GAS TURBINES FOR ENERGY NETWORK SYMPOSIUM
BANFF, ALBERTA, CANADA
OCTOBER 2023

23-GTEN-101

Design, Test and Validation of a 100% Hydrogen Fueled Gas Turbine – Enabling Energy Transition

Authors: C. Rimlinger[1]*, M. Baldini[2], S. Gabriele[2], F. Gerbi[2], G. Sarti[2]

[1]Baker Hughes Energy Services, 575 N. Dairy Ashford Rd, Houston, TX 77079 (USA)
[2]Baker Hughes, Via Felice Matteucci 2, 50121, Firenze (Italy)

*Corresponding author; email: colleen.rimlinger@bakerhughes.com

ABSTRACT

Hydrogen gas is playing a crucial role as a major source of carbon-free energy able to drive greenhouse gas emission reductions towards global net zero targets.

Although interest in hydrogen has increased significantly over the last decade, the use of hydrogen blended fuels in gas turbines is not a new concept. Leveraging experience gained over the past decades, a new generation of gas turbines are being designed to operate with lower exhaust gas emissions across the entire engine operating range. The engineering effort necessary to design and implement a low emission hydrogen combustion system is considerable and represents the state of the art in innovative development technology.

Predictive modelling is fundamental to combustion development and provides an accurate and reliable starting point for design optimization. Due to the complexity of combustion physics, the reliability and robustness of the predictive models depend heavily upon real time testing activities for data correlation.

In the NovaLT™16 development an hierarchical approach to combustion testing has been adopted. Predictive modeling accuracy has been benchmarked against both single fuel injector and full annular rig test data. Although simplified, these tests have the advantage of being controlled and providing measurements, data and details not available during a full-sized gas turbine test. Results of this testing are presented in this paper.

NOMENCLATURE TABLE

CO_2	Carbon Dioxide
d_h	Fuel Injection Hole Diameter [m]
d_h^-, d_h^+	Lower and Upper Fuel Injection Hole Diameter Limits [m]
α_h	Fuel Injection Angel [rad]
α_h^-, α_h^+	Lower and Upper Fuel Injection Angle [rad]
DLE	Dry Low Emissions
GHG	Greenhouse Gas
GT	Gas Turbine
GTons	Giga Tons
HPC	Hydrogen Park and Consortium
HRSG	Heat Recovery Steam Generator
IGCC	Integrated Gasification Combined Cycle
LD	Lean Direct Injection
MP	Main Premixed Fuel Injection Line
NG	Natural Gas
NO_x	Nitrogen Oxides
O&G	Oil and Gas
OEM	Original Equipment Manufacturer
OPEX	Operating Expenses
PD	Premixing Duct
PG	Power Generation
PL	Pilot Fuel Injection
TRL	Technical Readiness Level

INTRODUCTION

General Global Overview

The average global temperature has increased significantly over the last 150 years, reaching an average value of 1°C hotter than the average temperature of the pre-industrial era. An increase in the average global temperature of 1.5-2°C is considered a critical threshold, triggering an irreversible change in the global climate. This in turn will have severe consequences to the health and well-being of the human race, as well to global ecosystems and species. Several studies have demonstrated that the main cause for this rapid temperature increase is the enhanced greenhouse effect resulting from human activity; mainly related to the combustion of fossil fuels. Since 1990, the total CO_2 emissions from combustion and industrial processes has increased by approximately 80% from 20 Gt of CO2 emissions to 36.8 Gt, Figure 1. This has been driven, for the most part, by the power sector as shown in Figure 2.

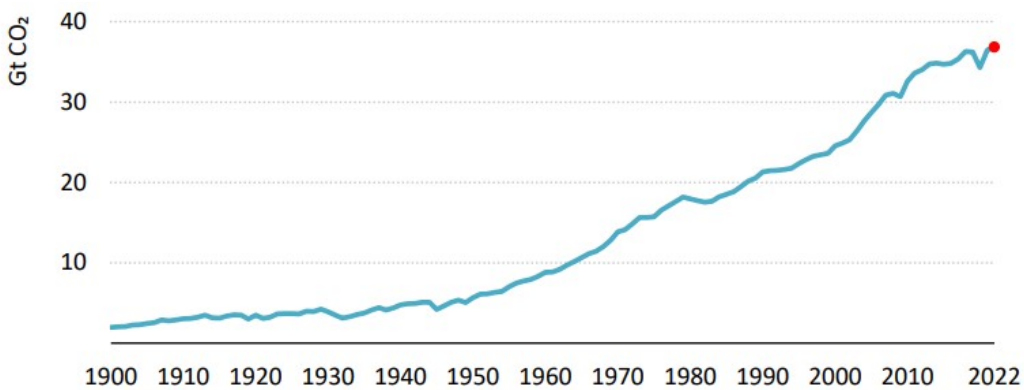

Figure 1: Global CO_2 Emissions from Energy Combustion and Industrial Processes, 1900-2022 [1]

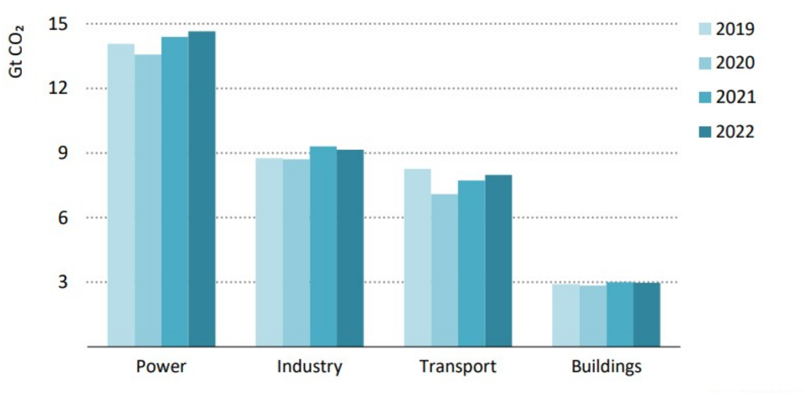

Figure 2: Global CO_2 Emissions by Sector, 2019-2022 [1]

The Paris Agreement defines the importance of remaining below the 2°C average global temperature rise, while reaching a Net-Zero CO_2 emissions target by 2050 [2]. To limit global warming to 1.5°C, greenhouse gas emissions must peak before 2025 and decline by 43% by 2030.

Concurrently during this period, global electricity and hydrogen consumption is still expected to grow to 50% of the total global energy mix due to world population and wealth growth [3]. This energy challenge is known as the energy trilemma, defined by the World Energy Council as the need to find a balance between energy security, affordability, and sustainability, while minimizing the impact on daily lives. In this context, low carbon energy solutions are a key ingredient to meeting global energy demands while significantly reducing carbon emissions. To evaluate the effectiveness of each potential reduction solution, the impact of each of the interdependent trilemma axis variables must be properly and thoroughly assessed [4].

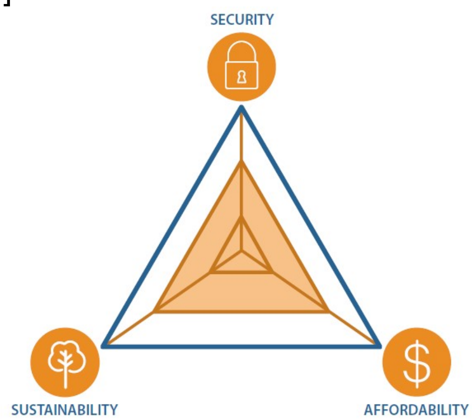

Figure 3: Energy Trilemma Concept, World Energy Council [4]

Globally, affordable and secure energy resources are required which are also sustainable and enable the effective impedance of climate change.

Canadian Hydrogen Plan

Canada's 2050 Vision is laid out in the Canadian Net-Zero Emissions Accountability Act [5] and is aligned with the Paris Agreement. The target is to reduce GHG emissions by 30% below 2005 levels by 2030 and to achieve net-zero emissions by 2050. The Hydrogen Strategy for Canada [6] has identified hydrogen as a critical component of its path towards achieving net zero. In the near term (2020-2025), the groundwork will be laid by developing new hydrogen sources and distribution networks while upgrading the mature hydrogen market sources and applications, to include traditional oil and gas processes. Canada's current production is at approximately 3MTPA of high carbon intensity hydrogen [6]. Mid-term (2025-2030) plans include growth and diversification through the addition of new hydrogen hubs and increasing new and large-scale hydrogen production plants. This will lead to hydrogen and natural gas blending for use by industrial, commercial, and residential users in regional hubs as well as it being used as a feedstock for localized power and chemical production. The 2030 Canadian production target is 4MTPA of low carbon intensity hydrogen [6]. Canada's Long Term (2030-2050) plan will be rapid market expansion to increase new commercial applications. The target production is 20MTPA of low carbon intensity hydrogen by 2050 [6]. Figure 4 summarizes the Canadian long-term goals and milestones which make up the 2050 Vision.

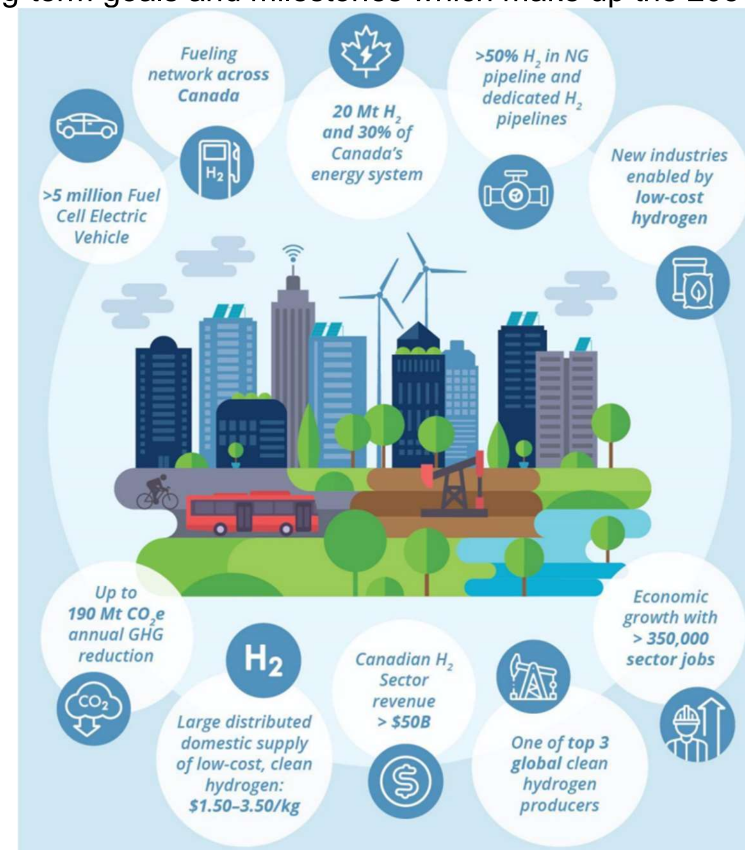

Figure 4: Canada's Hydrogen Vision 2050 [6]

With increased hydrogen production, its use as a gas turbine fuel becomes more realistic.

The Hydrogen Value Chain

In current power generation, industrial and transportation markets where the adoption of hydrogen as an energy source is advancing, traditional oil and gas turbomachinery manufacturers can provide extensive experience in the design, manufacturing and operation of equipment utilizing this element. Globally, traditional original equipment manufacturers (OEMs) have been linked to hydrogen for over a century and have designed, installed and operated rotating equipment fleets either compressing or using hydrogen as a fuel gas for many hundreds of thousands of hours. In addition to traditional equipment applications, today's turbomachinery is being "re-engineered" to serve the non-traditional applications across the "new" hydrogen value chain, that is to say, hydrogen produced utilizing low carbon power sources.

Hydrogen Fueled Gas Turbines

Clean fueled gas turbines will play a significant role in the energy transition journey. As shown in Figure 5, a gas turbine can operate using 100% natural gas, 100% hydrogen gas and blends of the two. As the percentage of hydrogen gas increases in the mixture, the carbon dioxide emissions are reduced. If holding the total energy input constant, the CO_2 emissions are reduced by almost 50% when the fuel ratio reaches 75vol% H_2/25vol% CH_4.

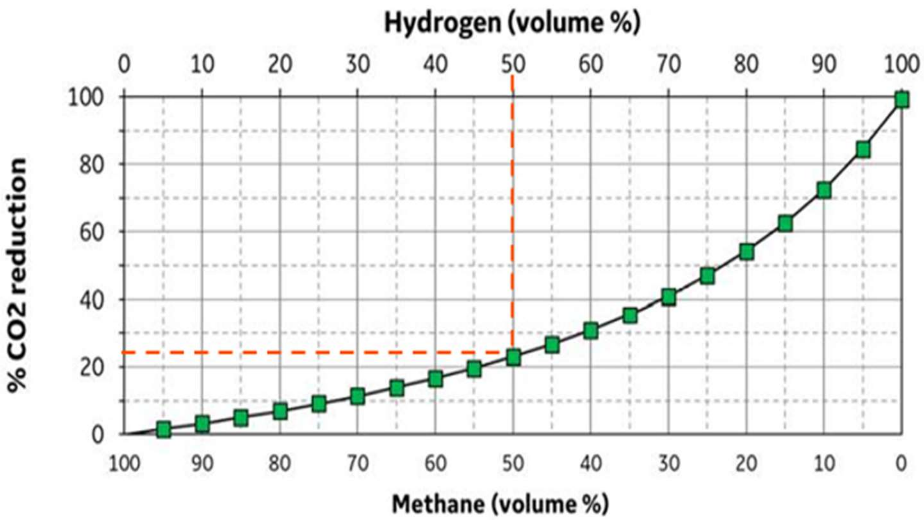

Figure 5: Reduction of CO2 Emissions by Increasing Hydrogen Content in NG-HYDROGEN Fuel Blends.

The ability to use both pure and blended hydrogen fuels would benefit both greenfield and brownfield applications. Upgrade solutions for brownfield equipment will minimize the impact of the transition to hydrogen fuel on the installed fleet and as hydrogen production increases, this fuel will play an increasingly crucial role in greenfield power generation and mechanical drive applications which are inherently difficult to decarbonize. The hydrogen gas turbine also compliments solar and wind power as a reliable backup power source [7], [8].

Current field experience has proven that gas turbines ranging from 5 to 120 MW are capable of combusting varying amounts of hydrogen from 10 to 100 vol%. The hydrogen capability depends upon the gas turbine model and combustion system type, i.e., whether it is a standard diffusive flame combustor or Dry Low Emissions (DLE) type system. Laboratory and field experience data from the operating fleet using these fuel gas mixtures have been used to optimize the most recent gas turbine designs. Figure 6 shows the maximum volumetric amounts of hydrogen fuel continuously combusted in different gas turbine models operating in the field and spanning the different types of gas turbines, ie. Industrial, frame and aeroderivative models.

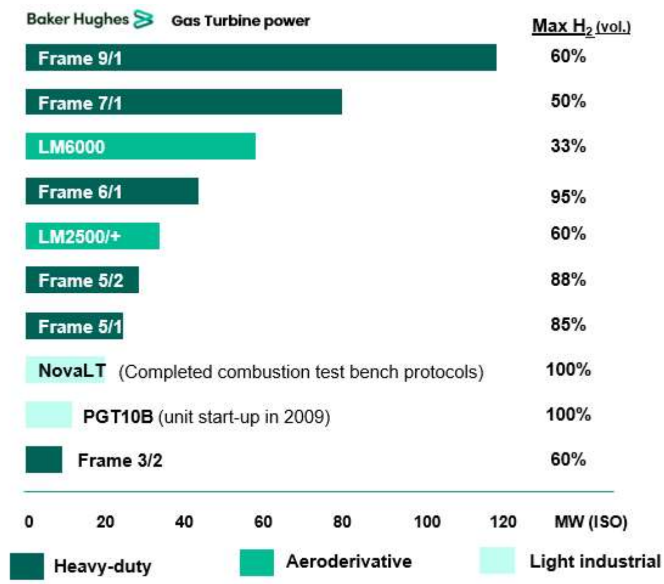

Figure 6: Baker Hughes Gas Turbine Hydrogen Experience. © 2023 Baker Hughes Company - All rights reserved.

INITIAL SITE TESTING [9]

PGT10/1 Site Experience

A zero-emissions, integrated gasification combined cycle (IGCC) plant was designed in Fusina, Italy with a PGT10/1 model hydrogen-fueled gas turbine at its core along with a heat-recovery steam generator (HRSG) and a steam turbine generator (STG). The system was installed in a location where a significant amount of hydrogen was available from nearby petrochemical plants. Baker Hughes, ENEL, and the Hydrogen Park Consortium (HPC) were the members of the joint development program. The unit was operated using both 97vol% hydrogen as well as 100 vol% natural gas in a diffusion flame fuel injector using the PGT10/1's standard single silo combustion system.

The project achieved approximately 4,000 operating hours between September 2009 and 2012 using 97vol% hydrogen fuel blend. Natural gas was used as the startup and backup fuel for the project and hydrogen was the primary fuel during all other operating scenarios. In situ instrumented engine tests focused on assessing the full operability range of the machine and were used to measure and analyze NOx emissions in the exhaust gas.

During the testing, the NOx emissions increased significantly as the hydrogen content in the fuel was increased. To reduce these levels in the conventional diffusion flame combustion system, a steam injected diluent was utilized (ref. Cossi). Unfortunately, there is a known reduction in component life and increased OPEX when applying the diluent NOx reduction technique (ref). Alternately, an SCR can be used in the exhaust system and, although highly effective at reducing NOx levels to required permitting levels and while having no impact on component life, this equipment represents an increased operational expense, larger equipment footprint as well as requiring an ammonia handling system. These two NOx reduction methods are viewed as short term solutions to bridge the gap to dry low NOx technologies.

The PGT10/1 generated approximately 12 MWe and demonstrated a plant efficiency of 41.6%. More than 25,000 tons/year of CO_2 were eliminated versus an equivalent natural gas fired plant, and more than 13,000 tons/year of CO_2 when compared to the earlier Unit 4 coal-fired plant emissions.

HYDROGEN GAS TURBINE DESIGN

The development of the NovaLT^{TM}16 industrial gas turbines began in 2012 and the first unit was commissioned in 2017 and has accumulated over 48,000 operating hours. The current hydrogen gas fueled version is the result of an extensive design and validation testing campaign which has spanned the past decade. The current work reports the design results through the end of the full scale, full range combustion system verification phase, which allows the achievement of the Technical Readiness Level (TRL) 5.

Combustion System Development Strategy

The combustion development strategy was to build a gas turbine capable of long term safe and reliable operation while using 100% pure hydrogen fuel with minimal changes to the gas turbine flange-to-flange components or to the auxiliary systems which were in direct contact with the hydrogen fuel. The key drivers were:

1. Operational safety
2. Reduced NO_x emissions
3. Fuel and operational flexibility, including the:

    - Capability to startup using pure hydrogen
    - Capability of bumpless transfer between natural gas and hydrogen fuel
    - Capability of combusting any blend of hydrogen and natural gas

Combustion System Design [10]

The combustion system is the gas turbine sub-system most affected by using hydrogen fuel. The behavior of hydrogen is very different from natural gas. At 25^{o}C and 1 atm, the laminar burning velocity is approximately 1.85 m/s (stoichiometric hydrogen/air mixture), the auto ignition temperature is 560^{o}C, and the wide flammability range spans from 4 to 75vol% hydrogen in air. By comparison, methane has a 0.44 m/s laminar burning velocity (CH_4/Air stoichiometric mixture), an autoignition temperature of 540^{o}C and a flammability range from 5.5 to 15vol% CH_4 in air. The combustor design required several modifications to ensure an adequate design margin to avoid fuel flashback, while minimizing the NOx emissions to within an acceptable range.

The design of the hydrogen combustion system was performed by using numerical analysis simulations as well as real-time component test feedback from both in field and controlled atmospheric single burner test environments. The most promising solutions were then selected to advance to full-scale combustion rig testing.

A cross section of the NovaLT^{TM}16 fuel injector is shown in Fig. 7, displaying the main premixed (MP) and the pilot (PL) fuel injection lines, both of which were designed and thoroughly characterized for dry low emissions service using natural gas [11]. No changes were made to these two fuel lines for hydrogen service.

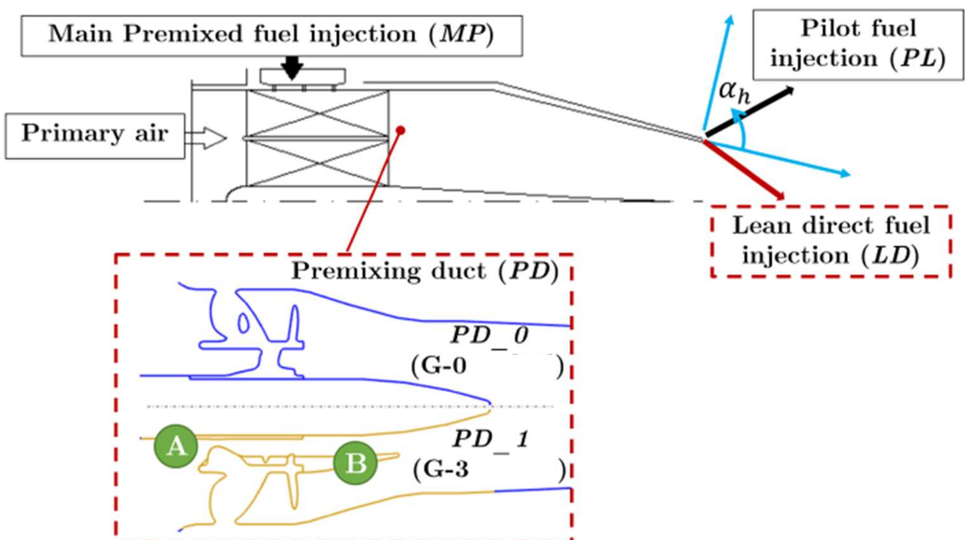

Figure 7: NovaLT^{TM}16 Combustion System Schematic [10]

The two principal areas of design improvement addressed by the hydrogen development program were related to the optimization of:

1. The Lean Direct (LD) fuel injection design
2. The Premixing Duct (PD) design

The introduction of lean direct injection (LD) technology was the major design improvement. [12]

Lean Direct fuel injection was achieved by introducing a newly designed fuel circuit to minimize the presence of a flammable mixture in the burner premixing ducts while allowing for fast mixing of the fuel and air downstream to maintain low emissions levels. Figure 7 shows the LD injection port. The optimization of the fuel injection geometrical parameters for operation with hydrogen was carried out by adding more fuel ports to allow for the maximum amount of hydrogen thermal input [10]. Retaining the original main premixed (MP) and pilot fuel injection (PL) designs while maximizing the volumetric flow of hydrogen through the LD and PD ensured that the dual gas fuel injectors were optimized for hydrogen fuel, while retaining the baseline DLE characteristics when using natural gas.

Earlier work by Meloni et al [13] suggested that NOx levels are most affected by the angle between the direct fuel injection and the primary air stream, while the number of injection holes had a reduced effect. The velocity of the fuel injection stream was also expected to have an effect on the flame stability which would, in turn, impact the NOx levels.

The design and atmospheric testing of the LD circuit, therefore, focused on the effects of varying the lean direct injection angle, α_h, and injection hole diameter, d_h.

The redesign of the Premixing Duct began with an exploratory investigation to define the injector modifications needed to increased resistance to flashback in baseline burners [13].

The simulation results revealed the dominant role of through-burner air velocity in establishing flame stabilization in the pure hydrogen fuel injections in the Premixing Duct, PD. Concurrently, no advantages were predicted by changing the injection hole's size, the inclination angle or the cross-sectional shape and area of the PD. Only minor benefits were predicted by reducing the jet penetration; however, this did have a significant impact on the fuel and air concentration profiles at the exit of the Premixing Duct. The result was the occurrence of recirculation zones either downstream of the main fuel injection holes or downstream of the swirler vanes. These recirculation zones led to flame anchoring inside the burner.

The baseline PD design was therefore modified by:

1. reducing the inner swirler passage to increase air velocity behind the point of fuel injection (Area A in Figure 7) and

2. elongating the inner passage downstream of the swirler to reduce downstream turbulence (Area B in Figure 7).

Five burner configurations were selected for atmospheric reduced scale rig testing as shown in Table 1. The baseline design is identified as G-0. Injector designs G-1 and G-2 varied only the lean direct fuel injection angle, α_h. Injector G-3 only varied the design of the Premixing duct as previously described. Injector designs G-4 and G-5 isolated the effects of varying the injection hole diameter, d_h.

	Lean Direct Fuel Injection Angle, α_h	Premixing Duct Modifications	Lean Direct Injection Hole Diameter, d_h.
Baseline, G-0	0	0	0
G-1	-1	0	0
G-2	+1	0	0
G-3	0	1	0
G-4	0	0	-1
G-5	0	0	+1

Table 1: Atmospheric Test Hydrogen Fuel Burner Configurations

VALIDATION AND TESTING

Validation Testing Strategies

A validation strategy of the proposed combustion system was developed to progressively reduce the technical risks and incrementally increase the Technology Readiness Level (TRL) of the hydrogen fuel combustor design.

Laboratory scale testing of the prototype configurations was completed in the early phases of the technology development in 2021. Additive manufacturing technology and design methods were leveraged to allow accelerated experimental verification of the design prototypes using the atmospheric test rig and the configurations shown in Table 1. The time to market and the development costs were both significantly reduced. Fig. 8 shows the test facilities used to achieve each specific TRL.

Figure 8: NovaLT™16 Combustion Verification Testing and Strategy

Component Testing

Burner Atmospheric Test Setup

The single fuel burner atmospheric test rig is a common testing arrangement across the industry. It is the most reliable and accelerated way to get preliminary information on new prototype burner designs. The atmospheric test bench used for this project is located at the Baker Hughes Campus in Florence, Italy. Figure 9 is a schematic of the test rig and shows the flame tube surrounded by a flow sleeve which distributes both the cooling and the quenching air. The combustion air is conveyed to the flame tube through a single burner. NOx emissions are measured through sampling ports within the exhaust duct.

The test rig is capable of combusting and controlling a wide range of fuel gas mixtures, to include natural gas, hydrogen, nitrogen and ammonia blends, as well as varying diluent injections such as nitrogen and water. Exhaust emissions (NOx, CO, unburnt hydrocarbons) are measured in real time and recorded together with all other test operating conditions. Special instrumentation is installed to monitor and measure critical parameters of the combustion burner test such as combustion inlet temperature, pressure, fuel mass flow and adiabatic flame temperature. These data are then compared to predicted engineering analysis results.

The atmospheric screening test assessed the NOx emissions levels of each preliminary configuration shown in Table 1 by feeding the LD fuel circuit. The atmospheric rig test also allowed preliminary evaluation and selection of the most suitable split between the lean direct fuel injection and premixed lines. The design which resulted in the lowest NOx emissions while avoiding flashback, was selected.

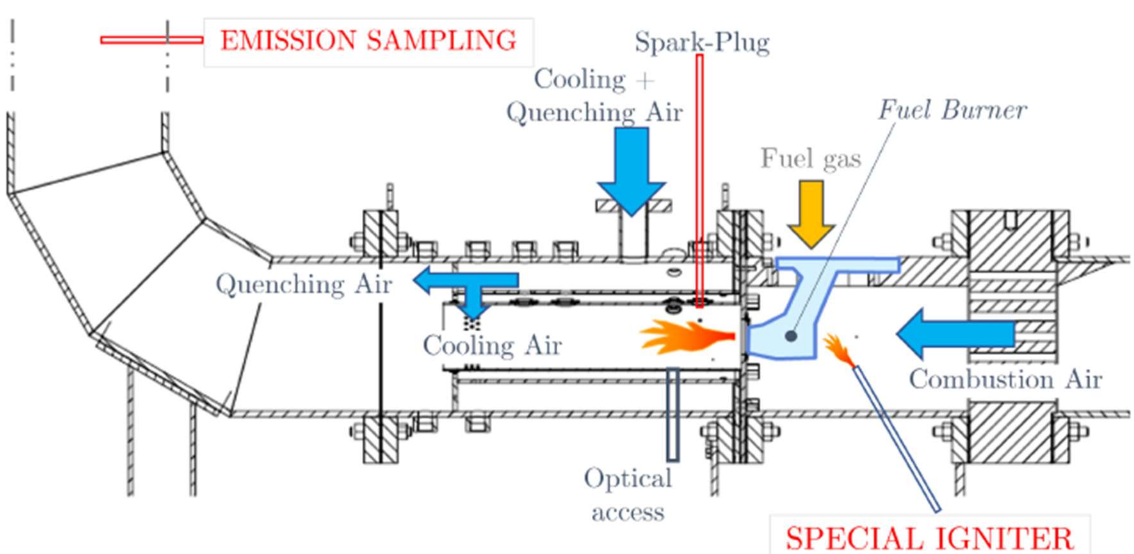

Figure 9: NovaLT™16 Atmospheric Single Burner Test Rig [10]

Burner Atmospheric Test Results

The most effective configuration in reducing the NOx emissions was burner G-1 which used the baseline Premixing Duct design (PD) and the baseline fuel injection hole diameter, d_h, but which implemented the lower boundary of the fuel impingement angle, α_h. This was the angle which impinged the most on the main burner axis.

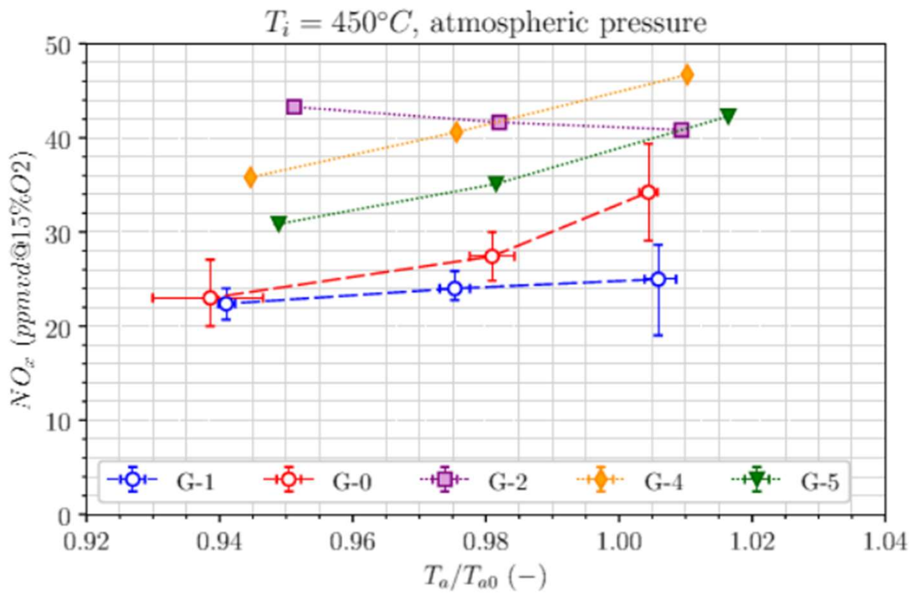

Figure 10: Nox Emissions as a Function of Normalized Adiabatic Flame Temperature for Different Burner Configurations [10]

Figure 10 shows the result of the atmospheric testing of all configurations. NOx emissions are shown as a function of adiabatic flame temperature as normalized to a reference value for the five different test component configurations. Burner G-1 showed improved NOx emissions over the baseline configuration G-0. Uncertainties were noted because of the rig cooling air design and are denoted by the horizontal and vertical uncertainty bars in the results for G-0 and G-1. Actual liner cooling is achieved by convection cooling whereas the atmospheric rig injects cooling air into the flame region and the uncertainty bars show the sensitivity of the NOx emissions to the variation in cooling flow rate. As anticipated, the largest variability was seen at the highest test temperatures.

Injection hole diameter variation, both increased and decreased from the baseline diameter, increased NOx emissions. This was due to increased hole to hole diameter variability when measuring the effect of the larger diameters in injector G-4 and decreased jet penetration for injector G-5.

Injector design G-3 evaluated the effects of redesigning the Premixing Duct (PD) as described earlier. Negligible improvement was noted and the baseline premixing duct design (G-0) was chosen to move forward to the full annular rig test.

Full Scale Combustion Chamber Test Setup (Full Annular Rig FAR) (10)

The final burner configuration verification test using burner design G-1 was performed in an annular full-scale combustor in the SestaLab facility, owned by CoSviG. The full annular rig (FAR) can reach full combustion air flow, pressures and temperatures with the same profiles as seen in a fully operational NovaLT^{TM}16 gas turbine. A fuel mixing skid enabled the methane and hydrogen gases to be controlled from 100 vol% methane to 100 vol% hydrogen and mixtures of the two in between.

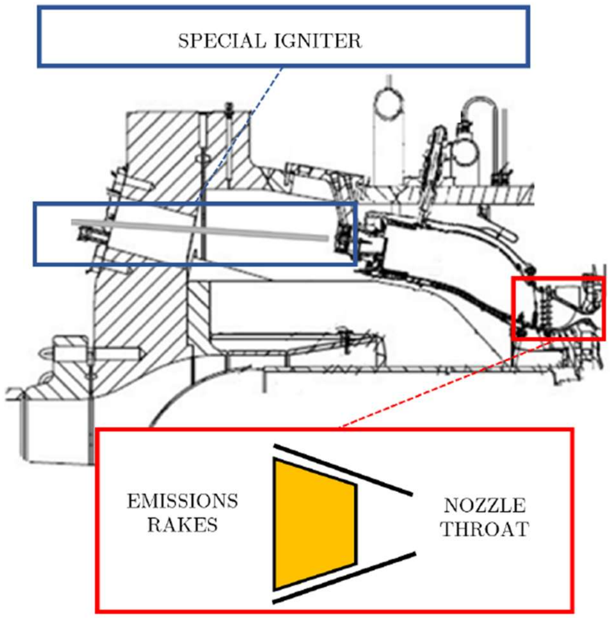

Figure 11: NovaLT^{TM}16 Full-Annular Test Rig Special Instrumentation [10]

As shown in Fig. 11, the exhaust gases are sampled at the exit of the combustor by water cooled, aerodynamically shaped rakes. The gas is then sent to a refrigerator through a heated pipe to prevent condensation. The analysis of the exhaust emissions for NOx, CO and O_2 was performed using standard reference methods EN 14792, EN 15058 and EN14789.

High frequency pressure transducers were used to monitor combustion instabilities. The signals were sampled at 10kHz. The range of interest is from 10 Hz to 3 kHz, with a spectral resolution of 0.6 Hz.

For complete characterization of the final test configuration, differential static pressure transducers and K-type high temperature thermocouples were installed on the combustion chamber components similar to what was used in the atmospheric rig.

To replicate a realistic operation profile, all three fuel circuits were simultaneously fed hydrogen fuel and controlled to keep the overall thermal input to the combustion system constant.

The operational range limits were also explored for the final selected design configuration.

NOx and pressure pulsation amplitudes for the hydrogen fuel were tested and covered the entire range of combustion inlet temperatures.

Full Annular Test Rig Results

Figure 12 shows the result of increasing the LD split on NOx emissions and pressure pulsations. The red points indicate the results where the main premixed (MP) was held to a minimum value of 5% to avoid flashback. As the LD split increases and the PL decreases, the NOx levels decrease and remain reduced from 65-90% LD split. The pressure pulsations remained low over the entire range investigated.

The blue points in Figure 12 explored the effect of holding the pilot fuel injection (PL) to a minimum while varying the MP and LD split. The NOx reduces as the LD percentage split decreases and the MP increases, however, the pressure pulsations increased.

This test validated the effectiveness of using the LD design to reduce NOx emissions as compared to the conventional pilot design and also showed the main premixed (MP) and LD split to be the most effective method.

As predicted, no flame blowout events occurred using the final design. The feasibility for low emissions operation was proven and data were obtained to begin proper sizing of an SCR NOx emissions abatement system downstream of the gas turbine exhaust duct.

According to the results achieved during the test campaign, the combustor design was considered finalized and ready for full engine test validation.

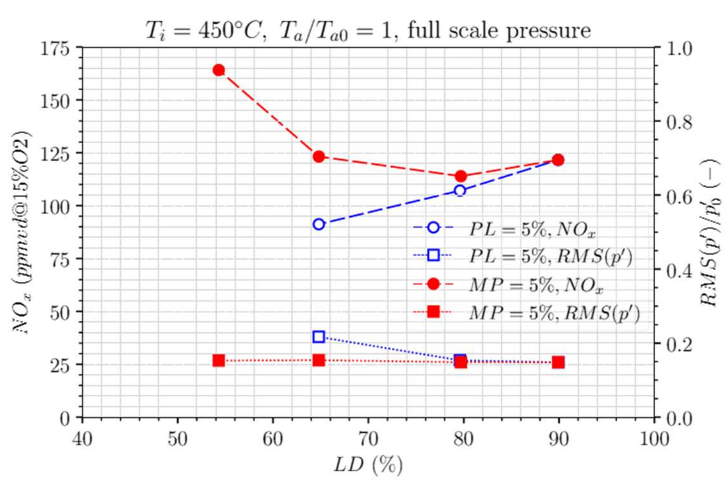

Figure 12: NOx Emissions and Normalized Pressure Pulsations as a Function of LD Split [10]

2023 Full Scale Engine and Package Test

Test Bench and Infrastructure Upgrade

To enable the full scale/full load testing of a gas turbine engine using 100% hydrogen fuel, the NovaLT^{TM} test cell was upgraded with the design, construction, and installation of a hydrogen fuel storage system.

The system was designed for a total capacity of 2,500 Kg of hydrogen, sufficient to run a 17 MWe gas turbine using 100% hydrogen fuel continuously at full speed full load (FSFL) conditions. This amount of hydrogen will allow for all mechanical and performance testing to be completed with full data acquisition.

Hydrogen gas is stored at 300 bar pressure and is contained in three main storage areas separated by concrete walls for safety and protection. The containers are connected to the high-pressure distribution line and then to a pressure reduction skid, which drops the pressure from storage to gas turbine delivery pressure of 50 bar.

The low pressure distribution line connects the reduction skid to the test bench where hydrogen is fed into the blending skid.

The blending skid allows for control of the fuel composition ranging from 100vol% natural gas to 100vol% hydrogen and any mixture in between the two extremes. The skid is equipped with regulation valves for gas mass flow control, double block and bleed shutoff valves, mass flow meters on both the hydrogen and natural gas lines as well as on the mixture line. The exact mixture composition monitored using an in-line gas chromatograph. The desired fuel mixture is set in the test bench unit control system and the closed loop controls regulate the fuel composition and pressure during both steady state and transient testing operations.

The test bench is equipped with real time emission monitoring, enabling verification of the engine combustion system behaviour in all operating conditions and with all fuel mixtures.

Future Test Deliverables

The first full engine and package test scheduled for October 2023 will enhance the combustion system functionality; operability and control; and verify the integration of the supporting auxiliary system components.

The following items will be tested using natural gas, hydrogen and intermediate blends of the two:

- Ignition and operability at full load and during transient operating conditions
- Load step management and full and partial load rejection
- Control logic and sequence optimization

- Performances validation (power, fuel consumption, heat rate, exhaust temperature and pressure, efficiency)
- NOx emissions
- CO emissions during case of blended fuel tests
- Flame detection
- Staging valve tuning

Data post-processing will be analyzed and will be the subject of a future paper, which will also include a detailed discussion of the combustion system characterization as a function of load variation and fuel composition.

CONCLUSIONS

The research and development effort over the last three years has led to the successful design and validation of a gas turbine capable of operating continuously using 100% hydrogen fuel.

The core of the design and validation activity has been focused on the NovaLTTM16 combustion system, using past gas turbine hydrogen experience with current design methodologies, numerical model simulation, component and full-scale combustion rig testing.

ACKNWOLEDGMENTS

This project has received funding from the European Union’s Horizon 2020 research and innovation program agreement No. 884157.

REFERENCES

[1] International Energy Agency Report, CO2 Emissions in 2022, IEA Publications, March 2023.

[2] UNFCCC, Paris Agreement, Paris Climate Change Conference – November 2015, United Nations Committee on Climate Change, 2015.

[3] McKinsey & Company Report, McKinsey Energy Insights Global Energy Perspective 2022, McKinsey & Company, April 2022.

[4] World Energy Council Report, World Energy Trilemma Index 2022, World Energy Council in partnership with Oliver Wyman, 2022.

[5] Canadian Net-Zero Emissions Accountability Act, S.C. 2021, C.22, http://laws-lois.justice.gc.ca, March 31, 2023.

[6] Government of Canada Report, Hydrogen Strategy for Canada, Seizing the Opportunities for Hydrogen, A Call to Action, December 2022.

[7] D. Bellotti, S.Gabriele, J.Runyon, L.Pilotti, A. Cancelli, and A. Kalantari, Hydrogen Deployment In Centralised Power Generation A Techno-Economic Case Study, European Turbine Network (ETN) Global Report, April 2022.

[8] M. Bothien, P. Brehaus, P. Griebel, B. Kaplan, G. Laagland, and P. Stuttaford. Hydrogen Gas Turbines – The Path Towards a Zero-Carbon Gas Turbine, European Turbine Network (ETN) Global Report, January2020.

[9] Baker Hughes Case Study, Our Turbine for the Fusina Power Plant was at Least 13 Years Ahead of the Hydrogen Curve, Bakerhughes_Case_FusinaH2GasTurbine_A4-092722, https://www.bakerhughes.com/case-study/our-turbine-fusina-power-plant-was-least-13-years-ahead-h2-curve, September 12, 2022.

[10] M. Cerutti, E. Pucci, C. Romano, V. R. Dabiru. “Development Of A Hydrogen Fueled Gas Turbine Combustion System From Conceptual Through Full Scale Verification Test”, GT2023-102502, Proceedings of ASME Turbo Expo 2023 (Boston, Massachusetts, 2023).

[11] M. Cerutti, N. Giannini, G. Ceccherini, R. Meloni, E. Mastoni, C. Romano, and G. Riccio. “Dry Low NOx Emissions Operability Enhancement of a Heavy-Duty Gas Turbine by Means of Fuel Burner Development and Testing”, GT2018-76587, Proceedings of ASME Turbo Expo 2018 (Olso, Norway 2018).

[12] D.R. Noble, Q. Zhang, A. Shareef, J. Toothle, A. Meyers and T. Lieuwen. “Syngas Mixture Composition Effects Upon Flashback and Blowout”, GT2006-90470, Proceeding of the ASME Turbo Expo 2006. (Barcelona, Spain 2006).

[13] R. Meloni, M. Cerutti, A. Zucca, and M. Mazzoni. "Numerical Modeling of NOx Emissions and Flame Stabilization Mechanisms in Gas Turbine Burners Operating with Hydrogen and Hydrogen-Methane Blends", GT2020-15432, Proceedings of ASME Turbo Expo 2023, (Online, 2020).