

Review

Recent Combustion Strategies in Gas Turbines for Propulsion and Power Generation toward a Zero-Emissions Future: Fuels, Burners, and Combustion Techniques

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Abstract: The effects of climate change and global warming are arising a new awareness on the impact of our daily life. Power generation for transportation and mobility as well as in industry is the main responsible for the greenhouse gas emissions. Indeed, currently, 80% of the energy is still produced by combustion of fossil fuels; thus, great efforts need to be spent to make combustion greener and safer than in the past. For this reason, a review of the most recent gas turbines combustion strategy with a focus on fuels, combustion techniques, and burners is presented here. A new generation of fuels for gas turbines are currently under investigation by the academic community, with a specific concern about production and storage. Among them, biofuels represent a trustworthy and valuable solution in the next decades during the transition to zero carbon fuels (e.g., hydrogen and ammonia). Promising combustion techniques explored in the past, and then abandoned due to their technological complexity, are now receiving renewed attention (e.g., MILD, PVC), thanks to their effectiveness in improving the efficiency and reducing emissions of standard gas turbine cycles. Finally, many advances are illustrated in terms of new burners, developed for both aviation and power generation. This overview points out promising solutions for the next generation combustion and opens the way to a fast transition toward zero emissions power generation.

Keywords: combustion; hydrogen; ammonia; SAF; MILD combustion; RQL; lean combustion; emulsion



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1. Introduction

Every day, we are bombarded with news regarding the worrying evolution of the current global climate scenario. This frenzy by various stakeholders (mass media, politics, science) indicates a growing awareness of a really crucial issue that concerns all of us. “2030 is now” is the EU motto proposed by the European Economic and Social Committee on the Sustainable Development Goals to remind all of us that we need to work on all possible levels in order to achieve objectives that essentially depend on the way we start now to deal with them, even if they seem distant in time.

Among the different sectors, aviation and industry are considered “hard to abate” sectors characterized by high energy intensity and lack of scalable electrification solutions. According to the latest report published by the International Renewable Energy Agency (IRENA), aviation is one of the fastest-growing sources of greenhouse gas emissions. During the two last decades, CO₂ emissions related to the aviation sector have risen, reaching about 1 Gt in 2019, i.e., 2–3% of global emissions derived from fossil fuel combustion. In this analysis, IRENA forecasts that emissions will increase to 2.1 Gt/year by 2050 in the so-called Planned Energy Scenario, which is essentially an outlook based on the current strategic policies as proposed by governments [1].

According to the International Energy Agency (IEA), a strong effort is requested to increase aircraft efficiency by more than 3% per year until 2040 if we want to reach

decarbonization targets [2]. In this scenario, one of the main key players is the International Civil Aviation Organization (ICAO), which adopted the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) in 2016. The plan is organized in three main steps: a preliminary step (from 2021 to 2023), a first step (from 2024 to 2026), and a second phase (from 2027 to 2035). Both the preliminary and the first steps are voluntary, while the second step will be obligatory for all Member States [3].

In order to achieve higher sustainable levels, the aviation sector has to commit to deploy renewable and sustainable aviation fuels (SAFs), such as biofuels developed for jet aircraft. Biofuels for jet aircraft, known in the industry as biojet, are the most concrete solution for a significant emission reduction. Until today, the American Society of Testing and Materials (ASTM) has approved six biojet fuel production procedures, but among these, only one (i.e., the HEFA jet) is currently commercially available [4].

Although the market for biojet is currently limited, and price information is also limited, biojet use is likely to grow rapidly in the upcoming decades in a favorable scenario of strategies and regulations. Despite the fact that biofuel blends have been deployed in about 200,000 flights, the current worldwide share of SAFs in jet kerosene is still limited (<0.1%). Moreover, it must be highlighted that SAFs are more expensive than oil-derived jet kerosene, with break-even at oil prices above 100 USD per barrel. For this reason, political and economic strategies are necessary to boost the demand and, thus, the production [5]. Currently, many airlines (e.g., British Airways, Lufthansa, KLM, FinnAir, and Virgin Atlantic), are flying with biofuels. Airports are working to allow utilization of biofuels. For example, there are five airports that regularly distribute biofuels (Bergen, Brisbane, Los Angeles, Oslo, and Stockholm). KLM is programming to enlarge its fuel supply also with SAFs at the Schiphol airport by 2022 [2].

In industry, global energy-related CO₂ emissions have reached 31.5 Gt in the 2020, almost 8% lower than in 2019 following the energy demand reduction due to the COVID-19 pandemic [6,7]. Despite this decline, average annual CO₂ concentration showed the highest level in 2020 (412.5 parts per million). According to the latest Global Energy Review by IEA [8], global energy-related CO₂ emissions are projected to rebound in 2021 and grow by 4.8% as demand for coal, oil, and gas rebounds with the economy. In details, the power sector accounted for less than 50% of the drop in coal-related emissions in 2020, but it accounts for 80% of the rebound. CO₂ emissions related to natural gas combustion will reach a level of 7.35 Gt CO₂ in 2021.

Actually, these trends need to be changed as soon as possible. The first signal is given by renewables, which have shown good resilience despite the pandemic crisis. Moreover, a global widespread enthusiasm is growing toward a future carbon neutrality. More and more countries are embracing the cause by means of strategic plans. Regarding power generation for aviation and electricity production, a great effort needs to be addressed towards more research on fuels, combustion techniques and more efficient burners. For this reason, the present work aims to provide a survey on recent combustion strategies in gas turbines for aviation and power generation by focusing on specific aspects regarding nextgen fuels, burners and combustion techniques. The introduction provides a global overview of the current picture of both aviation and power generation sectors, the so-called “*hard to abate*” fields where a great effort is currently dedicated to decarbonization. Following the main intervention areas, the work initially gives an overview of new fuels (e.g., SAFs, hydrogen, ammonia and emulsions), which are supposed to gradually substitute the current ones (Section 2); then a description of different combustion techniques is proposed in Section 3. Afterwards Section 4 continues with recent proposals of burners, whose designs aim to obtain a more sustainable combustion.

2. Fuels

When talking about the power generation either for electricity production or aviation propulsion, the main source of energy still comes from the combustion process. This comes from the energy released from chemical reactions, which involve oxidants and one or more

fuels. Since the industrial revolution (1760) until now, many fuels have been employed to this end (wood, coal, oil, natural gas, etc.). Currently, the impact of GHG (greenhouse gases) regulations and the estimated depletion of fossil fuels [9] are leading to a revolution in the combustion community, since new sustainable power fuels are required. In this context, new fuels, blends and new technologies are under investigation aiming at the reduction of the human carbon footprint.

2.1. Sustainable Biofuels

Further complexity introduced by zero-carbon fuels in terms of storage and emissions control, e.g., hydrogen and ammonia, opens up the possibility to use so-called sustainable fuels; in the aviation sector, these are known as sustainable aviation fuels (SAFs) [10]. These fuels are similar to conventional fossil fuels, but they derive from sustainable feedstocks. In this way, the CO₂ abatement on the entire life cycle of the fuel would be 80%. They can be mixed with fossil fuels up to 50% without plants modifications, considerably reducing the GHG production.

As proposed by the International Civil Aviation Organization (ICAO), the most promising sustainable fuels are those based on the power-to-liquids (PtL) concept. Indeed, in the last H2020, the development of sun-to-liquid technologies has been funded by the European Union. These technologies are based on renewable energy, water, and CO₂. In addition to this, researchers are exploring the production of synthetic jet fuel using green hydrogen (i.e., hydrogen generated by electrolysis). In particular, at Rotterdam's Innovation Campus, highly innovative technologies are combined to produce jet fuel made (partly) from CO₂ to achieve a carbon-neutral future for the aviation sector. The idea is to capture CO₂ from the air and then to combine it with hydrogen produced by splitting water into hydrogen and oxygen with electrolysis. The result is a synthetic gas that can be transformed into a jet fuel. However, the project is still at the demonstration stage. Synthetic jet fuels still have a long way to go before they can become fully competitive, mainly due to their high costs.

Biofuels represent the kind of fuels coming from biomass such as plants and animal wastes, which has passed ups and downs from the second World War to the petroleum crisis in the 1970s. Currently, biofuels account for 3.4% of the total fuel employed in transportation, the most being produced in USA and Brazil [5]. A brief classification can be made. The first generation of biofuels comes from human and animal feedstocks and are also called conventional biofuels. The second generation is based on no-food feedstocks and the third generation uses microalgae. Compared to biofuels, PtL technologies have the advantage to require less yields and water. On the contrary, even though the CO₂ production is balanced in the life cycle of the fuel, the emissions related to a hydrocarbon fuel remains (e.g., soot, NO_x, sulphur, etc.). Actually, it is worth underlining how energy-dense liquid fuels are the best suited in the aviation sector. For this reason, it is really important to research and develop new production methods that involve lower GHG emissions. In addition, it must be taken into account that producing and using SAFs will not totally solve the climate impact issue but will partially reduce it. This can be explained because of the emissions related to the SAF production methods and the water vapor emitted and the contrails formed during the flights (which are considered two of the most significant non-CO₂ climate-forcing impacts [11]). These fuels, despite representing only 0.01% of the total fuel consumption, can represent a trustworthy and valuable solution during the transition to either zero carbon fuels or electric propulsion and mobility, but it does not represent a long-term solution for the GHG abatement.

2.2. Hydrogen

Currently, hydrogen is the main protagonist of the global energy future, being a carbon-free fuel. Indeed, many countries are working on programs at different levels (political, economic, technological) that endorse an even more carbon-neutral future. However, the hydrogen currently produced is not clean. Indeed, it is mainly produced using fossil fuels

(96%); only the remaining 4% is produced by electrolysis. This means that more clean hydrogen needs to be produced. Indeed, different methods are employed to produce hydrogen: coal gasification with water vapor (brown H₂), production from a generic fossil fuel (grey H₂), or methane formation (steam methane reforming) together with the carbon capture and storage process (blue H₂) and the electrolysis of water in special electrochemical cells powered by electricity produced from renewable sources (green H₂). The latter is the cleanest way to produce hydrogen, and it can substitute the fossil fuels with the aim to make combustion systems more sustainable.

Hydrogen use in combustion is attractive because of its wide flammability range, large flame propagation speed, and small quenching distance. These properties can be observed in Table 1, which compares the main characteristic of H₂ with conventional hydrocarbons used in aviation and industry (i.e., methane and kerosene). As summarized in Table 1, hydrogen shows wider flammability limits than those of conventional hydrocarbons. In details, the lean and rich flammability limits (LFL and RFL) in terms of volume % in air are equal to 4 and 75, respectively. Methane, on the other hand, is characterized by a flammability range of 5.5–15. Moreover, hydrogen has a higher flame propagation velocity than that of conventional fuels due to the faster reaction rates. Indeed, the flame speed in a stoichiometric H₂/air mixture is 1.85 m/s with respect to the methane (0.44 m/s). Since no carbon is involved when pure H₂ is burned, reactions including hydrocarbon intermediates, CO, and CO₂, are eliminated. The primary pollutant species produced during hydrogen combustion are the nitrogen oxides (NO_x).

The use of blends of hydrogen and conventional hydrocarbons in gas turbines is one of the most promising technical solutions during the transition toward full decarbonization. Thanks to the H₂ addition, the combustor can work in a leaner condition, thus with lower flame temperatures, which reduce NO_x formation. In addition, the mixture enrichment with H₂ involves the reduction of CO emissions. This is caused by two main factors: the reduction of carbon in the mixture due to the addition of H₂ and the increased production of radicals that promotes the oxidation of CO to CO₂.

Despite these positive aspects, hydrogen shows some other challenging technical issues that must be addressed, such as potential flashback and autoignition due to its significantly higher flame speed and shorter autoignition time. Furthermore, an excessive lean combustion can lead to dangerous thermoacoustic instabilities [12–17]. This will require some modifications of current design features. Moreover, due to the low density of H₂, its volumetric energy density is less than half of that of other fuels. For example, in Table 1, it can be seen that the lower heating value for H₂ is about 120 MJ/kg or 9.9 MJ/Nm³. The corresponding value for CH₄ is 50 MJ/kg or 32.6 MJ/Nm³ [18,19]. Thus, storing a sufficient amount of H₂ requires large volumes. A possible approach to this problem is storage at high pressures (68 MPa storage tanks are currently available and storage tanks up to 100 MPa will be available in the near future). Since the high complexity introduced by hydrogen, a great amount of research is necessary to fill the gap in terms of safety and storage. Meanwhile, many researchers suggest to store hydrogen in the form of ammonia, which is a fluid with physical properties close to the conventional gaseous fuels.

Table 1. Comparison between properties of H₂, CH₄, and kerosene ($T = 25\text{ }^{\circ}\text{C}$, $p = 1\text{ atm}$ and $\phi = 1$).

Property	Hydrogen	Methane	Kerosene
Density (kg/m ³)	0.0824	0.651	780
Flammability limits (volume % in air)	4–75	5.5–15	0.7–5
Stoichiometric flame velocity (m/s)	1.85	0.40	0.49
Stoichiometric adiabatic flame temperature (K)	2480	2226	2366
Lower Heating Value (MJ/kg)	119.7	50.0	43.1
Lower Heating Value (MJ/Nm ³)	9.9	32.6	-

2.3. Ammonia

Green hydrogen has been recognized as a potential enabler of a carbon-free economy, but issues associated to its storage and distribution represent a barrier for its implementation. Hence, alternative media have been considered for indirect chemical storage. Among these media, ammonia has been identified as one of the most promising solution for both energy storage and direct combustion.

Ammonia is easy and cheap to store because it can be liquefied through compression at 8 bar (at room temperature), it is characterized by a high volumetric energy density (45% higher than liquid hydrogen), and it has a competitive gravimetric energy density (22.5 MJ/kg, making it comparable to low-ranked coals). It has been estimated that ammonia storage over 182 days costs 30 times less than hydrogen storage [20]. Liquid ammonia contains 17.6% (in weight) of hydrogen, 1.7 times as much as liquid hydrogen itself (by volume) [21]; thus, an ammonia tank (at 1 MPa) contains 2.5 times as much energy as a hydrogen tank (at 70 MPa) [22], making ammonia a viable hydrogen-carrier fuel. Last, reliable infrastructures for production, transportation, and storage along with well-established safe handling procedures, already exist since ammonia has been massively produced throughout the world for more than a century, and it is one of the most transported bulk-manufactured chemicals in the world.

Ammonia is a colorless, light gas with a penetrating odor (density of 0.73 kg/m³, molecular weight of 17.03 kg/kmol). Under atmospheric condition, its boiling point is 239.8 K and its freezing point 195.5 K. Ammonia combustion is a topic of research because, being a carbon-free molecule, its products are only molecular nitrogen gas and water. Nevertheless, ammonia combustion is challenging due to its thermokinetic properties: high autoignition temperature (930 K compared to 859 K of methane), low laminar flame speed (about 5 times lower than that of methane), low flammability limits (18% to 28% by volume in air at atmospheric pressure), and lower heating value (18.6 MJ/kg) which make pure ammonia combustion difficult. Another issue associated to ammonia combustion is its propensity to emit large amounts of NO when burned. Contrary to conventional fuels, here, most of the NO is formed via fuel NO_x pathways. Hence, reducing flame temperature by operating lean, to penalize thermal NO_x pathways, is ineffective with ammonia-air flames to abate NO emissions below acceptable limits. For these reasons, blends with more reactive fuels such as methane and hydrogen have been attempted for practical applications.

In particular, ammonia-methane blends have been identified as a relatively easy technology to implement for a cofiring application, since the two fuels share similar density, viscosity, and heat capacity. Stability limits and exhaust NO performances of ammonia-methane-air swirled flames in a laboratory-scale burner has been experimentally determined over a wide range of equivalence ratios, ammonia fuel fractions, and operating pressures (up to 5 bar) [23] (This article was published in *Experimental Thermal and Fluid Science*, 114, A.A. Khateeb, T.F. Guiberti, X. Zhu, M. Younes, A. Jamal, W.L. Roberts, Stability limits and exhaust NO performances of ammonia-methane-air swirl flames, 110058, Copyright Elsevier (2020)). Results show that the stability region for ammonia-methane mixtures is given by three different limits: the lean blowout limit, the flashback limit, and the additional rich blowout limit (see Figure 1). For ammonia fuel fractions less than 50%, the stability region is bounded by lean blowout and flashback limits. The increase in the ammonia fuel fraction enlarges the flashback limit due to the reduced reactivity of the mixture, but it also increases the lean blowout limit. The equivalence ratio at flashback increases regularly with ammonia addition up to $\chi_{NH_3} = 0.50$, where a transition happens: here, even for equivalence ratio greater than unity, the flame is not fast enough to flashback. Thus, for higher ammonia fuel fractions, the flame extinction is due only to rich or lean blowout and the stability region enlarges.

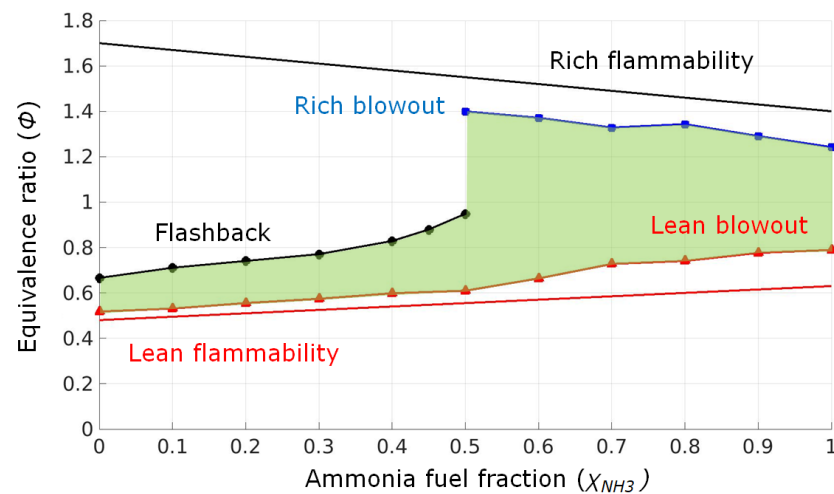


Figure 1. Stability limits of ammonia–methane–air swirl flames as a function of the ammonia fuel fraction (geometric swirl number $S_g = 1.00$ and $Re = 5000$), (adapted with permission from [23]. 2020, Elsevier).

Measurements of NO concentration in the exhausts show that reasonably low NO concentrations (<100 ppm) can only be found for stoichiometric or rich equivalence ratios. Under these conditions, for a fixed equivalence ratio, ammonia addition lowers NO concentrations. Under lean conditions, NO emissions exceed the limits imposed by current regulations by at least one order of magnitude (see Figure 2). As already mentioned, this is due to the fuel pathways of formation of NO different from thermal pathways. From a technological standpoint, this means that burners operating in lean premixed conditions with ammonia–methane flame that satisfy current regulations on NO emissions are far from feasible and that a two-stage combustion process is required to ensure globally lean operation and to avoid harmful unburned NH_3 emissions. Moreover, the blending of methane and ammonia can lead to the formation of hydrogen cyanide (HCN), which is a key point to be investigated.

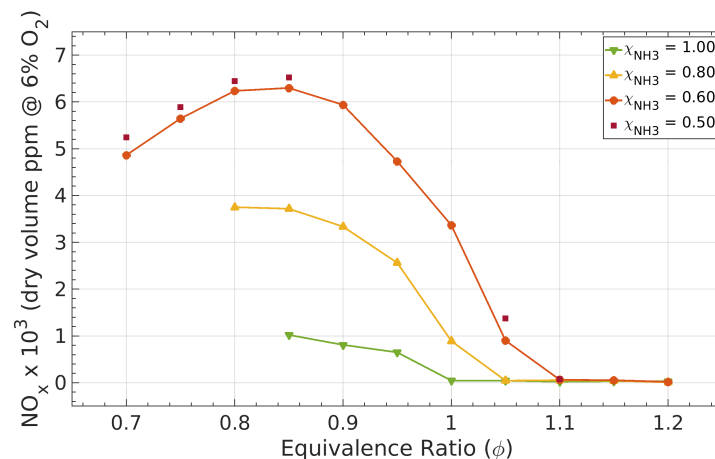


Figure 2. Measured exhaust NO concentration in parts per million (ppm) as a function of equivalence ratio (adapted with permission from [23]. 2020, Elsevier).

The issue related to the low reactivity of ammonia can be mitigated by blending with a more reactive fuel such as hydrogen. Recent studies [24,25] showed that ammonia–hydrogen flames can be stabilized and that broader stable range compared to pure hydrogen or ammonia can be achieved. Furthermore, due to the high reactivity of hydrogen, ammonia–hydrogen–air combustion can be operated at lean conditions with competitive

NO emissions (few hundreds of ppm or less). For these reasons, lean ammonia–hydrogen–air blends are promising candidates for gas turbines since elevated pressure is expected to reduce NO emissions even further. The main limitation of lean ammonia–hydrogen–air flames is the elevated production of N₂O under certain operating conditions [26]. N₂O is a dangerous greenhouse gas, around 250 times more effective than CO₂, and thus, it could potentially cancel the benefits associated with a carbon-free combustion. It is clear that some trade-off between NO and N₂O emissions exist and this topic is receiving a great amount of attention. Recently, stability limits and exhaust NO emissions of premixed ammonia–hydrogen–air swirled flames were measured in a laboratory-scale burner for a wide range of pressure, up to 5 bar [27]. The full range of ammonia fractions in the fuel was investigated. Stability limits were found to have a similar trend to methane–ammonia flames, but equivalence ratios at lean blowout and flashback are smaller for ammonia–hydrogen flames, resulting in a narrower zone of stability for lean conditions. Furthermore, the critical ammonia fuel fraction for which transition from flashback to rich blowout happens is larger for ammonia–hydrogen blends. It must be noted that for hydrogen fraction above 10 %, flames can be stabilized for equivalence ratio even smaller than $\phi = 0.6$ in this burner. This lean condition is competitive in terms of NO emissions (between 100 and 160 ppm). Unfortunately, N₂O emissions may become unacceptably large if the flame is operated with a low equivalence ratio.

As already stated, ammonia could be used as an hydrogen carrier, exploiting its vast infrastructure system to transport hydrogen from the production plant to the location of use. Here, ammonia must be partially dissociated (the process is also referred as cracking) resulting in a blend including nitrogen in addition to hydrogen, with a 3:1 nitrogen to hydrogen volume ratio. The stability limits of this blend show similar trends of ammonia–hydrogen blends [25].

Ammonia has been identified as a sustainable fuel for gas turbines and a potential enabler of the hydrogen economy. Research about the use of ammonia for large power generation is still ongoing—in particular, on the ill-defined kinetic processes that occur at high power outputs using various blends of ammonia with gases such as methane and hydrogen. Use of ammonia in propulsion system is receiving increasing interest. The potential of methane–ammonia–oxygen blends to allow deflagration to detonation transition and its applicability in propulsion system, has been discussed [28,29]. Results showed that flame speeds were modest for all mixtures where the oxygen percentage was 39% or less. Microthrusters for propulsion of small space vehicles, fueled with ammonia and acetylene have been studied and developed in Russia, China, and USA [30,31]. Although the technology is promising, literature on micropropulsion systems using ammonia as a fuel is still scarce, opening the possibilities for further research.

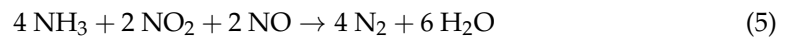
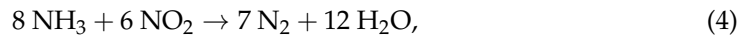
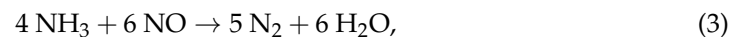
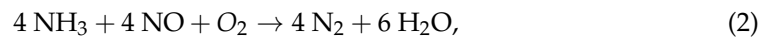
2.4. Emulsions

Fuel emulsions have been proposed to significantly improve the atomization of the liquid fuel and enhance the combustion process. Water has been first used with fuels. The main idea behind this concept is promoting the complete combustion. Indeed, microexplosions of water particles involve splitting of fuel droplets that contain them. This significantly enhances the air/fuel mixture in combination with the reduction of the local temperatures due to the high specific heat and latent heat of vaporization of water [32–34].

Recent works are focusing on the use of urea instead of water with the aim to produce ammonia during the combustion [35,36], as highlighted by the overall decomposition in Equation (1).



The ammonia production is the key factor of this idea because it acts as a reducing agent for NO_x. The reaction of ammonia, NO, and oxygen carries out the formation of nitrogen and water vapor, as explained by Equations (2)–(5).



Actually, neither urea nor water/urea emulsified fuels contamination have been applied yet to aeroengines as combustion control technique. Potential drawbacks are represented by stability of emulsions, the cold-start problem and corrosion, and the risk of ice, which can be overcome using surfactants, especially nonionic surfactants. Moreover, the lean flame stabilization with the extension of the lower flammability limit, coupled with the emissions reduction without significant efficiency penalty, is still worth of further investigation [35].

3. Combustion Techniques

Currently, 80% of the energy in the world is produced by combustion, but the world population rises and its related energy demand does not match with the new emissions regulations emanated to avoid the climate change. For this reason, in the last decades new technical solutions have been developed to burn fuels more efficiently, reducing fuel consumption and pollution, and to improve their fuel flexibility. Further investments are required to apply old and new promising technologies, thus triggering the transitions toward a zero-carbon power production, propulsion, and mobility.

3.1. MILD

In 1989, Wüning discovered during his experimental tests with a self-recuperative burner that a “flameless” combustion could be obtained since it does not occur on a flame front but rather on the entire volume of the combustion chamber. This combustion technique has been called MILD combustion, which means moderate or intense low-oxygen dilution. Its working principle is to preheat the reactants by the hot flue gas (rich in N_2 and CO_2) at a temperature higher than the autoignition temperature of the fuel and to work with low oxygen concentration (3–13%). In Figure 3, the operating field of the MILD combustion is represented. This kind of combustion has many benefits: the production of smooth temperature distributions, flame stability, high efficiency, and low NO_x and CO emissions [37].

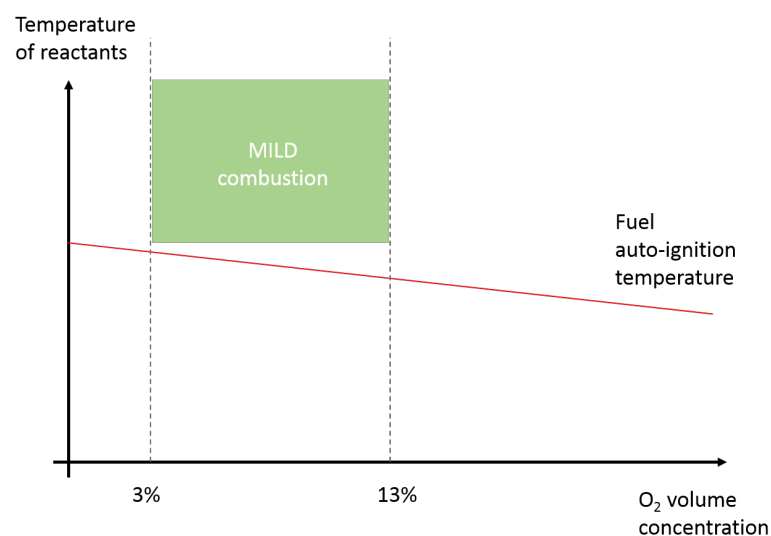


Figure 3. Scheme of the operating range for a MILD combustion.

The MILD combustion can not be ascribable to the standard flame structures: deflagration and diffusive flames, which indeed are related to a “diffusion ignition”. The preheating by itself increases the unburnt gases temperature, thus increasing the adiabatic flame temperature and the NO_x production. Operating above the self-ignition temperature with diluted products, the maximum temperature of the combustion is reduced, and, therefore a more uniform temperature distribution is reached allowing the reduction of energy consumption.

This combustion technique seems to be a good candidate to replace conventional gas turbine combustors due to low maximum temperature (reducing costs and complexity of the turbine design), noiseless characteristic (preventing humming), flame stability, and low pollution. Anyway, few works can be found in the literature on MILD combustion for gas turbine (GT) application because of the characteristic time related to the autoignition delay time and the complexity of the preheating systems. Indeed, the chemical and turbulence scales have the same characteristic times (Damköhler number close to 1). The Lean Azimuthal Flame (LEAF) project is one of recent works on MILD combustion, and it will be discussed in detail in Section 4.2. The application of MILD combustion with a regenerator that works on the exhaust gases can increase the combustion efficiency of 30% and reduce the emissions of 50%. Moreover, the radiant heat transfer is increased.

New advances demonstrate that the preheating of the air is no longer needed, since the air is heated by the inner recirculation inside the combustion chamber and the oxygen diluted as well. Furthermore, open furnaces can be a valuable alternative in industrial applications. The main challenge for open furnaces is the air preheating system. In this case, a closed exhaust gas recirculation (EGR) chamber is needed [38].

3.2. RQL

The RQL burner concept, which stands for rich-burn quick-mix lean-burn, was introduced in 1980. It was developed for aviation propulsion due to its inherent safety compared to lean combustion systems, which were more susceptible of instabilities. Following the fluid flow from the inlet to the outlet of the burner (Figure 4), the RQL works as follows: primarily, a rich combustion is produced in the primary zone (since its high efficiency); then, the first products, containing intermediate compound of the combustion and some important pollutants, such as carbon monoxide (CO), are quickly mixed with air in order to create a lean mixture. In the end, a lean combustion will occur before the exit. In this way, the NO_x production is contained since in the primary rich zone the level of oxygen is really low [39], and afterward, in the lean region, the temperature are low enough to avoid NO_x formation.

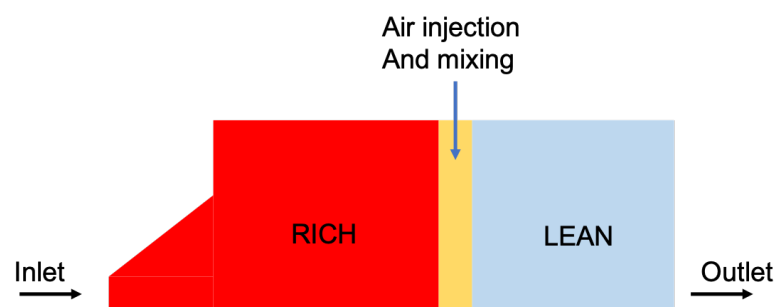


Figure 4. Mimic of a RQL burner; in red, the rich combustion zone, in yellow, the small part in which the air is efficiently mixed with the products and in light blue the final stage with a lean combustion.

This combustion technique focuses on the NO_x abatement. Indeed, the rich combustion in the primary zone produces an efficient combustion with stable flame and high share of NO_x , ever lower than those produced at the stoichiometric condition; on the other hand, the gases are rich in intermediate composites. After that, a quick injection of air

does not produce other NO_x ; eventually, a lean combustion to complete the oxidation of intermediates and fuel in excess is preformed, with a small addition of NO_x .

For most of the last decades, the mixing process between air and the products of the rich combustion has been widely investigated (wall-jet injection) as it represents the core component of this system [40].

3.3. Pressure Gain Combustion

Gas turbines are one of the main means of propulsion and energy production. One of the most studied topics, with a view to decarbonization, is the increase of their thermodynamics efficiencies. Gas turbine cycle (GTC) is based on the Joule–Bryton cycle and its efficiency is largely driven by pressure ratio, β , and turbine inlet temperature (TIT). Present state of the art is TIT = 1600 °C with cycle pressure ratio $\beta \sim 23$. New technologies are being developed to increase TIT by means of new materials and cooling techniques. An alternative path is to act on the stage where most of the irreversibility of the Brayton cycle arises, i.e., during the isobaric heat addition phase.

Pressure gain combustion (PGC) utilizes multiple physical phenomena to increase the effective pressure across the combustor while consuming the same amount of fuel in a standard constant pressure combustor. This results in a lower production of entropy during combustion for the same turbine inlet temperature and thus, a more efficient thermodynamic cycle. The methodology is based on the Humphrey (or Atkinson) cycle (see Figure 5), and it has been identified as a promising technique to achieve higher efficiencies in gas turbine power systems [41].

In general, any set up of processes/engine configurations that increases total pressure as part of combustion process within fixed volume combustor are termed pressure gain combustions. Among these, the most promising techniques are pulse detonation engine (PDE), rotating detonation engine (RDE), and wave rotor combustor (WRC).

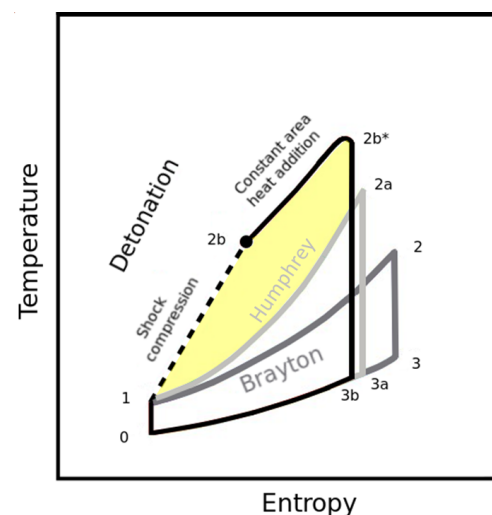


Figure 5. T-s diagram for the ideal PDE, Brayton, and Humphrey cycles.

3.3.1. Pulse Detonation Engine (PDE)

Pulse detonation engines could represent a groundbreaking propulsion technology that can provide several advantages in terms of reliability, functioning, and system simplicity [42]. PDE utilizes an induced detonation (i.e., supersonic) wave instead of a deflagration wave during the combustion. The supersonic combustion wave shortens combustion period in order to perform a nearly constant volume exothermic process. A basic PDE consist in a shock tube closed at one end and open to atmospheric conditions at the other end, a delivery system for the fuel–oxidant mixture, and a device to trigger the detonation wave. The PDE process consists of several phases based on the Humphrey cycle (see Figure 6). First, the fuel/air mixture enters the shock tube. The detonation is triggered

either directly or through a transition from deflagration to detonation. The detonation wave propagates through the chamber and compresses the mixture ahead of it. This compression is followed by constant volume combustion [43]. High values of temperature and pressure are reached with the aim to generate the thrust. The detonation wave travels the shock tube and when it reaches the open end, the pressure decreases due to the increase of flow momentum [44]. This phenomenon is followed by an expansion wave that travels back through the shock tube, and its reflection at the left end of the combustion chamber causes the needed pressure drop that allows the injection of fresh reactant, hence the restart of the cycle. In addition to a better thermodynamic efficiency, PDEs are capable to provide higher energy heat release and propulsive thrust compared to a traditional turbo-jet engine [45–47]. Furthermore, since the compression and expansion phases take place entirely into the shock tube, compressor and turbine are not necessary, leading to a more compact, lighter, and cheaper engine. PDEs are noisy [46] and are usually run with liquid fuels (that are bulkier [48]) and oxygen that must be generated on board or carried in tanks, adding weight to the vehicle [49]. PDEs performance at low speeds is poor in terms of thrust and specific fuel consumption [50] and, most of all, the detonation combustion is an unsteady process that generates intermittent thrust (at a few hundred Hz of frequency) that causes mechanical problems associated to structural integrity such as vibration, acoustics, high stress, and fatigue [51]. Recently, pulse detonation engines have received interest from researchers. For instance, Debnath et al. [52] studied by means of LES simulations the effect of different half angles of the ejector on detonation combustion wave propagation for liquid kerosene and gaseous hydrogen–air mixture. Investigations on the feasibility of pulse detonation combustion with alternative and carbon-free fuels [43,53] and on NO_x reduction methods [54,55] have been conducted by several research groups.

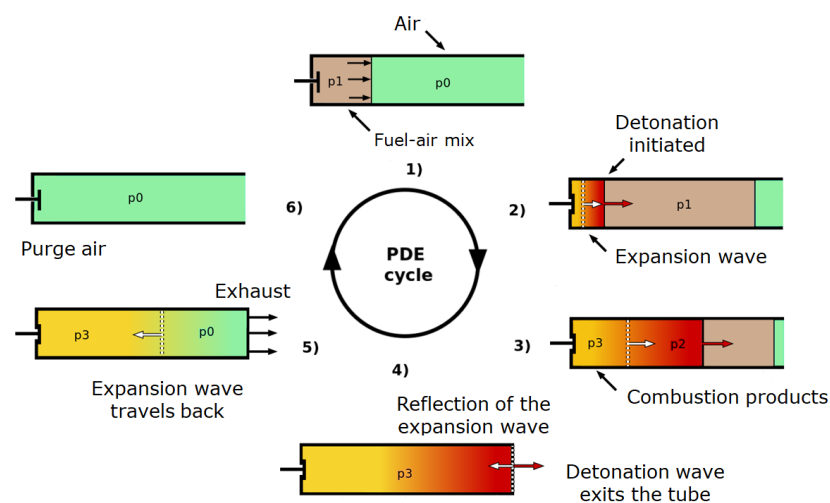


Figure 6. Mimic of Pressure Detonation Engine Cycle.

3.3.2. Rotating Detonation Engine (RDE)

Rotating detonation engines (RDE) use controlled detonation waves traveling tangentially around an annular channel. The wave is sustained by a continuous injection of fresh reactants in the axial direction. In contrast to PDEs, such concept allows operation at kHz frequencies, and it does not require complex hardware implementations (e.g., valves) nor a cyclic start of the detonation wave [56]. Furthermore, since it can be integrated in a traditional turbogas unit, the RDE concept has received increasing attentions in the last years. The detonation wave is generated by the coupling of a leading shock and chemical reactions, and it travels tangentially into the combustion chamber, preceded by an oblique shock wave. Fresh combustion products (produced by the last detonation front) are separated from those produced by the preceding detonation fronts by a slip-line. The detonation front leaves behind a high pressure zone that prevents fuel

injection. Away from the detonation front, a Prandtl–Meyer expansion accelerates the flow. This involves a pressure reduction to the injection conditions (for details, refer to figures in [57,58]). In this zone, the fresh mixture of reactants can refill the chamber and the cycle starts again [57]. The combustion products are ejected along the exit of the combustor at relatively high speeds to provide thrust. The rotating detonation engine operates on nonstationary conditions: at a given instant, each stream line is in a different point of compression process. Several fuels have been investigated in different engines, but up to now, the most promising seems to be the H_2 /air mixture thanks to the high flame speed of hydrogen, which makes this mixture easy to detonate [59]. Due to the high complexity of the physics behind detonation combustion, the fundamental understanding of this phenomenon has been rather curtailed. Nevertheless, RDEs are being studied due to their promising performances in terms of NO_x emissions. An experimental analysis of a flow-through hollow water-cooled RDE fueled by a hydrogen–air mixture was performed for 30 s in order to measure NO_x emissions at a fixed operating point [60]. Maximum NO_x production was observed close to the combustor walls, while near and across the central axis the concentrations of NO_x were negligible. These results were coherent with the engine design that produces a flow characterized by a cold and almost nonreacting core and a high temperature region near the combustor walls [61,62]. Across the several test cases analyzed, the average NO_x measured in the combustion chamber have been attested around 35 ppm by volume. Schwer and Kailasanath [63] used a H_2/O_2 kinetic mechanism with NO_x chemistry to study the combustion across RDE in order to calculate two-dimensional emissions profile and to determine which parameters have the highest influence on it. Equivalence ratio has been identified as the most influential parameter: a decrease from stoichiometric condition to 0.6 leads to a reduction of NO_x emission from 500 to 20 ppm. Feed pressure and RDE length were found to be a negligible factor for the NO_x production.

3.3.3. Wave Rotor Combustors (WRC)

Wave rotor combustors (WRC) implement the combustion process in the rotor channels (“on-rotor” combustion). Indeed, they consist of multiple axial channels placed circumferentially around a rotating drum. The rotation of the drum periodically connects the axial channel to the inlet and outlet ports. The sudden opening and closing of the intake ports produces, respectively, compression and expansion waves that travel into the channels of the engine [64]. For more details, the reader is invited to refer to the work of Nalim and Paxson [65]. In WRC, the pressure increase across the channels is achieved thanks to a combination of the pressure wave phenomenon and confined combustion. These devices were initially developed as simple dynamic pressure exchangers for gas turbines, used to increase the turbine inlet pressure to produce a larger net pressure drop while maintaining steady operations at elevated pressure of the combustor.

Premixed fuel–air mixture enters the channel, and it is ignited after a precompression by the shock wave, in order to obtain a deflagration for easier integration with turbo-machinery. Combustion is triggered in all channels by continuously firing stationary igniters at one of the end-plates. Combustion happens at a nearly constant-volume condition since both end of the channel are closed after the recharge phase. Therefore, combustion products are discharged through the opening of the seal plate to the manifold [66]. Unlike PDE and RDE, WRCs can operate at nearly stationary conditions (except for the combustion chambers) due to the considerable number of channels receiving and discharging continuously flow during the rotation. Furthermore, the lack of valves makes the filling/purging phase almost lossless. Additionally, WRCs do not require a detonation process to achieve a pressure gain if combustion is fast enough [67]. Recently, several works on the feasibility, design, and thermodynamic analysis of the combustion cycle of WRCs have been performed [68,69]. Design and experimental testing of a WRC achieved stable operations at near-atmospheric inlet conditions over a wide range of overall equivalence ratios [70]. Experimental data showed that for high equivalence ratios in the fuelled com-

bustion region, the combustion was found to be more stable. A lack of backfire during the test as been observed, indicating the excellent isolation of combustion from premixed filling provided by this design. Results showed the viability of this concept for building a pressure-gain combustor and its applicability for the design of future turbine engines. Li et al. [71] performed an analysis on a simplified test system of WRC to understand how the pressure rise depends on parameters such as the filling speed of reactants mixture, equivalence ratio, and rotating speed of the inlet/outlet ports. Authors found that an increase of the rotating speed causes a significant increase of the peak pressure and a narrowing of the operating range of equivalence ratio.

3.4. Steam Injection

Steam injection in gas turbines is a concept that dates back to the beginning of the twentieth century. The basic idea behind this technique is that the injection of steam (or water) downstream of the compressor increases the mass flow rate through the turbine, and thus the specific power output since the work done by the compressor remains constant and the work done to compress the water is negligible compared to the work done to compress the gas. The hot exhaust gases are used to preheat water and generate steam that can be used for both steam injection and turbine blade cooling. Apart from increased specific power output and cycle efficiency, steam injection causes a more homogeneous temperature distribution during the combustion, which reduces NO_x formation. Some authors stated that a combustion with 20% (by weight) of water vapor can lead to a reduction of NO_x formation by around 80% at temperatures that are typical for aircraft engine operations [72]. Recently, MTU Aero Engines presented a novel concept of a steam injection turbine cycle [73–75]. The Water-Enhanced Turbofan (WET) engine concept, schematized in Figure 7, offers the potential to reduce or even avoid the formation of contrails. In addition to the steam injection, through a condenser downstream of the steam generator, the water is brought back to its liquid phase and then recovered from the exhaust gas–steam mixture. The condenser is cooled by the air from the propulsion system bypass or from a separated blower. The WET engine concept aims to reduce (or even avoid) NO_x creation and to reduce CO_2 emission by 15%. Even if the concept is in an early stage of research and development, a first estimate of the effects based on preliminary design studies suggests that, if sustainable aviation fuels or hydrogen are used, the operation of an aircraft equipped with WET engine(s) could be almost near to climate neutrality [76].

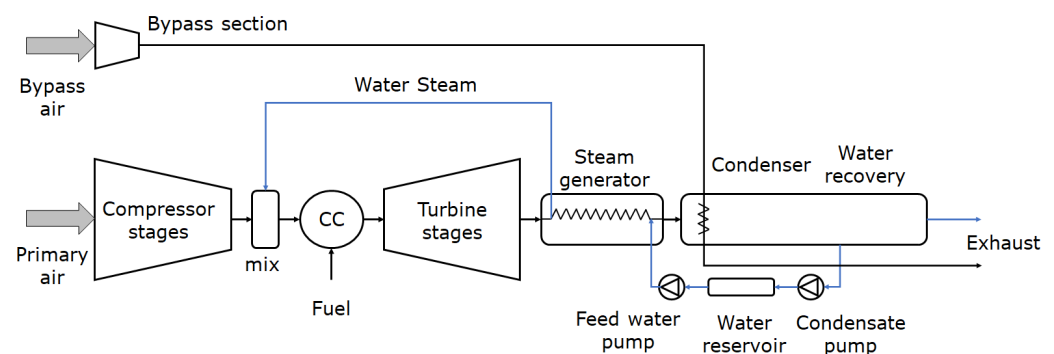


Figure 7. Schematic of the Water-Enhanced Turbofan (WET).

4. Burners

The rising request of renewable energy power plants with the storage of exceeded energy as hydrogen and the proposition of new kinds of fuels to balance the CO_2 production point out the necessity of wide range of fuel flexibility for the new generation of burners. Indeed, these new fuels are characterized by physical properties far from the conventional fossil fuels. For this reason, the standard dry low emissions or dry low NO_x technology cannot be used in the exact same manner. In the following section, the recent novelties in terms of industrial and lab-scale burners will be presented.

4.1. Micro-Mixer

In the last decade, Kawasaki Heavy Industries LTD together with Aachen University of Applied Sciences have numerically and experimentally tested a new burner concept to burn pure hydrogen. The micromix (MMX) combustor proved to be able to burn hydrogen with air by keeping a low level of NO_x .

The fuel is injected from microholes in a crossflow air and microdiffusion flames are generated (see Figure 8). Thus, an enhanced mixing and a decreased residence time of the reactant in the hot zone are fulfilled. This allows to mitigate the NO_x emissions (the only pollutant in a hydrogen–air mixture combustion), which are usually high for diffusion flame compared to premixed ones. Furthermore, the generation of diffusion flames avoids flame instability problems. The burner has been designed to achieve partial loads; hence, each ring can be switched on and off depending on the thermal power required by the system (see Figure 8) [77].

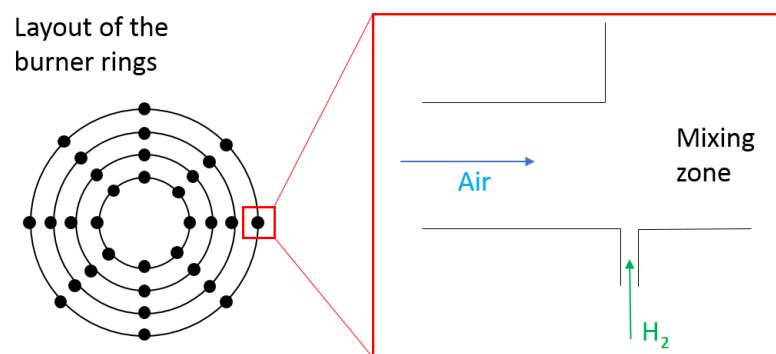


Figure 8. Schematic of the micromix burner. On the left, the front view with the rings, and on the right, a sketch of the air and fuel ducts and the mixing zone.

4.2. LEAF (Lean Azimuthal Flame)

The new burner developed by researchers at Cambridge University [78] is a MILD burner. It is characterized by specific azimuthal fuel injection and an opposite air flow injection, which both emphasize the dilution of the fresh air and fuel with the hot gases (for more details, the reader is invited to refer to the work of Oliveira et al. [78]). This particular burner was demonstrated to work with both methane and kerosene spray with a single digit CO and NO_x production.

Since burning liquid fuels introduces a further complication due to evaporation, the burner is characterized by an intense mixing. The air enters the combustion chamber by three ways: two tangential ports, one core swirled flow and at the last from tangential ports on the top. The fuel is introduced tangentially in an air cross-flow. These different flow managements allow the user to optimally control and stabilize the reaction.

4.3. PRECCINSTA

In order to achieve high cycle efficiency, gas turbines are required to operate at high firing temperature and operating pressure. However, higher firing temperature leads to high temperature peaks that enhance the production of thermal- NO_x . One of the most simple and efficient technique used to obtain a lower and more uniform temperature, and thus reduce NO_x emissions, is lean premixed combustion. However, lean premixed combustion is prone to combustion-induced instabilities such as thermoacoustic pressure oscillation, unsteady stabilization, and even flame extinction [79]. Thermoacoustic instabilities narrows the operational range of the gas turbine, preventing further reduction of NO_x emissions. In order to address the issues related to thermoacoustic instabilities in the gas turbine burner, the “Prediction and Control of Combustion Instabilities in Industrial Gas Turbines” project (abbreviated to “PRECCINSTA”) was set up by a consortium of gas turbine manufacturers and research centers [80]. Thermoacoustic instabilities, in a

premixed swirl stabilized gas turbine combustor derived from an industrial design by Turbomeca, have been investigated both experimentally and numerically.

The air enters the plenum through a 25 mm diameter inlet section and then passes into the swirler, composed by 12 radial vanes. The fuel is injected through 1 mm orifices in the swirl vanes. Here, the fuel–air premixing takes place and the flow enters the combustion chamber through a burner nozzle with an exit diameter of $D = 27.85$ mm and a conical inner bluff body. The combustion chamber has a squared cross-section of 85×85 mm² and a height of 114 mm and ends with a conical surface followed by an exhaust duct with 40 mm inner diameter (see Figure 9).

Experimental and numerical unsteady acoustic analysis of the cold flow showed the existence of two acoustic modes: a mode around 360 Hz present everywhere in the burner and a 540 Hz hydrodynamic mode caused by a precessing vortex core (PVC) localized near the burner inlet. Results showed that the combustion damps the hydrodynamic mode and enhances the acoustic level of all modes [81,82].

Recently, the effects of hydrogen enrichment on the dynamics of the flame (heat release distribution, combustion instability characteristics, and flow dynamics) for varying conditions of pressure and H₂ volume fractions (up to 50%) were studied experimentally [83,84]. Results showed that hydrogen enrichment leads to a shortening of the flame length and causes the transition from an M-shaped to a V-shaped flame.

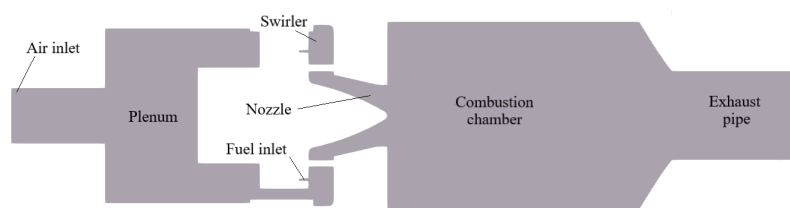


Figure 9. 2D section of the PRECCINSTA burner.

4.4. TUB Swirled Stabilized Burner

In the last decade, the Technical University of Berlin (TUB) developed a new swirled stabilized burner. Lean premixed combustion is a well-established solution to burn fuel efficiently. Nevertheless, the burners that work with lean mixtures are prone to lean blowout and flashback. To avoid flashback, the TUB developed a swirled stabilized burner with a fresh air splitting system, which conveys part of the flow rate in an axial duct (orifice) and the rest through the swirler, (for details, the reader is invited to refer to the work of Reichel et al. [85]). Moreover, the fuel is injected through small axial ducts. Experiments and numerical simulations demonstrated that when burning hydrogen, the axial momentum due to the low density of the fuel controls the axial position of the centred recirculation zone. Thus, choosing opportunely the size of the orifice, the flashback can be neutralized in the range of the equivalence ratio ($\phi = 0.2$ – 1) independently on the air mass flow rate [85].

5. Discussion and Conclusions

The effects of climate change have revealed the necessity to change the direction of the energy production and its dispatching. Transportation and energy production sectors are the main responsible of greenhouse gas emission production; thus, a quick action of the government supported by academia and industry is required to contrast the critical effects on our planet. Moreover, the rising of the world population and the increase in energy demand open a discussion on energy management and consumption. Indeed, 80% of the energy produced in the world is still based on combustion of fossil fuels; hence, new strategies that are greener and safer are needed. The transportation sector is responsible for 15% of global greenhouse gas production, and the aviation sector, with its emissions at high altitude, demonstrates to be even more dangerous for the planet. In this framework, new advances in the field of combustion have been carried out in recent years. The analysis

of the fuel framework suggests the use of sustainable aviation fuels (SAFs) as a valuable solution to balance GHG production during the transition to either zero carbon fuels or electric propulsion.

After that, the transition to carbon free fuels seems mandatory to reduce the CO₂ emissions in the atmosphere. In terms of combustion strategies, the introduction of new fuels, with physical–chemical properties different from fossil fuels rebrought to light old and new techniques such as MILD and PVC combustion, which are particularly suited to highly reactive fuels such as hydrogen. New fuel mixtures, e.g., methane–hydrogen–ammonia, allow the application of new burner techniques discarded in the past for their inefficiency or elevated NO_x and CO production. Eventually, a fervent production of new burners in collaboration between industry and academia is available. New strategies to contrast flashback for highly reactive flows, the return of microdiffusive flames, and the improved efficiency of the MILD burner are available. The results collected in this review are reassuring, but most of them need to be converted into industrial applications, increasing their TRL (technology readiness level) up to 9.

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Abbreviations

ASTM	American Society of Testing and Materials
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CNG	Compressed natural gas
EU	European Union
GHG	Greenhouse gas
GT	Gas turbine
GTC	Gas turbine cycle
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LFL	Lean flammability limit
MILD	Moderate or Intense Low-oxygen Dilution
PDE	Pulse detonation engine
PGC	Pressure gain combustion
PtL	Power-to-liquid
PVC	Precessing vortex core
RDE	Rotating detonation engine
RFL	Rich flammability limit
RQL	Rich-fuel quick-mix lean-burn
SAF	Sustainable aviation fuel
TIT	Turbine inlet temperature
TRL	Technology readiness level
WRC	Wave rotor combustor

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