern, but in either case the goal is to design each stage to optimize particular performance aspects. The main advantages or major drawbacks of each type have been discussed by Lefebvre [25].

3.4. Mild combustion

Heat recirculating combustion was clearly described by Weinberg as a concept for improving the thermal efficiency [40]. In 1989, a surprising phenomenon was observed during experiments with a self-recuperative burner. At furnace temperatures of 1000°C and about 650°C air preheated temperature; no flame could be seen, but the fuel was completely burnt. Furthermore, the CO and NO_x emissions from the furnace were considerably low [41]. Different combustion zones against rate of dilution and oxygen content is shown in figure 9. In flameless combustion, the oxidation of fuel occurs with a very limited oxygen supply at a very high temperature. Spontaneous ignition occurs and progresses with no visible or audible signs of the flames usually associated with burning. The chemical reaction zone is quite diffuse, and this leads to almost uniform heat release and a smooth temperature profile. All these factors could result in a much more efficient process as well as reducing emissions.

Flameless combustion is defined where the reactants exceed self-ignition temperature as well as entrain enough inert combustion products to reduce the final reaction temperature [42]. In the other word, the essence of this technology is that fuel is oxidized in an environment that contains a substantial amount of inert (flue) gases and some, typically not more than 3–5%, oxygen. Several different expressions are used to identify similar though such as HiTAC⁵, HiCOT⁶, MILD⁷ combustion, FLOX⁸ and CDC⁹. HiTAC refers to increase the air temperature by preheating systems such as regenerators. HiCOT commonly belongs to the

⁵ High Temperature Air Combustion

⁶ High-temperature Combustion Technology

⁷ Moderate or Intense Low-oxygen Dilution

⁸ FLameless OXidation

⁹ Colorless Distributed Combustion

wider sense, which exploits high-temperature reactants; therefore, it is not limited to air. A combustion process is named FLOX or MILD when the inlet temperature of the main reactant flow is higher than mixture autoignition temperature and the maximum allowable temperature increase during combustion is lower than mixture autoignition temperature, due to dilution [42]. The common key feature to achieve reactions in CDC mode (non-premixed conditions) is the separation and controlled mixing of higher momentum air jet and the lower momentum fuel jet, large amount of gas recirculation and higher turbulent mixing rates to achieve spontaneous ignition of the fuel to provide distributed combustion reactions [43]. Figure 10 schematically shows a comparison between conventional burner and flameless combustion.

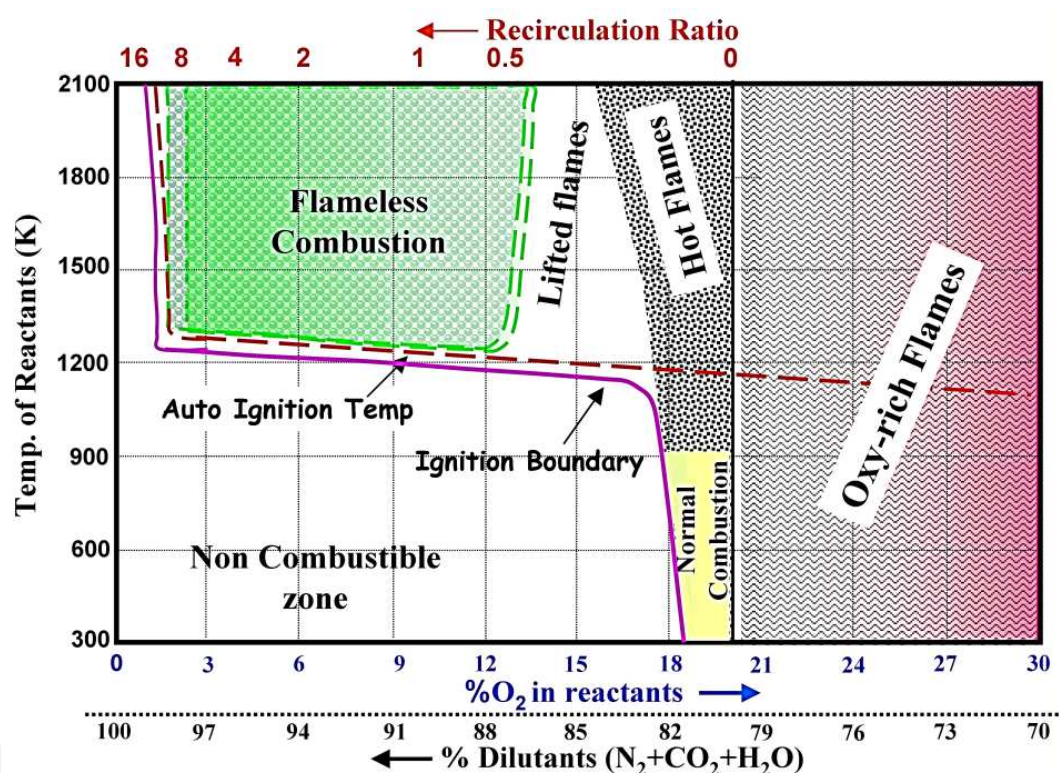


Figure 9. Different combustion regimes [64].

To recap, the main characteristics of flameless oxidation combustion are:

- Recirculation of combustion products at high temperature (normally $> 1000\text{ }^{\circ}\text{C}$),
- Reduced oxygen concentration at the reactance,
- Low Damköhler number (Da^{10}),
- Low stable adiabatic flame temperature,
- Reduce temperature peaks,

¹⁰ A dimensionless number, equal to the ratio of the turbulence time scale to the time it takes chemical reaction.

- Highly transparent flame,
- Low acoustic oscillation and
- Low NO_x and CO emissions.

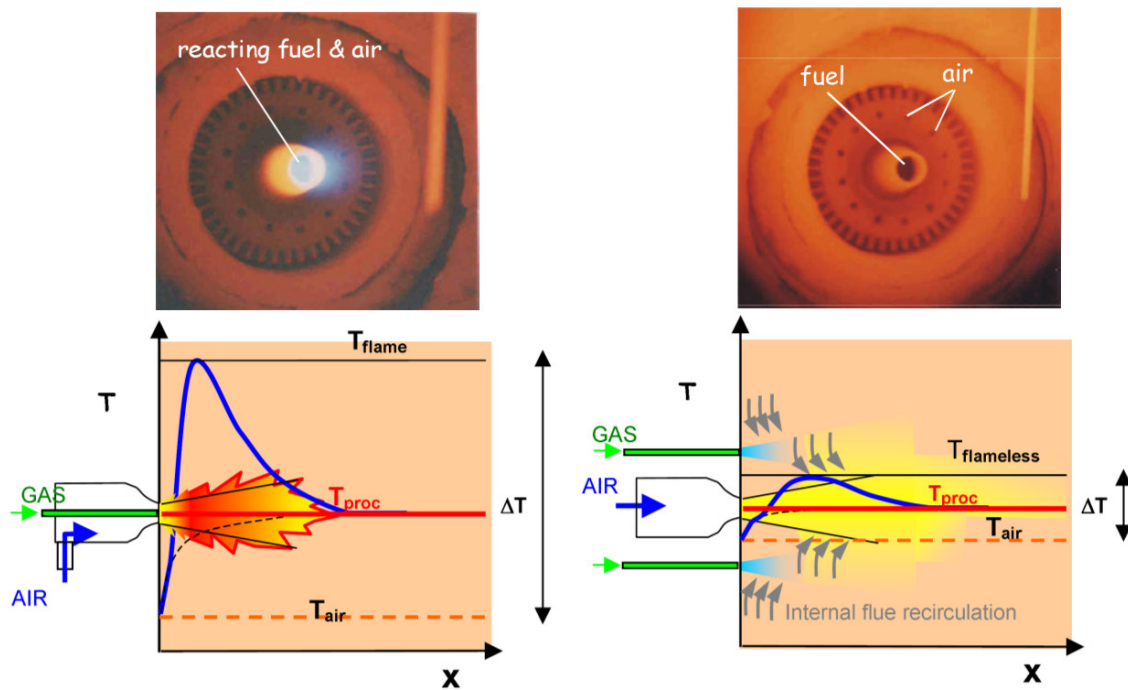


Figure 10. Flame (left) and flameless (right) firing.

In spite of a number of activities for industrial furnaces, the application of flameless combustion in the gas-turbine combustion system is in the preliminary phase [44]. The results from techno-economic analysis of Wang et al. showed that the COSTAIR and FLOX cases had technical and economic advantages over SCR [45]. Luckerath, R., et al., investigated flameless combustion in forward flow configuration in elevated pressure up to 20atm for application to gas turbine combustors [44, 46]. In a novel design of Levy et al. that named FLOXCOM, flameless concept has been proposed for gas turbines by establishing large recirculation zone in the combustion chamber [47, 48]. Lammel et al. developed a FLOX combustion at high power density and achieved low NO_x and CO levels [49]. The concept of colorless distributed combustion has been demonstrated by Gupta et al. for gas turbine application in a number of publications [43, 50-55].

3.5. Surface stabilized combustion

One specification of gas turbine combustor is higher thermal intensity range (at least 5 MW/m³-atm) than industrial furnaces which operate at thermal intensity of less than 1 MW/m³-atm. Therefore, designs of gas turbine's combustors are based on turbulent flow concept, except a technology named NanoSTAR from Alzeta Corporation. Alzeta reported

the proof-of-concept of high thermal intensity laminar surface stabilized flame by using a porous metal-fiber mat since 2001 [56-58]. Lean premixed combustion technology is limited by the apparition of combustion instabilities, which induce high pressure fluctuations, which can produce turbine damage, flame extinction, and CO emissions [59]. However, full scale test of NanoSTAR demonstrated low emissions performance, robust ignition and extended turndown ratio [60]. In particular, the following characteristics form the key specifications of NanoSTAR for distributed power generation gas turbine combustors [61]:

- The combustor fuel is limited to natural gas.
- Total combustor pressure drop limited to 2-4% of the system pressure.
- Operation at combustion air preheat temperatures up to 1150°F.
- Volumetric firing rates approaching 2 MMBtu/hr/atm/ft³.
- Turbine Rotor Inlet Temperatures (TRIT) over 2200°F (valid for the Mercury 50, although Allison has operated combustors at 2600°F).
- Operation with axial combustors or external can combustors.
- Expected component lifetimes of 30,000 hours for industrial turbines.

A single prototype burner Porous burner which sized to fit inside an annular combustion liner (about 2.5 inches in diameter by 7 inches in length) is shown in figure 11 with its arrangement in a typical combustor.

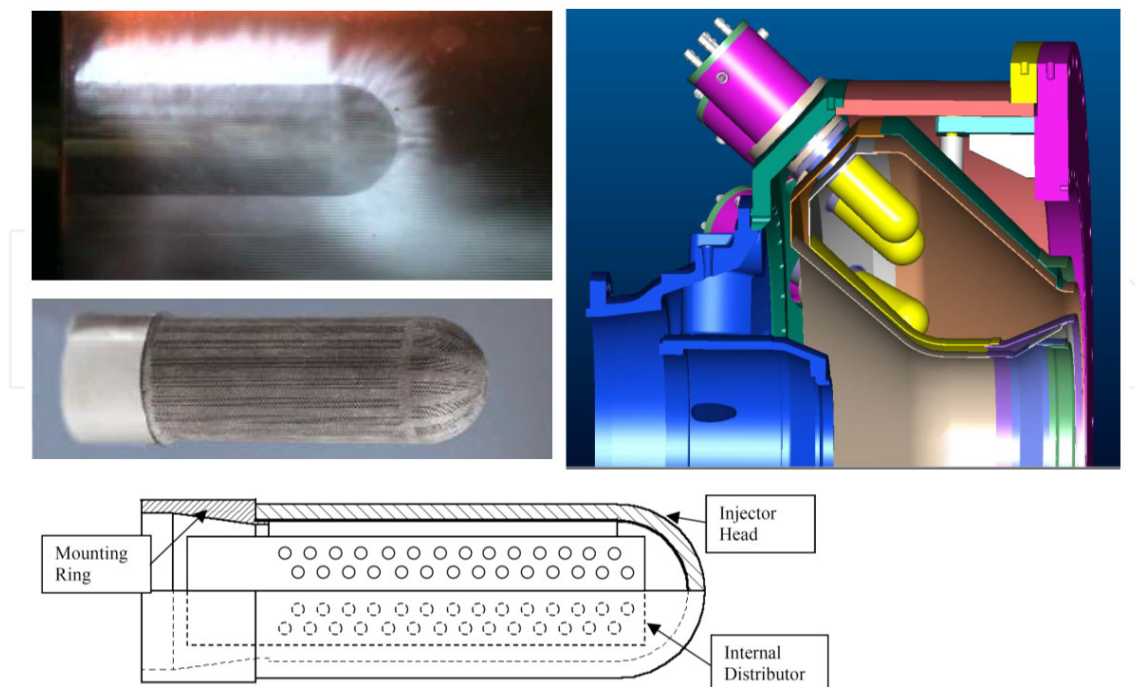


Figure 11. NanoSTAR burner and its arrangement in a canted combustion system [62].

The operation of this type of surface stabilized combustion is characterized by the schematic in Figure 12(left), which shows premixed fuel and air passing through the metal fiber mat in two distinct zones. Premixed fuel comes through the low conductivity porous and burns in narrow zones, A, as it leaves the surface. Under lean conditions this will manifest as very short laminar flamelets, but under rich conditions the surface combustion will become a diffusion dominated reaction stabilized just over a millimeter above the metal matrix, which proceeds without visible flame and heats the outer surface of the mat to incandescence. Secondly, adjacent to these radiant zones, the porous plate is perforated to allow a high flow of the premixed fuel and air. This flow forms a high intensity flame, B, stabilized by the radiant zones so, it is possible to achieve very high fluxes of energy, up to 2MMBtu/hr/ft² [63]. A picture of an atmospheric burner in operation clearly shows the technology in action (right of figure 12).

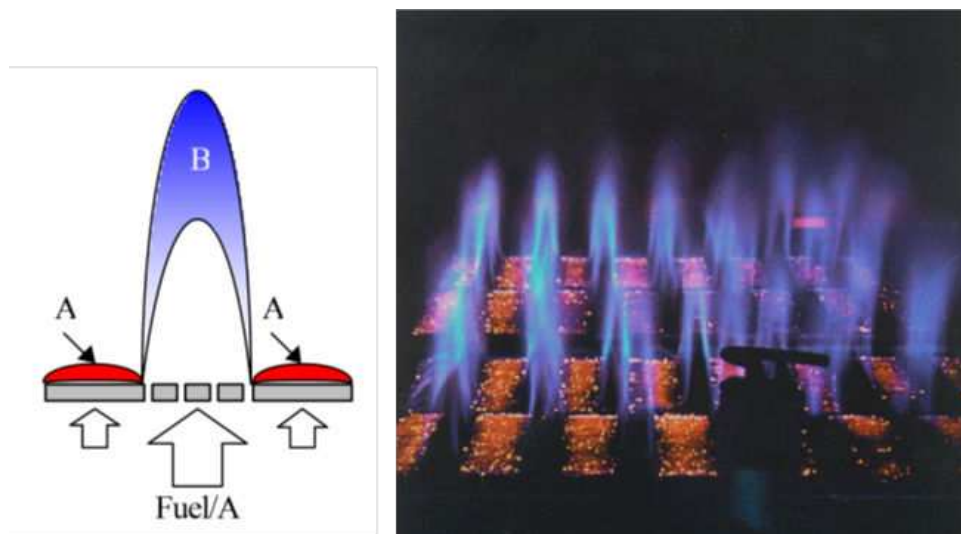


Figure 12. Surface stabilized burner pad firing at atmospheric conditions.

The specific perforation arrangement and pattern control the size and shape of the laminar flamelets. The perforated zones operate at flow velocities of up to 10 times the laminar flame speed producing a factor of ten stretch of the flame surface and resulting in a large laminar flamelets. The alternating arrangement of laminar blue flames and surface combustion, allows high firing rates to be achieved before flame liftoff occurs, with the surface combustion stabilizing the long laminar flames by providing a pool of hot combustion radicals at the flame edges.

4. Conclusion

A review of technologies for reducing NO_x emissions as well as increasing thermal efficiency and improving combustion stability has been reported here. Trade-offs when installing low NO_x burners in gas turbines include the potential for decreased flame stability, reduced

operating range and more strict fuel quality specifications. In the other word, although, the turbine inlet temperature is the major factor determining the overall efficiency of the gas turbine but higher inlet temperatures will result in larger NO_x emissions. So the essential requirement of new combustor design is a trade-off between low NO_x and improved efficiency.

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