



The EU Framework Programme
for Research and Innovation

HORIZON 2020



**Marie Skłodowska-Curie Actions (MSCA)
Innovative Training Networks (ITN)
H2020-MSCA-ITN-2019**

861079 – NextMGT

**(Next Generation of Micro Gas Turbines for High Efficiency,
Low Emissions and Fuel Flexibility)**

**A review report on fuel flexibility and
emissions**

**Deliverable No. 17
Relative number 2.2
Public deliverable**

**Date: 20/12/2022
Lead Beneficiary: UCLouvain**



Contents

1. Executive summary.....	3
2. Introduction.....	4
3. Review on Alternative Fuels: Hydrogen, Methane, Ammonia and related NO _x emissions (ESR7) 5	
3. Review on alternative combustion modes (ESR 8).....	14
4. Combustion of low calorific value gases in a SOFC-MGT hybrid concept (ESR 9)	17
5. Conclusions.....	22

1. Executive summary

This deliverable summarizes the work performed within “NextMGT” project until month 36 (December 2022), and more specifically it covers the progress of work package two (WP2) regarding fuel flexibility and emissions of micro-gas turbines. “NextMGT” is a European funded project that focuses on the development of the technical expertise and scientific knowledge which enables a substantial enhancement in understanding the fundamental design and operation aspects of next generation micro-gas turbines towards to a successful commercialisation.

2. Introduction

This deliverable reflects part of the work performed in WP2 and summarised the review work performed by the three ESRs involved in this WP.

3. Review on Alternative Fuels: Hydrogen, Methane, Ammonia and related NO_x emissions (ESR7)

The energy transition to a renewable-based economy involves many technical challenges. Grid balancing and stability as well as energy storage being a few very relevant ones. Therefore, several storage strategies and solutions are currently being developed and investigated. Hydrogen is part of the solutions and can be used as an energy storage medium as well as a fuel for various end-use applications in stationary generation of electricity & heat and in the transportation sector. Hydrogen is also needed for the synthesis of other H-containing species, such as methane (CH₄), methanol (CH₃OH), ammonia (NH₃), which exhibit some superior characteristics as energy carriers and fuels compared to hydrogen.

Alternative fuel: hydrogen

Hydrogen is the simplest and most abundant element in the universe; it is colorless, odorless, tasteless and non-toxic for human health. On earth, hydrogen is found as a free element in small quantities (less than 1 ppm), but it is mostly found in compounds with other elements, for example that is the case for water. Hydrogen can be produced via water electrolysis, in this process electricity is used to split the water molecule into its constituents, hydrogen and oxygen.

Hydrogen offers an alternative to conventional hydrocarbon fuels, especially in a scenario where excess renewable electricity is used to produce it (via electrolysis). The hydrogen molecule can then act as a storage medium (energy vector) and it can be utilized when needed. One of the options to convert back the chemically bounded energy into electricity, heat, or mechanical power, is to burn hydrogen in a gas turbine or in other prime movers. Hydrogen is currently being researched as a fuel additive for many applications as well as a stand-alone fuel [1,2,3,4,5].

Property	Hydrogen	Methane
Specific gravity at NTP ¹	0.07	0.55
Lower calorific value by mass (MJ/kg)	119.93	50.02
Lower calorific value by volume at NTP (MJ/m ³)	10.05	33.36
Flammability limits in air (by volume)	4 to 75	5.3 to 15
Minimum ignition energy in air (mJ)	0.02	0.29
Autoignition temperature (K)	858	813
Maximum adiabatic flame Temperature in air at NTP ^{1,2} (K)	2376	2223
Maximum laminar flame speed in air at NTP ^{1,2} (cm/s)	306	37.6
Thermal diffusivity at NTP ^{1,2} (mm ² /s)	153.26	23.69
Momentum diffusivity at NTP ^{1,2} (mm ² /s)	105.77	16.81
Mass diffusivity in air at NTP ^{1,2} (mm ² /s)	78.79	23.98

Table 1 Thermophysical and chemical properties of hydrogen and methane [6]. Properties have been computed with Cantera [7] using the GRI-Mech 3.0.

Table 1 shows some important chemical and thermophysical properties of hydrogen. In comparison to other conventional hydrocarbon fuels, hydrogen is characterized by extremely high gravimetric energy density and extremely low density and volumetric energy density. For these reasons, hydrogen storage and transportation are really challenging and, for any practical applications, hydrogen needs to be either compressed or liquefied.

Hydrogen liquefaction requires reaching extremely low temperatures, around 22K at atmospheric pressure. Consequently, this process requires a significant amount of energy, for conventional liquefaction processes, about one third of hydrogen lower heating value is required. Under elevated pressures and temperatures, hydrogen causes severe mild steel decarburization and embrittlement (hydrogen has very high diffusivity), posing a challenge on the materials selected for the design of

storage vessels. Additionally, hydrogen has high propensity to leakages, because of its small molecular weight and low viscosity. For the complexity of the challenges posed by hydrogen and the relatively recent interest into its adoption on a large scale, the development of hydrogen storage and transportation infrastructure are still at an early stage [8].

When it comes to hydrogen combustion fundamental properties, hydrogen is characterized by high laminar burning velocity, adiabatic flame temperature, low minimum ignition energy and very wide flammability range (equivalence ratios from 0.1 and 7.1 [9]). At stoichiometric and ambient conditions, hydrogen-air laminar flame speed is greater than 2.5 m/s, reaching its maximum value at an equivalence ratio of about 1.8 [10]. Because of fast chemical kinetics and high diffusivity, hydrogen flame speed is much higher than the other commonly used hydrocarbon fuels. For these reasons, hydrogen shows high propensity to flashback and its adoption in conventional gas turbine combustors is extremely challenging. Flashback represents a critical safety hazard to the hardware components of a gas turbine combustor. Flashback occurs when the conditions allow the flame to move upstream, from the designed anchoring position to other regions, which cannot withstand such high temperatures. This phenomenon leads to overheating and damages to important hardware components of the engine.

For what concerns NO_x emissions, only gas turbines equipped with diffusion flame combustors are currently capable of operating with pure hydrogen. In these applications, the NO_x emissions are about three times higher than when natural gas is used [11]. NO_x emissions have also been measured in a gas turbine running with premixed flame combustor technology [12]. In this work, stable engine operations in fully premixed mode (no piloting) were considered. The results ranged from 5ppm to 17ppm (corrected for 15%O₂ and dry conditions), at equivalence ratios varying from 0.25 to 0.34. According to their numerical simulations, only a limited amount of NO_x were produced through the Zeldovich mechanism (about 20%), which is highly dependent on temperature. The majority of NO_x production was attributed to the NNH mechanism. These findings would imply that further reduction of adiabatic flame temperature could not be employed as a strategy for NO_x emissions reduction (as it is normally possible to do for hydrocarbon fuels).

In summary, before hydrogen will be a viable alternative to conventional fossil fuels, many challenges have to be addressed. Both for what concerns achieving safe and low emissions combustion of hydrogen, as well as, if not especially, developing large scale storage and mature network infrastructure for hydrogen distribution.

Alternative fuel: methane/hydrogen

Ramping up H₂ production from renewable energy and developing the necessary infrastructure will take several years (decades), therefore transition scenarios, like admixing gradually increasing amounts of hydrogen into existing transportation & distribution pipeline networks for natural gas (NG), will play an important role. Unfortunately, as shown in Figure 1, it will take a large hydrogen volumetric ratio to reduce significantly the carbon footprint of the energy produced. For example, to halve carbon dioxide emissions hydrogen content in the fuel mixture should be around 80%.vol in the fuel mixture.

For what concerns fundamental combustion characteristics, hydrogen-methane behavior is strongly related to the hydrogen concentration in the fuel mixture. In particular, laminar flame speed change with hydrogen addition to the hydrogen-methane fuel mixture indicates the change in chemical kinetic effects. Figure 2 shows laminar flame speed as function of hydrogen content for various equivalence ratios.

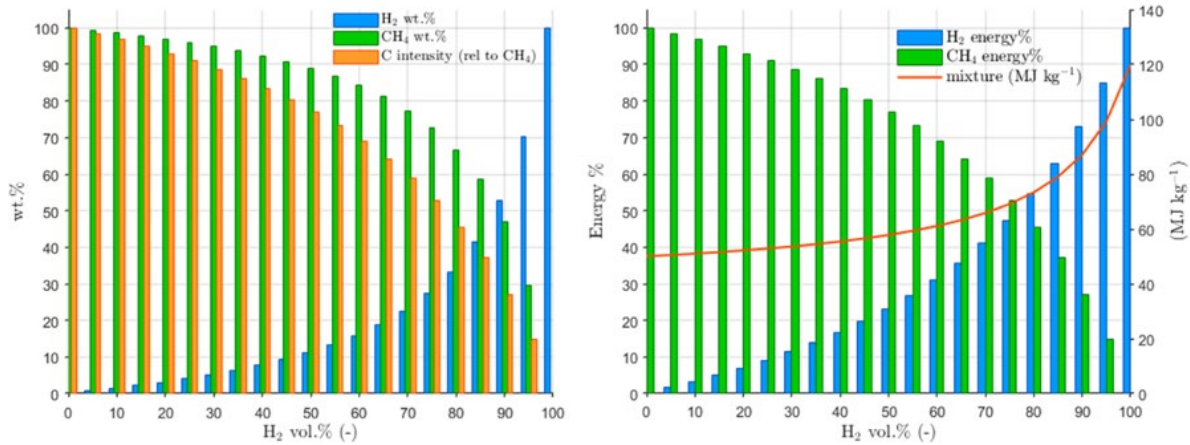


Figure 1. Energy content and C-footprint for CH₄/H₂ mixtures

The simulations have been carried out in Cantera [7] using the AramcoMech1.3 chemical kinetics mechanism [13] at a combustor inlet temperature of 673 K and a pressure of 5 bar. For low to medium hydrogen content, laminar flame speed increases weakly in an almost linear fashion. As hydrogen content in the fuel mixture is increased, the laminar flame speed grows exponentially

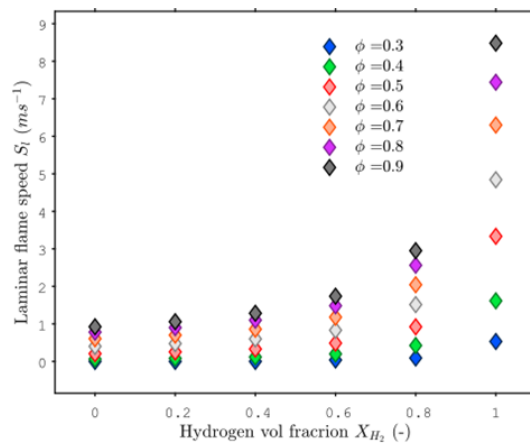


Figure 2: pressure 5 bar, preheating temperature 400 C, AramcoMech 1.3 [13], Cantera[7]

The larger the equivalence ratio, the more severe the exponential growth is going to be. Fundamental chemical kinetics simulations are extremely valuable, nevertheless, they neglect several important parameters that are relevant in real applications. The turbulent flame speed is an experimentally derived quantity that can give us a better understanding of the fuel-air mixture reactivity in a real gas turbine combustor. In Figure 3, we see that the turbulent flame speed behavior as a function of hydrogen concentration. Additionally, Figure 3 also includes the laminar flame speed calculated at the relevant conditions. The trend of turbulent and laminar flame speed are initially very similar. The leaner the fuel/air mixture is, the longer the linear trend behavior is maintained. However, the turbulent flame speed starts showing a strong non-linear behavior at much lower hydrogen content than the laminar flame speed. This implies that, besides chemical kinetic effects caused by H₂ (and expressed by the change in the laminar flame speed), additional (physical) features of H₂ trigger an accelerated consumption rate of the fuel species.

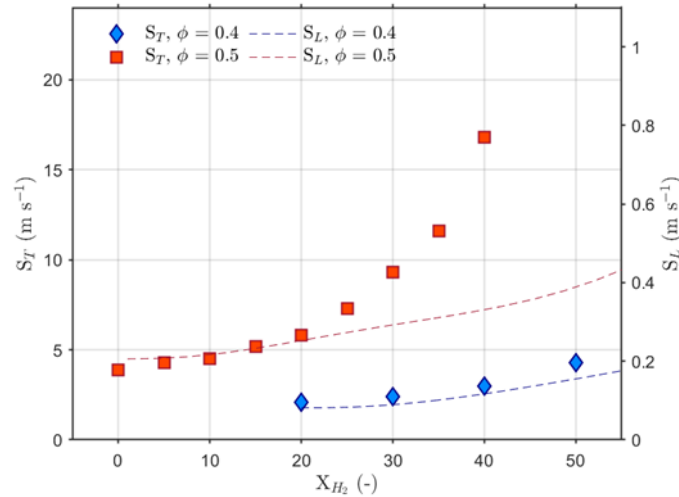


Figure 3. Laminar and turbulent flame speed data for CH₄/ H₂ gas mixtures [14]; laminar flame speed calculated with Cantera [7], using the AramcoMech 1.3 reaction mechanism [13].

For what concerns NO_x emissions, several chemical kinetics calculations have been carried out. From [15], it appears that hydrogen addition to methane leads to an increase of NO_x emissions. However, when the same results are compared in terms of mass per unit energy, the apparent disadvantage of adding hydrogen disappears. In fact, at flame temperatures above about 1750 K, hydrogen additions results to be beneficial.

In other studies [15,16], it was shown that NO_x emissions decrease at elevated pressure and hydrogen content in the fuel mixture. Further development of chemical kinetic modelling schemes and methods, as well as more experimental data, are required to confirm these results.

Alternative fuel: ammonia

Ammonia (NH₃) is a simple molecule consisting of one nitrogen atom and three hydrogen atoms bound to it, making ammonia a carbon-free molecule. Ammonia is highly toxic for human health and for the environment, but high standards and procedures are already in place, due to its wide and long history of application [17]. Indeed, ammonia has already been considered in the past as energy carrier and a possible fuel for prime users [18,19,20]. Only in recent years, it has regained interest as an alternative to hydrocarbon fuels [21,22,23,24,25]. This renewed interest around ammonia is motivated by the necessity to reduce GHG emissions and by ammonia properties, which allow storing it and transporting it in a relatively easy way.

Table 2 shows some of ammonia's important chemical and thermophysical properties, in comparison with hydrogen, methane (which to a large extent represents natural gas) and methanol. In relative terms, ammonia is characterized by low gravimetric energy density and high volumetric energy density. When stored in liquid form, ammonia show superior volumetric density than natural gas, hydrogen and commercial batteries [26]. Liquid ammonia has to be stored at 240K and 1 atm or, alternatively, at around 8-10 atm and ambient temperature [25]. These conditions are easily achievable, especially compared with the ones needed for liquid hydrogen. These features make ammonia very suitable to be transported and stored. Additionally, ammonia's production, storage and transportation infrastructure are already well developed and established. Among other purposes, ammonia is commonly used as fertilizer. In 2018 alone, 180 million metric tons have been produced, transported and stored all around the world [27]. Nonetheless, there are several challenges and issues, which have to be addressed before ammonia could represent a viable fuel alternative to hydrocarbons, especially when considering ammonia's fundamental properties relevant for combustion.

	Methane (CH ₄)	Hydrogen (H ₂)	Methanol (CH ₃ OH)	Ammonia (NH ₃)
Density (kg/m ³)	0.66	0.08	786	0.73
Dynamic viscosity x 10 ⁻⁵ (Pas)	11.0	8.8	594	9.9
Low heating value (MJ/kg)	50.05	120.0	19.92	18.8
Laminar burning velocity (m/s) – close to stoich.	0.38	3.51	0.36	0.07
Minimum ignition energy (mJ)	0.28	0.011	0.14	8.0
Auto-ignition temperature (K)	859	773 - 850	712	930
Octane number	120	-	119	130
Adiabatic flame temperature (with air) (K)	2223	2483	1910	1850
Heat capacity ratio, γ	1.32	1.41	1.2	1.32
Gravimetric hydrogen density (wt%)	25.0	100.0	12.5	17.8

Table 2: Ammonia combustion characteristics and comparison with other fuels, at 300 K and 1 bar [21].

Ammonia is characterized by low adiabatic flame temperature. From gas turbine perspective, a lower flame temperature could allow reducing combustor and turbine cooling system complexity. However, when compared to hydrogen, methane and other hydrocarbons, ammonia also has low laminar burning velocity, high minimum ignition energy and auto-ignition temperature. Its flammability range is pretty narrow (equivalence ratio: 0.63 -1.4), even more than methane's one, which is already considered to be narrow (equivalence ratio: 0.5 -1.7 [9]).

For what concerns NO_x emissions, even though its “low” adiabatic flame temperature to a certain extent limits the NO_x production related to the Zeldovich mechanism, the fuel-bond nitrogen is a significant source of additional NO_x emissions. Interestingly, NO_x production drops drastically at high pressures and rich conditions [28]. However, ammonia's toxicity makes its use in gas turbines under rich conditions, at which not all the fuel is oxidized in the combustor, very complex. Indeed, ammonia slip during operation and transportation has to be prevented.

Because of its poor combustion performance and efficiency [20], pure ammonia is not a great option when employed as a fuel. Blending ammonia with other molecules can however drastically improve its performance [21,29,30,31,32]. One of the most interesting options is blending ammonia with hydrogen.

Ammonia/Hydrogen blends

Blending hydrogen and ammonia allows compensating for the poor combustion performance of ammonia, in particular low laminar flame speed and narrow flammability range, while still benefitting from ammonia volumetric energy density, existing infrastructure and storage network. Tailoring the molar fraction of hydrogen in the ammonia-hydrogen fuel mixture permits to “modulate” fuel mixture reactivity and fundamental properties. An appealing feature of employing hydrogen-ammonia blends is that hydrogen could directly be produced by cracking Ammonia. Ammonia cracking is a highly endothermic catalytic process, which allows ammonia molecule decomposition into hydrogen and nitrogen.

There is some ongoing research to uncover how this process affects combustion [17,19,33]. Combustion behavior of ammonia-hydrogen blends change drastically based on their volumetric fraction in the fuel mixture. Consistently with the expectations, high hydrogen content ammonia-hydrogen mixture behavior resembles closely the one of pure hydrogen and, therefore, is subject to similar issues, such as flashback. On the other hand, when hydrogen content in the fuel mixture is too low, Ammonia's behavior leads to narrow flammability range, low adiabatic flame temperature and flame speed.

Several studies have been carried out to understand the effect of hydrogen addition and of other relevant parameters to gas turbine operations (equivalence ratio, pressure, preheating temperature), on combustion fundamental properties. Laminar flame speed (SL₀) of various ammonia-hydrogen blends, and the effect of pressure, has been measured experimentally [35,36]. The laminar flame speed increases exponentially as the hydrogen content increases, while it decreases with rising pressure levels.

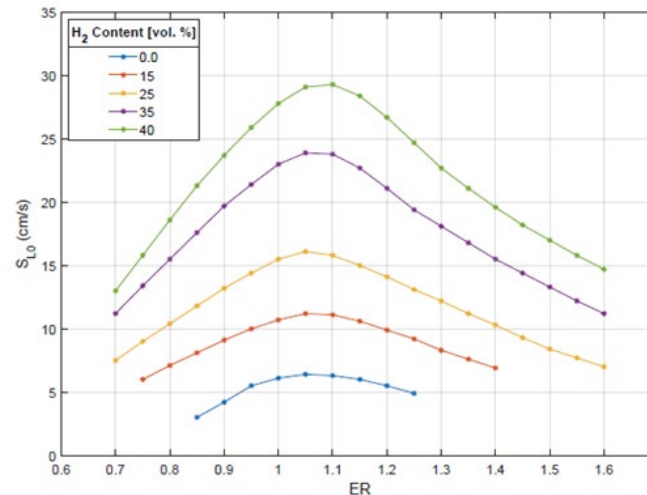


Figure 4: Unstretched laminar flame speed at 1 atm and 25 °C of the combustion of NH₃/H₂ blends with air. [34]

The effect of preheating temperature has also been addressed [37] by measuring laminar flame speed in outwardly propagating spherical flames.

Ignition delay time has also been measured in shock tubes, with pressure reaching up to 70 bar and temperature approaching 2500 K at several equivalence ratios [38,39,40,41,42].

It has been shown that a modest addition of 5% vol hydrogen to the hydrogen-ammonia fuel mixture, leads to an extremely significant reduction of ignition delay time (by a factor 28) [43].

Understanding NO_x emissions of ammonia-hydrogen fuel mixture is a complex task. There are indeed two contrary tendencies. Low hydrogen content in the ammonia-hydrogen mixture will promote the role of the fuel-bound nitrogen in the formation of NO_x. However, on the other hand, high hydrogen content will lead to locally higher adiabatic flame temperatures, which in turn will boost NO_x production via Zeldovich path. To further complicate the picture, one should also remember that, according to work in [12], the role of the Zeldovich path in pure hydrogen flames NO_x formation contributes to “only” 20% of the total NO_x production. Suggesting that the other HNN path would be the most significant for NO_x formation.

Most of the NO_x emissions and formation studies available in the literature are numerical simulations [38,44,45]. One of the limitations affecting these studies is that accurate chemical kinetics mechanisms are necessary to produce meaningful numerical results. A kinetic mechanism consists of thermodynamic and transport properties for all the involved species, as well as rate constant for each of the elementary reaction [46]. Chemical kinetics mechanisms need validation. Typically, experimental data on laminar flame speed, ignition delay time and NO_x concentration are used for this purpose. Several kinetic mechanisms have been compared with each other and benchmarked to experimental data [25,28,38,47]. However, a reliable and accurate mechanism for a relatively wide set of operating conditions (preheating temperatures, equivalence ratios, pressures, hydrogen content) is still not available. Therefore, additional work and research in this direction are needed.

In summary, hydrogen-ammonia blends combine the ammonia’s extremely mature network of distribution, production and storage with the “superior” hydrogen performance with respect to combustion.

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3. Review on alternative combustion modes (ESR 8)

MILD Combustion for micro gas turbines

Gas turbines play an important role, both in the transport and energy sector. Thus in order to reduce global warming and to make our environment more sustainable, it is important that the emissions from gas turbines are reduced substantially.

Even though the advances in combustion sciences made in the 20th century were phenomenal with the progress in experimental techniques and numerical modelling, we still do not understand every aspect of combustion. The advances in combustion in the 21st century will be driven by fuel flexibility and emission reduction.

Among the technologies proposed, Flameless combustion (FC) has been seen as a promising alternative combustion technique to reduce pollutant emissions of gas turbine engines. It takes place when the inlet mixture is preheated to a level higher than its autoignition temperature, and maximum temperature rise is limited to a few hundred Kelvin.

This combustion mode is characterized by well-distributed reaction zones, which can potentially decrease temperature gradients, acoustic oscillations and, consequently Nox emission. However, the application of FC to gas turbines is still not a reality due to the inherent difficulties faced in attaining the regime while meeting all the engine requirements.

What makes such technology very attractive is the large fuel flexibility. Indeed, the process allows burning, in a clean way, even low calorific gases in industrial conditions (such as those derived from biomass gasification).

MILD combustion for aeronautical gas turbines [1]

A few approaches have been investigated and attempted as new combustion concepts for aeronautical gas turbines, such as the Trapped Vortex Combustor (TVC) and Lean Direct Injection (LDI). However, these concepts are not likely to be able to meet the ambitious emission reduction goals for aero engines as the pressure ratio and operating temperatures are being increased in the pursuit of increasing efficiency. Therefore alternative combustion concepts like Flameless Combustion (FC) have to be explored. A qualitative comparison of different types of combustors with FC is shown in Table 1 [1], in which the advantages of FC are clear. The well-distributed reactions that characterise the FC regime of ten yield low temperature gradients, low Nox emissions, high stability and low acoustic oscillations.

Moreover, the large fuel flexibility offers a promising technology for low-calorific value fuels, high-calorific industrial waste as for hydrogen-based fuels.

Table 1
Qualitative comparison of different combustor types.

	Combustor type			
	Lean premixed	Lean direct injection	RQL	Flameless-based
Combustion efficiency	High	High	High	High
Combustion instability	High	Low	Low	Low
Fuel flexibility	Moderate	High	High	Moderate
Integration into engine	Moderate	Moderate	Easy	Difficult
Mechanical complexity	Moderate	High	Moderate	Moderate
NOx emission	Low	Low	Moderate	Ultra-low
Operating range	Moderate	High	High	Low
Soot emission	Very Low	Low	Moderate	Low
Volume requirement	Moderate	Low	Low	High

JHC burners [10]

Jet-in-hot-coflow are useful academic burners to study the flame structure in MILD conditions. A high-speed turbulent jet issues into a slowly moving coflow of hot and lean combustion products. This mimics the exhaust heat recovery and dilution due to intense recirculation rates typically found in clean combustion technologies.

Literature reports on experimental research on several jet-in-hot-coflow burners contributed to a better understanding of the stabilization mechanism and structure of these flames. Autoignition was suggested as part of the flame stabilization mechanism for H₂/N₂ and CH₄/Air jet flames.

Effect of oxygen addition[3] [4]

The oxygen level in the coflow was found to control the OH distribution and peak mean temperature values in the reaction zone of a CH₄/H₂ jet flame.

Effect of hydrogen addition [4]

The OH distribution and peak mean temperatures can be also affected by the amount of hydrogen present in the fuel. From predictions in well stirred reactors, it was computed that adding small amounts of hydrogen to methane enhances the reactivity of the mixture and the hydrogen oxidation kinetics significantly affect the kinetics of pure methane.

Increasing the hydrogen content of the fuel reduces the lift-off height. The short exposure time photos show the transition in the flame stabilisation structure. The stabilization zone of By gradually increasing the hydrogen concentration in the fuel, the typical autoignition kernels observed in natural-gas flames are detected at more upstream positions. At sufficient high hydrogen concentrations, the autoignition kernels are not detectable and the flame zone becomes a single continuous region.

The results show that hydrogen is an excellent flame stabilisation agent even at hydrogen concentrations in the fuel as low as 5%. The presence of hydrogen changes significantly the flame structure compared to natural-gas flames. These changes include a substantial upstream shift of the stabilisation region.

For different hydrocarbon fuels (natural gas, ethylene and LPG) mixed with hydrogen, a similar reaction zone structure is observed regardless the major differences in the combustion properties of each pure hydrocarbon fuel.

Besides turbulent mixing also differential diffusion has an important role in the stabilisation mechanism when the fuel contains hydrogen. By gradually increasing the hydrogen concentration in the fuel, the typical autoignition kernels observed in natural-gas flames are detected at more upstream positions. At sufficient high hydrogen concentrations, the autoignition kernels are not detectable and the flame zone becomes a single continuous region.

Biogas utilisation [9]

It was found that by biogas utilisation the net emission of three greenhouse gases CO₂, CH₄ and N₂O decreased drastically in comparison with pure methane. Biogas flameless combustion has great capability to reduce pollutant constitution, especially soot formation. Under the biogas flameless combustion the performance of flameless chamber remained constant. Indeed, CO and NO_x formation were recorded very low.

The efficiency of biogas flameless combustion is higher than traditional mode due to heat recovery of exhaust gases in heat exchanger. Also, the high concentration of CO₂ in biogas flameless combustion products causes higher heat capacity, better radiation heat transfer and higher absorption capacity which improve the performance of heat exchanger.

The profile of CH₄ and CO formation inside the chamber indicates that in biogas flameless combustion the reaction zone is distributed along the whole length of the furnace. Therefore, the temperature inside the furnace is uniform in biogas flameless mode and hot spots are eliminated and thermal NO_x are suppressed. Fuel consumption reduction, low noise and pollutant formation are the other advantages of biogas flameless combustion.

Presence of corrosive gases such as water vapor and H₂S in biogas combination, high costs of biogas purification and low calorific value of biogas are the main obstacles for development of biogas utilisation.

CFD MODELS – NOX MODELLING [6 -7- 8]

The distinguishing feature of MILD combustion is the very strong interactions between chemical kinetics and fluid mixing, so that models based on the scale separation between turbulence and chemistry will fail in predicting the main features of such a combustion regime. Therefore, models that account for finite-rate chemistry must be considered.

The direct implementation into CFD codes of large kinetic mechanisms for the prediction of pollutant emissions is still unfeasible, due to computer time limitations which become particularly relevant when considering the typical scale of the industrial applications. Therefore, simplified modelling approaches are generally adopted, as they allow reducing the computational effort associated with the numerical

simulations. With regard to NO formation, simple one-step mechanisms are used to describe each of the relevant routes contributing to the overall generation of NO, i.e., thermal, prompt. The main drawback associated to a simplified NO formation approach lies, however, in the extreme sensitivity of the lumped rates on the thermo chemical state which define the combustion system of interest. Then, a proper description of turbulence/chemistry interactions must be employed in the CFD model, to provide a realistic background for the estimation of NO emissions. This becomes particularly important in MILD combustion regime, which generally requires an accurate description of the gas-phase oxidation, due to the kinetic control on the overall combustion process.

Several numerical investigations establish a possibility for the engineering modelling of NO formation in turbulent flames with a finite-rate chemistry combustion model that can incorporate a detailed mechanism at an affordable computational cost.

Employing KEE and GRI2.11 chemical mechanisms results show that the choice of the combustion model has a higher impact than the selection of the kinetic mechanism for the investigated cases, indicating that biases in the turbulent reactive flow closure are as important, if not more, as the level of the accuracy of the chemical scheme employed.

Moreover, the sensitivity of the NO emissions to the uncertain kinetic parameters of the rate-limiting reactions of the NNH pathway is found to be significant when a detailed kinetic mechanism is used. An engineering modification of the PaSR combustion model is proposed to account for the different chemical time scales of fuel oxidation reactions and NO_x formation pathways. It shows an equivalent impact on the emissions of NO than the uncertainty in the NNH pathway kinetics. At the cost of introducing a negligible mass imbalance, the adjustment leads to improved predictions of NO.

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4. Combustion of low calorific value gases in a SOFC-MGT hybrid concept (ESR 9)

Background and Literature

Research communities and governments across the world are actively working to develop advanced technologies for more efficient energy conversion systems with lesser impact on the environment. A hybrid Solid oxide fuel cell and Micro-gas turbine (SOFC-MGT) is one of the most promising technologies available to achieve the above goals. The SOFC-MGT hybrid power plants are evaluated to achieve electrical efficiency to ~ 60-65% and NO_x emission under 1 ppm, which is much lower than conventional power plants[1,2].

Often in the hybrid power plant cycle, SOFC is embedded as topping cycle and MGT as a bottoming cycle. Low calorific value reactive gases from topping SOFC are burned to generate additional power in the bottoming MGT. The SOFC accepts H₂ as the main fuel, other fuels such as natural gas (NG), biogas/syngas and high hydrocarbons can also be used as fuel in the SOFC and in such cases an internal or external fuel reforming is required to convert the fuel to an H₂-rich mixture before it enters the SOFC[1,2]. Hence, the hybrid system also satisfies the requirement of fuel-flexibility. Adding to the complexity of the hybrid system, the use of biogas requires an additional Sulfur (H₂S) removal step from the biogas, since H₂S affects the performance of the fuel cell significantly. The use of biogas also leads overall reduction in efficiency of the hybrid system to 52.4% as per the study conducted by Sucipta et al. [3]. To further improve the efficiency and power output of SOFC for the same fuel-cell stacks, the SOFC is often pressurized with compressed air from micro-gas turbine[3,4].

A most common configuration of the pressurized SOFC-MGT hybrid cycle is shown in Figure 1. The figure shows that the air (from compressor) and fuel (from reformer) entering the cathode and anode of the SOFC respectively, where they are electrochemically converted to produce electricity. The anode side exhaust gas (Anode off-gas) from NG-fueled SOFC predominantly contains H₂O and CO₂ with very less amount of H₂ and CO. The typical range of anode off-gas composition of a NG-fueled SOFC contains H₂ ~ 0.5-2%, CO ~ 5-10%, H₂O ~ 40% and CO₂ ~ 50% as presented in Lingstadt et al. [6]. SOFC anode off-gas compositions for fuels such as NG, pure methane and biogas/syngas from various literatures are presented in Table 1. Depending upon the operating conditions (i.e., base load or part load), the lower heating value (LHV) of the anode off-gas composition ranges from 1- 4.6 MJ/kg which are much lower than that of convention fuels [7]. At the cathode side, the oxygen is depleted during the electrochemical conversion process and hence, the cathode off-gas contains 6-8% less O₂ than the ambient air condition [8]. The fuel cell stacks operate at high temperatures (i.e.>1000 K) and exhaust gas temperatures typically ranges from 1051 to 1173 K. The fuel cell operating pressure is dictated by the compressor ratio of the MGT and for small gas turbines this ratio results in typically < 10 bar pressure [9]. The operating conditions for the present study will be based on the off-gas compositions with the initial temperature from 300 - 1073 K and initial pressures up to 10 bar.

One of the significant challenges is to design a combustor to ensure stable operation given the low calorific value fuel and O₂-depleted air, as the heat loss mechanisms become more significant. A combined homogeneous (gas-phase), and heterogeneous (catalytic) combustion technique is the choice of interest for this study because of the low activation energy upstream catalytic reaction pathway. Damo et al. [2] reviewed other challenges including (1) reliability issues of the hybrid system, (2) system control issues due the increased complexity of integrated SOFC/MGT, and (3) fuel cell degradation issues that significantly affects the component lifetime.

Bucheler et al. [8] developed a jet-stabilized combustor for a 30 kW_{el} SOFC-MGT demonstrator which is established at German Aerospace Centre (DLR). The combustor is based on flameless oxidation (FLOX) or MILD combustion concept. An SOFC off-gas emulator provides the typical off-gas compositions to the combustor at atmospheric pressure and temperature > 1000 K. The study shows that the developed combustor has wide operational range with NO_x and CO emissions lower than 3 ppm and 10 ppm respectively. Lingstadt et al. [6] investigated the FLOX combustor for lower LHV off-gas compositions (due to increased fuel utilization in the SOFC) and compared to Bucheler [8] as part of EU 2020 “Bio-HyPP” project. The investigation shows that the addition of natural gas for low LHV compositions improves the flame stability at the expense of system efficiency. CO emissions for different fuel/air ratios were also reported. In another paper [10] by the same author, biogas/NG mixture was used in addition to the Low LHV off-gas composition for flame stability. The power output is lower in the case of biogas addition as compared to the NG addition. The use of biogas is motivated by the utilization of renewable energy source in the system.

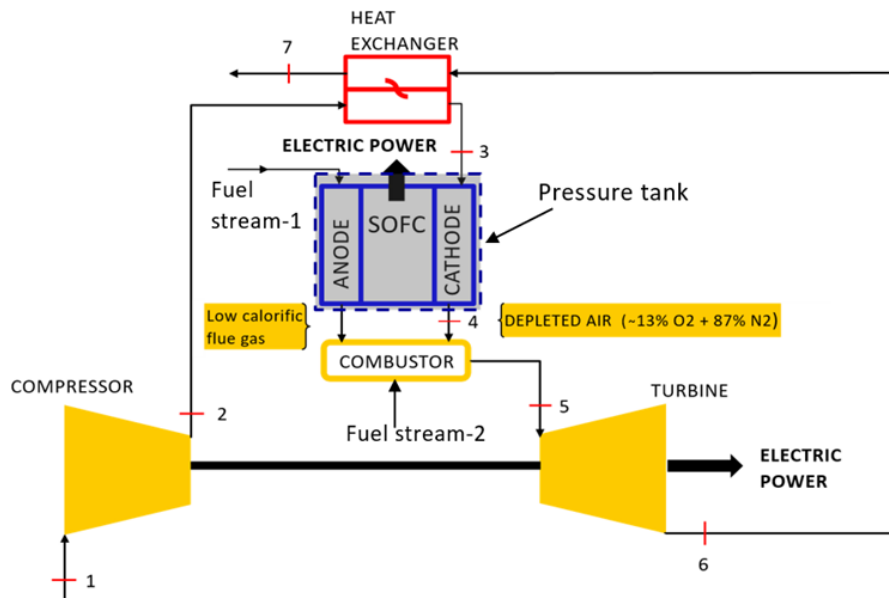


Figure 1: Most Common configuration of SOFC-MGT hybrid cycle.

Table 1: Anode side off-gas composition for different fuels and operating conditions of SOFC from various literatures.

Ref.	SOFC operating condition	SOFC fuel	SOFC anode off-gas composition						T _{offgas} (K)	P _{offgas} (kPa)
			H ₂ (%v)	CO (%v)	CH ₄ (%v)	H ₂ O (%v)	CO ₂ (%v)	N ₂ (%v)		
[6]	Base load #1b	NG	1.48	9.67	-	39.57	49.28	-	1051	294.4
	Base load #2b		1.26	8.47	-	40.42	49.85	-	1060	278.8
	Base load #3b		1.10	7.58	-	41.06	50.25	-	1070	267.9

	Base load #4b		0.96	6.82	-	41.61	50.61	-	1079	259.7
	Base load #5b		0.84	6.14	-	42.08	50.94	-	1089	254.4
	Base load #6b		0.74	5.54	-	42.48	51.25	-	1099	250.4
	Part load #1p		0.85	5.50	-	41.89	51.76	-	1041	194.4
	Part load #2p		0.846	5.46	-	41.63	51.43	-	1041	194.4
	Part load #3p		0.841	5.42	-	41.36	51.10	-	1041	194.4
	Part load #4p		0.825	5.32	-	40.58	50.14	-	1041	194.4
[12]	100% load	-	9.6	4.8	-	38.5	19.4	27.5 1	1103	-
[7]	Estimated	-	8	5	-	57	29	1	1100	1000
[13]	Fuel utilization 70%	CH ₄	18.29	5.69	-	61.71	14.31	-	1073	-
	Fuel utilization 75%		15.12	4.83	-	64.88	15.17	-	1073	-
	Fuel utilization 80%		12.11	3.91	-	67.89	16.09	-	1073	-
	Fuel utilization 85%		9.05	2.96	-	70.95	17.04	-	1073	-
[8]	Base load	NG	25.73	11.91	-	41.17	21.19	-	1073	-
	Part load		20.69	9.49	-	46.2	23.61	-	1073	-
[14]	At design point	CH ₄	0.40	4.09	-	44.3	51.2	-	1173	-

[15]	Steam/Syngas ratio (S/C) =0	Biogas / Syngas	9.0	13.7	0.2	11	18.6	47.5	1173	101.3
	Steam/Syngas ratio (S/C)=20%		9.0	6.4	0.15	26.3	19.6	38.4	1173	101.3

Grimm et al. [11] also used a jet stabilized FLOX combustor with low calorific value off-gas and investigated it numerically and experimentally. The numerical study was conducted by solving steady state RANS equations along with detailed mechanisms of syngas chemistry. Experimental measure of OH* chemiluminescence signal were done to obtain the flame shapes. The temperature distributions from numerical results were compared and validated against the OH* signals. The objective was to study the heat loss effects in the combustor with low calorific value fuel.

Frenzel et al. [16] developed an innovating two-stage burner for the combustion of SOFC-off gases with low to high calorific values. A proper splitting of cathode air between first stage and second stage results in wider operational range in terms of calorific value. In case of low calorific value (high SOFC fuel utilization), complete combustion occurs in the first stage itself. In case of high calorific value (low SOFC fuel utilization), complete combustion happens via both the first and the second stage. Jaimes et al. [7] developed a dual stage low emission burner for SOFC-GT hybrid system. The developed burner was investigation using a CFD model in ANSYS FLUENT. The results show that the burner is able to maintain stable combustion while reducing CO and NOx emissions.

Sung et al. [17] analyzed catalytic conversion of SOFC off-gas composition for different types of catalyst. They showed that perovskite supported CuO or Mn₂O₃ has good thermal stability compared to amorphous Cu-Mn supported by Alumina. Also, conversions of H₂, CO and CH₄ over range of initial temperatures for both perovskite supported CuO/Mn₂O₃ and Alumina supported Cu-Mn were presented.

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5. Conclusions

Hydrogen and H-containing species, such as methane (CH₄), methanol (CH₃OH) and ammonia (NH₃), are promising alternative fuels that can contribute to the future carbon-free economy.

Gas turbines relying on diffusion burners are already capable of operating with pure hydrogen. However, this combustion technology leads to high NO_x emissions. Premixed burners can currently only tolerate from low to moderate amounts of hydrogen. Some technical challenges to be overcome are flame stability and flashback, as well as NO_x emissions. Other major issues regarding hydrogen are hydrogen large-scale production, storage and distribution, which will require several years for their development.

In a transition scenario, gradually increasing amounts of hydrogen can be admixed to natural gas and added into the existing transportation & distribution pipeline networks. This would allow ramping up hydrogen production, while starting reducing greenhouse gas emissions.

Ammonia is another important carbon-free fuel alternative. When compared to hydrogen, ammonia's distribution network and storage are extremely developed and show superior characteristics. However, ammonia is characterized by poor combustion performance and efficiency.

Blending ammonia and hydrogen could drastically improve combustion performances. A particularly appealing option that would allow modulating the hydrogen content in the hydrogen-ammonia fuel mixture would be direct ammonia cracking.

Mild combustion is a really fuel-flexible combustion technique. The stabilisation of the flame is achieved by the introduction of the hot coflow, which heats up the reactants above their self-ignition point and leads to similarities on the flame structure between different fuels. With the addition of hydrogen this similarity is even more evident. This makes this innovative combustion mode very attractive to be used in gas turbines, in which different fuels can be burned without changes in the combustor.

Moreover, since it is characterised by really low NO_x emissions and CO₂ production, this technology can play a key role meeting the reduction emission targets set for 2050. However, modelling NO_x, which is already complex in standard combustion modes, is still an open challenge for this regime.

ESR 9 will investigate experimentally and numerically the combustion of low calorific value reactive gases, which have compositions typical to the exhaust gases of a SOFC (mixtures of H₂, CO, CH₄, O₂ with large H₂O, CO₂ and N₂ dilution) and initial temperatures 300-1073 K. As the SOFC-MGT system is envisioned to operate at pressures up to 10 bar, combustion studies will encompass the range 1-10 bar. Given the low chemical reactivity of the SOFC exhaust gas reactive mixtures, heterogeneous (catalytic) or heterogeneous-homogeneous (catalytic and gas-phase) combustion methodologies will be studied. Goal is to assess the combustion stability of these mixtures, understand the underlying chemistry, and construct detailed operating envelopes (in terms of pressure, temperature and gas composition) of stable combustion.

