MOVING GAS TURBINE PACKAGE FROM CONVENTIONAL GAS TO HYDROGEN BLEND

Baldini, M.[1], Cinelli, R.[2], Minotti, S.[3], Pampaloni, G.4, Quartieri, E.[5], Rossin, S.[6]
[1] Baker Hughes, Via F. Matteucci 2, Firenze, 50127, Italy, marco.baldini@bakerhughes.com
[2] Baker Hughes, Via F. Matteucci 2, Firenze, 50127, Italy, rossella.cinelli@bakerhughes.com
[3] Baker Hughes, Via F. Matteucci 2, Firenze, 50127, Italy, stefano.minotti@bakerhughes.com
[4] Baker Hughes, Via F. Matteucci 2, Firenze, 50127, Italy, giacomo.pampaloni@bakerhughes.com
[5] Baker Hughes, Via F. Matteucci 2, Firenze, 50127, Italy, eugenio.quartieri@bakerhughes.com
[1] Baker Hughes, Via F. Matteucci 2, Firenze, 50127, Italy, stefano.rossin@bakerhughes.com

ABSTRACT

The current greatest challenge, that all gas turbine manufactures and users have in front of them for the years to come, is the energy transition while reducing CO2 footprint and to contrast climate change. To this aim the introduction of hydrogen as fuel gas (or its blend) is playing a very important role. The benefit from an environmental point of view is undisputed, but the presence of hydrogen introduces a series of safety related aspects to be considered for the design of all systems of a gas turbine package. Most of the design standards developed and adopted in the past are based on conventional natural gas, however physical properties of hydrogen require to analyze additional aspects or revise the current ones. In this context, the design for safety is paramount as it is strongly impacted by the low energy ignition of hydrogen blend fuels. Baker Hughes has built its experience on several sites, different Customers and applications currently installed. These gas turbines run with a variety of hydrogen blends, with concentration as high as 100% hydrogen. Baker Hughes has achieved several milestones moving from design to experimental set up leveraging the internal infrastructures consolidating design assumptions. In this work the critical aspects such as material selection, instrumentation, electrical devices and components are discussed in the framework of package safety with the aim to evolve conventional design minimizing the impacts on package configurations.

1.0 INTRODUCTION

The world climate change is imposing to mankind a great challenge, all of us needs to radically modify our lifestyle. This is mainly true for those countries which are the greatest energy consumers and to accomplish this mission, all companies in the energy market are called to introduce new ways, new technologies, new methods to deliver energy. This is essential, since at the same time it shall be guaranteed the continuous development and growth of all countries in a sustainable way reducing the carbon footprint. In this context of energy transition, renewable energy sources, mainly wind and solar energy, will have a crucial role. For their own nature, they are not sufficiently stable to provide a continuous power availability. The gas turbines can be efficiently integrated with renewable energy sources since they are flexible and capable to perform frequent starts giving a fast response of power demand. In this scenario, gas turbines operated with hydrogen will facilitate energy transition for carbon footprint reduction and generally contribute to clean energy taking advantage of missing CO2 emissions from combustion [1] (see Fig. 1). This goal can be reached by using green or blue hydrogen as combustion fuel. The role of gas turbine is essential since they can balance the energy system both in short and long term period. Currently, they are able to accept hydrogen as part of fuel blend up to 100% in some cases, with the aim of extending the ability to burn pure hydrogen on all gas turbines.

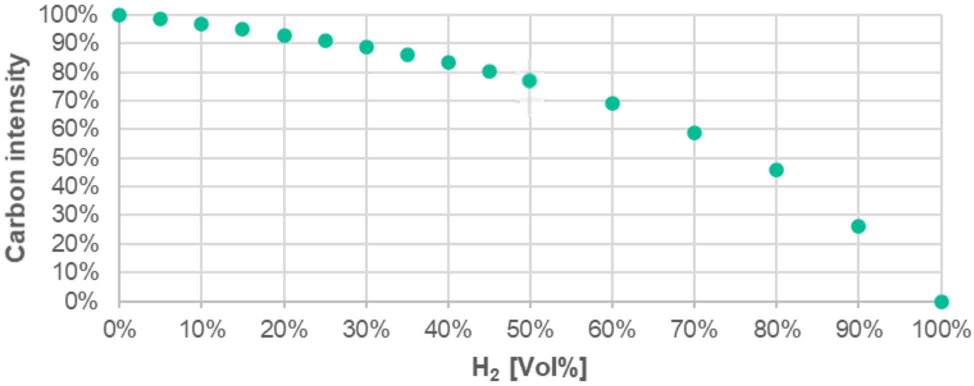

Figure 1: carbon intensity of methane vs. hydrogen blends
© 2021 Baker Hughes Company – All rights reserved

For all these reasons, Baker Hughes, as manufacturer and packager of gas turbines, is committed to reducing emissions by 50% by 2030 and net-zero by 2050. Baker Hughes is developing solutions to be implemented on engines capable to burn hydrogen blends or 100% strong of its experience, both for new projects and at the same time retrofit on existing and operating units. The use of pure hydrogen as fuel for gas turbine is very attracting for the fact the exhaust gas is completely free of CO2, but another potential benefit is given by the possibility to combine hydrogen with natural gas in several worldwide applications, from upstream to downstream, in order to reduce the carbon emissions with immediate effect. Looking across Baker Hughes gas turbine fleet, the maximum allowable hydrogen concentration varies significantly depending on different combustion technologies. However, the introduction of hydrogen generates challenges such as: proper selection and maintenance of combustor material, combustion dynamics, stability and related consequences on NOx emissions and finally the design of auxiliary systems.

A gas turbine engine is packaged with all mechanical and electrical items required for its corrected functioning. Commonly, a gas turbine and part of these items are installed inside an acoustic enclosure that is used to isolate the engine from the surrounding environmental. Therefore, a gas turbine package can include beyond the gas turbine itself (inlet plenum, axial compressor, combustors, turbine and exhaust plenum) several components like bleed, supply, drain and vent piping, various equipment like control and safety valves, instrumentation, electrical cables etc. This work will mainly review and focus on the impacts derived by hydrogen introduction for the design of gas turbine package and generally all auxiliary systems. Such systems like fuel feeding, instruments and control logic, package ventilation, firefighting, are designed to ensure proper operation of the engine, but also to assure the safety of personnel and assets. For this reason, it is essential to use system engineering approach to define the key factors to be upgraded improving the safety and without increasing complexity of the entire system.

2.0 BAKER HUGHES PRODUCT OFFERING ON HYDROGEN

Baker Hughes has a deep and long lasting experience in developing and building unique solutions in the Oil&Gas, Power Generation and Industry space, deeply committed in reducing emissions by leveraging a large product portfolio across the hydrogen value chain (Fig. 2). Turbomachinery solutions are already present in several segments, from production to utilization, both on compression and gas turbines systems.

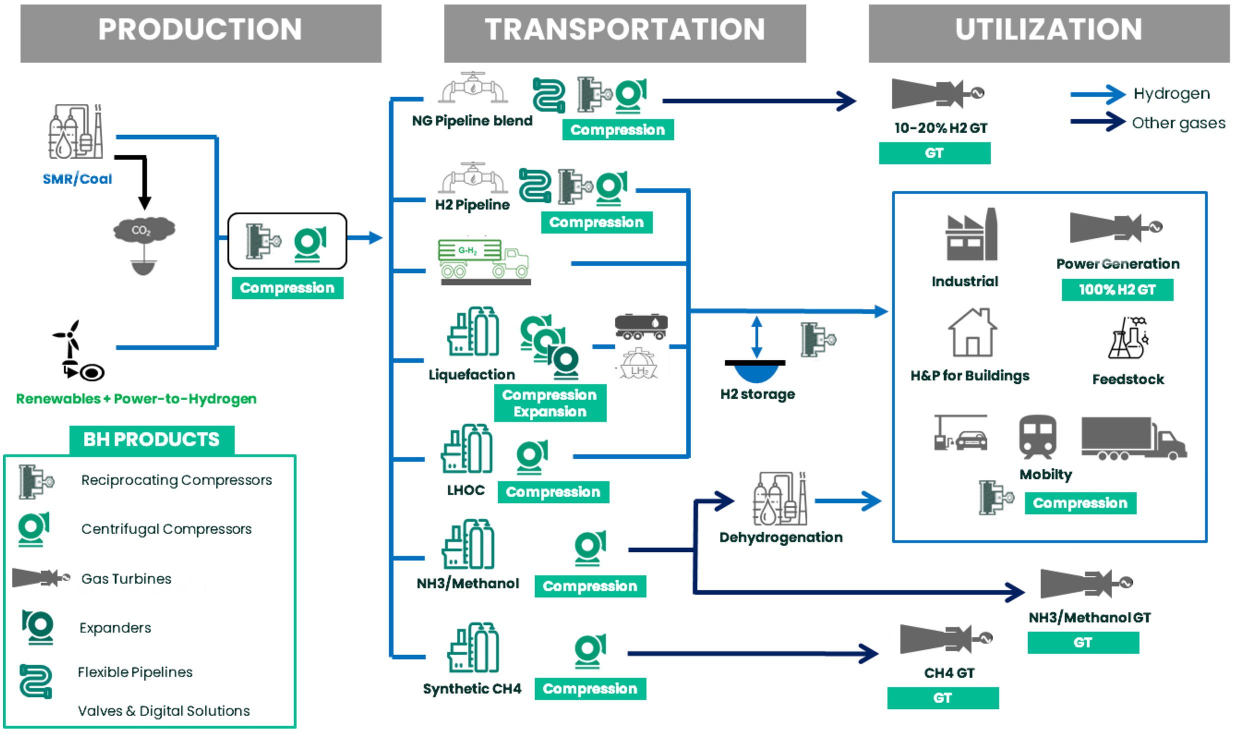

Figure 2: Baker Hughes portfolio across hydrogen value chain.
© 2021 Baker Hughes Company – All rights reserved

In the Turbomachinery business Baker Hughes has a long-lasting expertise on gas turbine burning a variety of fuels from liquid to conventional and synthetic gas as well as on the use of hydrogen as fuel blend since more than 50 years. More than 70 units are installed and running on hydrogen with fuel gas blends ranging from 10% to 100% hydrogen by volume depending on machine type and customer needs. Fig. 3 summarizes this range of experience of Baker Hughes. Specific solutions have been implemented on a large series of gas turbine models covering a large power range, from heavy duty to aeroderivative engines. Depending on specific models, these gas turbines are used in on-shore and off-shore applications, for generator or mechanical drive. Up to now, heavy duty engines demonstrated greater flexibility. Nevertheless, all gas turbines in Baker Hughes portfolio have the capability to burn hydrogen.

Fig. 3 shows that most cases have a fuel gas blend with a significant percentage of hydrogen around 50% by volume and in PGT10 case up to 100%. The first 100% hydrogen experience in the world, built in 2008 and commissioned is 2009, is a PGT10 turbine for Enel Fusina Hydrogen Power Project in Italy [2,3,4,5,6]. The PGT10 gas turbine is a heavy-duty single shaft engine and rated for 11.2 MW at ISO dry conditions (15°C, sea level according to ISO 3977 [7]). On the recently developed Nova LT family [7, 8], several internal tests have been successfully completed for the 16 MW model proving the ability to start and run on 100% hydrogen, with the capability to switch from natural gas to gas blends up to 100% hydrogen without significant hardware modifications. The annular combustor design and dual-shaft configuration enable wide operating range and a high degree of control. On gas turbine package side additional assessments are ongoing to release the final configuration.

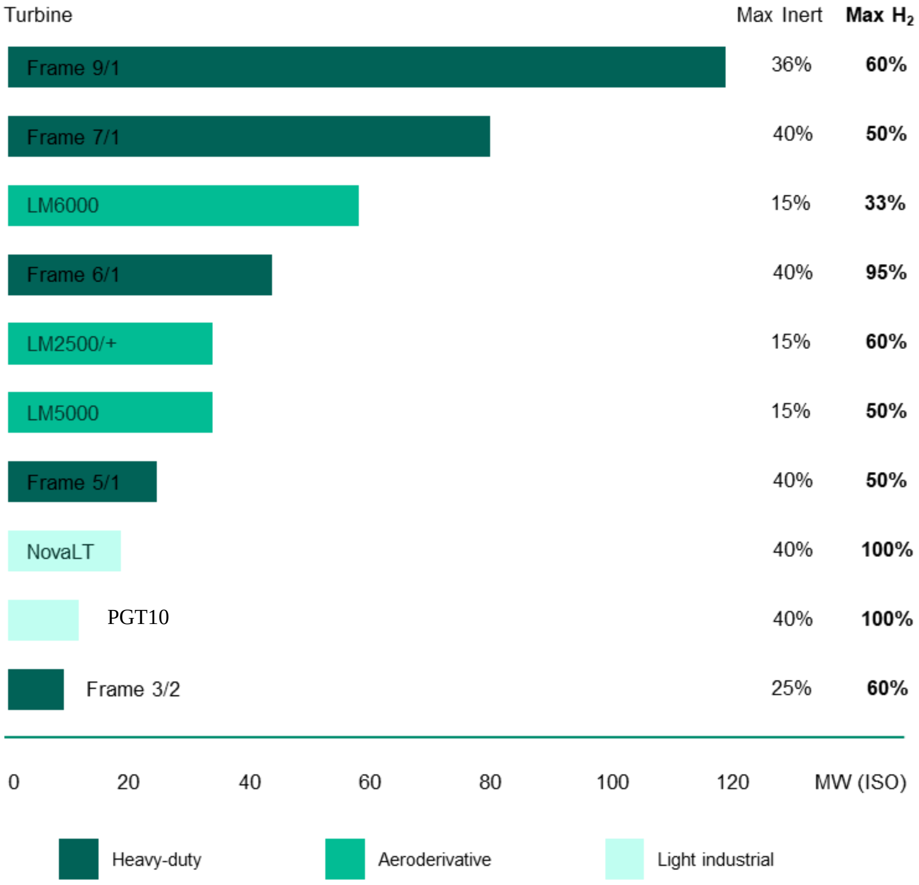

Figure 3: range of experience in burning hydrogen.
© 2021 Baker Hughes Company – All rights reserved

In the past decades, the usage of hydrogen as fuel in gas turbine applications was limited to the availability in refinery and chemical plants as a byproduct of other processes, without any specific decarbonization need. Today, the scenario is radically changed in the context of energy transition introducing a strong need for a wider portfolio in a framework of fuel flexibility. For this reason, it is crucial to have a well thought system engineering approach to evaluate in a holistic way the impact generated by hydrogen, with a strong focus on safety. Worthwhile to mention that the several communities growing around hydrogen developments are deeply focusing on the regulation, codes and standards definition for a robust approach in the safe management of hydrogen gas.

With respect to conventional natural gas, hydrogen has a larger flammability range (4-75% vs. 4.4-17% for methane) [9] with a lower ignition energy (0.017 mJ vs. 0.29 mJ for methane) [10], lower density (relative to air 0.07 vs. 0.55 for methane) [9] and a very high diffusivity within body-centered cubic structures generating the phenomenon of "Hydrogen Embrittlement” [10, 11]. All these characteristics affect the design of some auxiliary systems. The gas turbine packager shall take all the appropriate measures during the design phase to minimize any risk of leakage looking the opportunity to eliminate them whenever is possible. Main systems and items impacted are described in the following sections.

3.0 IMPACT ON AUXILIARIES

3.1 Impacts on fuel gas system

The impacts on fuel gas system arrangement depend on the hydrogen content as well as the specific operability requirements of each single engine. The percentage of hydrogen in the fuel gas blend is particularly important for the definition of the start-up phase. It could also create the need to control emissions, for example using DLN/DLE combustion systems, wet injection or selective catalytic reduction technology in the gas turbine exhaust duct.

Based on NFPA 69 [12] and Baker Hughes experience, fuel gas system can require an inert gas purge when hydrogen percentage is beyond a certain limit. An internal risk assessment can define this limit depending on the specific application. The purpose is to minimize the possibility of the formation of air-hydrogen mixture which could ignite. To be noted that even static electricity has been evaluated as a source of ignition, with static charge created by the gas flowing through the pipe. It could provide a sufficient energy to ignite the gas when there is flammable mix with air.

The inert gas, usually nitrogen, is used as a safety barrier between air, hence oxygen, and hydrogen everywhere they could be in contact outside of combustion chambers. This is necessary because the minimum energy required to ignite hydrogen fuel is significantly less than other gas turbine fuels.

The inert gas purge system has an impact on mechanical arrangement and control logic for the introduction of dedicated lines and control valves, as well as for the request of availability of inert medium at the required pressure. Purge can be required for example before a start-up, after a shut down or before a fuel change over in case of multi-fuel gas engine.

The system can have two main purposes:

- temporary flushing of fuel gas piping that could have air flowing in some operating phases;
- continuously buffering of certain volume to keep separated hot air from axial compressor and hydrogen.

3.2 Material selection

Component material of fuel gas system shall be selected taking into account the proper suitability for the service, avoiding any issue of hydrogen embrittlement (HE). The correct selection of material is essential to avoid numerous fuel leakages, since a common source of gas leak is due to piping and equipment rupture caused by hydrogen embrittlement.

HE can cause a significant deterioration in the mechanical properties of metals. This process produces a decrease of metal fracture toughness or ductility due to the presence of atomic hydrogen into the structure. Due to embrittlement, the reduction of fracture loads can occur at levels well below the yield strength of the material [13]. According to tests conducted by NASA [14], austenitic stainless steels should be selected as structural material for hydrogen service, because their microstructure is not very sensitive to embrittlement. In Oil&Gas applications, fuel gas pressure and temperature are usually delivered respectively around 50 barg and 100°C [1]. For these operating conditions, the metastable austenitic stainless steel (AISI 304/316L) is a material class tolerant to hydrogen embrittlement. The carbon steel should not be utilized when fuel temperature increases around to 200°C, due to the hydrogen migration through the material [15]. At this high temperature, 316/316L grade stainless steel should be preferred to carbon steel also to avoid Hydrogen Attack.

HE is also related to the stress level of material and its mechanical properties as hardness. Therefore, particular attention shall be posed to avoid high hardness martensitic steel and high-strength low-alloy steel (HSLA). These are often used as standard material for valve stem and trim, which are subject to tensile and torsional loads. As consequence of stress concentration and unqualified properties of materials, many failures can occur on valve stem as shown by Jiang et al. [16].

As hydrogen is more prone to leakage than other gases, great care should be paid to flanged connection and compression fittings. The taper-threaded joints NPT, defined in ANSI/ASME B1.20.1 [17], are also allowed with hydrogen fuel up to a pressure of 3000 psiG (20.7 MPa), as reported in ASME B31.12 [11]. It recommends the use of an anaerobic sealant on the thread. All elastomers and plastic materials, that are able to maintain their integrity at elevated temperatures, are compatible with hydrogen gaseous and they can be used for flange and valve gaskets or sealing elements [18]. The design shall incorporate features that minimize the release of hydrogen if the seal melts during a fire. Plastics such as PCTFE, PTFE (Teflon) and polyamide (known as Nylon) are commonly used. Elastomers such as Buna-N (Nitrile), chloroprene rubber (Neoprene), fluorocarbon rubber (known as Viton), and other suitable compounds also may be used depending on the service temperature [19]. In case a flexible connection is unavoidable it should be made of corrosion resistant metal with a metal braid and armor (as AISI 316/316L SS reinforced with braided metal) [20].

According to ASME B31.12 [11], welded connections should be preferred and shall be used wherever possible to minimize potential leak sources, except for welding that would negatively affect hardness and material properties. The qualified welding procedure shall meet the acceptance criteria (e.g. hardness limit, defect free) carried over in ASME standards as well. It is worth noting that, it is recommended to avoid or minimize cold plastic deformation from operations such as cold bending and the normalize or fully annealing cold-worked materials. These procedures could affect mechanical proprieties and may promote the hydrogen embrittlement of the materials.

3.3 Impact on firefighting system

In case of retrofit for introducing hydrogen in gas turbine packages, it is necessary to upgrade the fire-fighting system, if the extinguishing medium is CO2. When hydrogen content is above 4% by volume, NFPA12 [21] requires 75% by volume of CO2 concentration to extinguish the fire, while it is required only 34% for pure methane.

The flammability zone may be presented on either a triangular diagram. The discharge of inert gas allows to be out of this zone. Mixture of hydrogen gaseous and air is flammable within the range 4%-74% by vol. and the minimum carbon dioxide concentration to render the mixture nonflammable is at the "nose" of the triangular curve. Fig. 4 is extracted from the experimental works of the U.S. Bureau of Mines [22]. This shows the minimum carbon dioxide concentration to extinguish a hydrogen-air mixture.

According to NFPA 12 [21], the CO2 design concentration should be determined by adding a factor +20% to the minimum concentration. Since there are several flammable substances, the extinguish system design shall be based on the fuel with the highest extinguishing concentration. This means that a greater carbon dioxide concentration should be provided even with low hydrogen blend (4% by vol.).

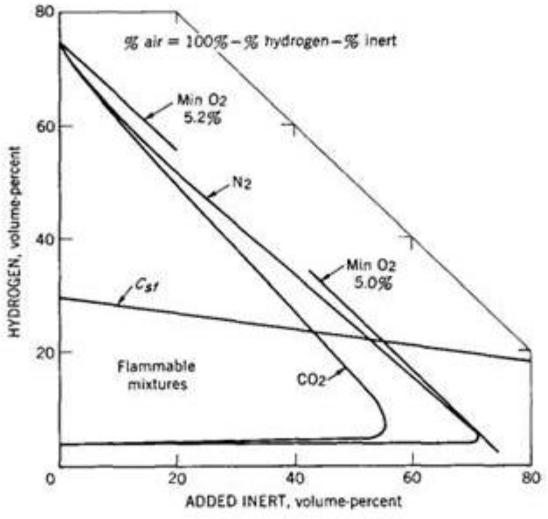

Figure 4: Flammability Triangular Diagram of the Hydrogen-Inert Gas-Air Mixtures. [22]

3.4 Instrumentation

All possible sources of ignition inside the package should be mitigated avoiding any potentially sparkling items. A systems-engineering approach is essential to select properly instruments and items compatible with hydrogen. In brownfield applications are mandatory a detailed assessment of materials used inside gas turbine package and on auxiliary systems.

The majority of the items do not require significant changes when hydrogen is up to 30% where common technologies can be adopted.

As per current installations, each component located in the hazardous area classified has to be in compliance with the required standard classifications, depending on the installation country (e.g. EN60079, IEC60079, NFPA70) and properly certified. The percentage of hydrogen in the fuel blended determines the hazardous area certification required for instruments and electrical devices. For mixture with hydrogen concentration greater than 30% vol. IIC or IIB+H2 certification is required for EN/IEC60079 standard [23] while for NFPA70 standard [24] is named certification for Group B. Therefore, the impact could be significant in case of retrofit existing units, since major part of components are typically certified for use in Group IIA or IIB.

Flame detectors commonly used with natural gas are also suitable for pure hydrogen or blend. Nevertheless, for high hydrogen content, these could require careful evaluation due to dim hydrogen flame. Compared to most common hydrocarbon flames, hydrogen emits little visible light or IR radiant heat. Furthermore, radiation of a hydrogen flame is low due to limited radiation emission in the infrared field, so the ultraviolet technology is recommended.

Ventilation flow analysis is needed to support the appropriate definition of the gas detection philosophy which is obviously affected by the dilution obtained through the ventilation flow [25, 26]. Gas detectors [27] are used to prevent the hazardous risks where a potential ignition could occur.

Currently for natural gas applications, the infrared technology is predominant to catalytic one due to some features such as response time and required maintenance intervals. This technology is not able to properly reveal hydrogen as they cannot detect diatomic gas molecules, but it can still be used in blended hydrogen gas taking advantage from the natural gas detection adjusting the threshold levels. If gas is detected above a certain value, the control system activates an emergency shut down and at the same time an immediate depressurization of the fuel gas system. Adopting infrared system, the response time is reduced respect catalytic one.

Gas detectors shall be located in the ventilation outlet duct since in this way they are able to monitor any possible leakage everywhere from the package and to generate an emergency shut down with fuel gas line depressurization. It is also recommended to install additional gas detectors inside the gas turbine enclosure (e.g. on the fuel gas skid) to anticipate as much as possible the emergency shut down and fuel gas depressurization considering that hydrogen is very reactive (minimum ignition energy of hydrogen-air stoichiometric mixture is 12 times greater than natural gas).

Actually, other technologies of gas detection are under investigation to reduce the response time, such as the ultrasound sensors. These have a very fast response, but they show some critical challenges due to the large noise spectrum of a gas turbine package during its entire operation.

3.5 Fuel gas analyser

It is a good practice to measure the gas composition with accuracy, to ensure that inputs to the unit control system not exceeding the defined limits and can vary during the operations. Gas chromatograph capable to detect hydrogen content is required for all cases where the expected concentration of hydrogen is high.

4.0 AUTO-IGNITION MECHANISMS

A proper selection of materials of fuel gas systems and package instrumentation and equipment is a preliminary condition to reduce the risk to have an ignition of an accidental fuel gas leak. Unfortunately, this is not sufficient to completely eliminate the risk, because for any gas turbine package it cannot be excluded the possibility to have a leak. The risk of the uncontrolled combustion of accidentally released hydrogen due to an auto-ignition mechanism has to be minimized. Understanding the auto-ignition mechanisms hazards is crucial to prevent and control them. The electrostatic sparks, hot surfaces and hot gas jets could represent the most common autoignition sources.

An electrostatic spark created by gas itself flowing through a pipe can be sufficient to cause an ignition in case hydrogen is mixed with air. Therefore, ATEX certified paints should be selected (i.e. Carbomastic 15LT ATEX or Carbocrylic 1290 ATEX) and tested in accordance to ISO 80079-36 [28], to dissipate electrostatic discharges (i.e. brush and propagating brush discharges). By using these conductive ATEX paints, it is possible to avoid discharges without limiting the piping paint thickness.

Moreover, as good design practice, a gas turbine packager shall compare the fuel gas autoignition temperature and the maximum skin temperature reached by any component of the package, regardless the presence of hydrogen. When the first one is lower, the engine can be defined “hot” in the perspective of hot surface ignition. Tabulated Auto-Ignition Temperature (AIT) values are obtained performing standard test procedures [9] and provide a quantitative description of autoignition likelihood for various fuels. These values have a limited range of applicability, since the standard tests are very close to adiabatic conditions where heat losses and the effect of the buoyant convective flow are minimized. The AIT value is obtained in an environment enclosed by heated surfaces, where the flammable gas-air mixture can stay indefinitely, since there is no way to escape. In gas turbine package the scenario is completely different, both buoyancy and turbulence created by ventilation flow promote dilution of flammable mixture its removal from hot surfaces. In such conditions, the ignition temperature will result to be much higher than the AIT to compensate a brief exposure time. Other factors also affect the ignition: flow regime, residence time, surface size and shape, material and flammable mixture pressure and temperature before the contact with hot surface [29]. Ignition temperature is lower for concave surfaces than convex ones, is inversely proportional to residence time and surface extension, while increases with higher turbulence due to greater convective heat exchange. For all these reasons, it is common to talk about Hot Surface Ignition Temperature (HSIT) [30] instead of AIT, since HSIT can be higher than AIT [30, 31, 32].

In the last years, several experimental results were published by different research groups. Significant experimental tests were performed by J. E. Shepherd et. al. [33, 34, 35] and Fig. 5 shows an ignition threshold temperature for stoichiometric hydrogen-air mixture above 700°C (1000°K) [33], while tabulated AIT value in [9] is 560°C.

Due to the complex nature of this phenomenon and all possible operation scenarios, it is not easy to define the exact HSIT for a gas turbine application. In order to assume a safety margin, the tabulated AIT can be considered, although these can be considerably lower than experimental outcomes. In any case, such assumption shall be based on a risk assessment that considers the whole package design.

Furthermore, a jet of hot air or gas could also produce ignition when it comes in close contact with a hydrogen-air mixture. The jet temperature required to ignite a flammable gas-air mixture depends on the dimensions, composition and velocity of the jet. Several experimental works demonstrated that the ignition temperatures due to hot jets are much higher than tabulated AIT, as in [36] where hot air jet above 600°C is required. Such phenomenon is not likely to occur in a gas turbine package for the high temperature required and the simultaneous presence of an unexpected gas leak.

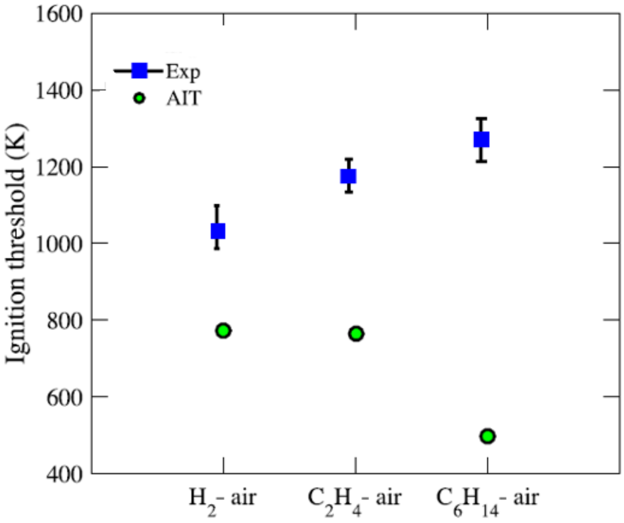

Figure 5: Comparison between AIT and experimental hot surface ignition temperature [33]

Finally, the hydrogen spontaneous ignition due to a sudden release from high-pressure equipment is a phenomenon requiring attention. In particular diffusion ignition for the first time defined by [37] can occur when high pressure hydrogen is present inside a pipe and released into the atmosphere through a hole. The experimental results performed by different research group as Molkov et al. [38, 39, 40] show that exists a hydrogen critical pressure leading to ignition. This critical pressure value depends mainly on the tube length and the diameter of the hole. In most experiments, the minimum pressure of hydrogen in fuel gas piping to have ignition is above 60 bar. In the gas turbine applications, the hydrogen gas pressure in fuel gas piping is limited to lower values and hence in a range where the diffusion ignition is uncommon.

5.0 VENTILATION SYSTEM

In this context, a fundamental role is played by the ventilation system of the gas turbine enclosure that has to dilute as much as possible the leaks everywhere they can occur. The ventilation flow can be seen like a safety barrier to avoid hydrogen ignition. For this reason, it is required to perform detailed analyses about the distribution of the ventilation flow inside the gas turbine enclosure in order to identify the zones less ventilated and so more prone to accumulate gas in case of leak [41, 42].

Since hydrogen is lighter than air and has a very high diffusivity, the zones considered critical for gas accumulation in case of conventional fuel could not be the same in case of presence of hydrogen. Further aspects to be considered are the ignitability of hydrogen and auto ignition temperature, respectively lower and higher than methane. All these aspects require dedicated CFD studies. The first goal is to identify the less ventilated zones inside the enclosure. Since these regions are more prone to accumulate gas in case of leak, it is necessary to identify the connections of fuel gas supply line that are the closest ones to these identified zones. Once selected, it is executed a study said gas leak analysis, where it is simulated a leak from fuel gas system. For this analysis, it is required to estimate the size of leakage section considering the fuel gas condition. Due to the high ratio between gas pressure inside piping and air pressure inside the enclosure, the resulting leak generates an under-expanded jet [43, 44, 45]. The final aim of this dilution study is to estimate the volume of the flammable cloud [46] entrapped inside the enclosure and to check its location, an example is shown in Fig. 6. It is important to check where this flammable cloud is located respect to the hot surfaces. Both steady and unsteady simulations are run [47].

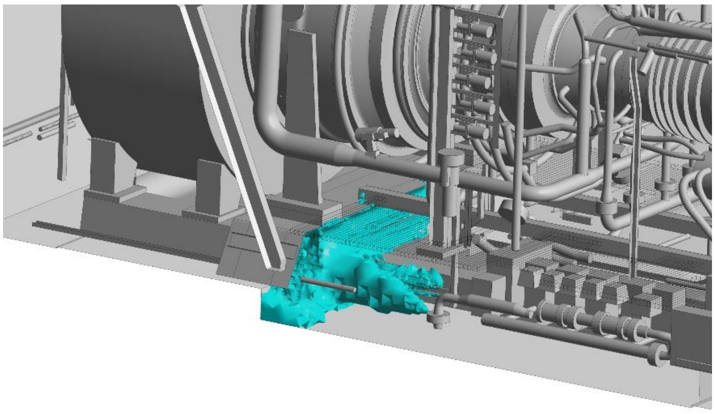

Figure 6: gas leak cloud at 100% LEL inside a gas turbine package.

All these aspects are much more relevant for “hot” engines. It is defined “hot” engine those gas turbines having the maximum metal skin temperature higher than AIT. Insulation of the engine is not considered a good solution because, even if it reduces the global heat rejection of the package, in case of leak it does not avoid contact between fuel gas and hot surface, since insulation does not have a perfect seal. At the same time, if this scenario occurs, the insulation itself represents an obstacle that could increase the residence time and reduce the convective heat exchange of air ventilation flow. Both these factors create a reduction of HSIT and for this reason, Baker Hughes prefers to avoid insulation to reduce the risk for hot surface ignition.

6.0 CONCLUSIONS

This work shows the main impacts in the design of gas turbine auxiliary systems due to the introduction of hydrogen. For the peculiarities of its physical proprieties, hydrogen somehow increases critical challenges that need to be accounted for in the gas turbine packaging. Hot gas ignition, hot surface ignition, spark ignition as well as diffusive ignition phenomena have to be considered during the design phases of all the systems around a gas turbine. These units are confined in an enclosed space where the chance of gas leak must be managed with an approach toward product and process safety, where an early and quick detection together with appropriate ventilation system can be key for a good, reliable and safe product.

The extremely low ignition energy, the low ignition temperature and the extremely thin density makes hydrogen a challenging gas for a gas turbine package where the many connections present require strict design rules. A good material selection, high quality procedures and a smart geometry configuration can be often the only solution for the new generation gas turbines.

There are many other apparently small aspects that come into picture, when considering for instance the dim flame characteristic which make the flame not being easily detected or even a more simple painting which can be a challenge in the electrostatic spark issue.

Baker Hughes is currently seeing a growing demand on hydrogen fuel gas turbine applications. However, the current gap in policies, regulation, codes and standard need to be addressed leveraging internal knowledge as well as laboratories and testing facilities. Baker Hughes as gas turbine OEM and packager, currently holds many domain expertise with a variety of specific competencies which well fit in the hydrogen space.

Baker Hughes is actively participating to international committees like Hydrogen Europe and Hydrogen Council contributing to such important energy transition challenge.

7.0 REFERENCES

1. ETN Global, Hydrogen Gas Turbine – The Path toward a Zero-Carbon Gas Turbine, January 2020.
2. Benovsky, P., Carrai, L., Sigali, S., The Enel Research and Development Program for a Pure Hydrogen-fed Gas Turbine, 30th Meeting on Combustion, Ischia, Italy, 2007.
3. Balestri, M., Benelli, G., Donatini, F., Arlati, F., Conti, G., Enel's Fusina Hydrogen-Fed Power Generation Plant, 2007 International Conference on Clean Electrical Power, 21-23 May, 2007, Capri, Italy.
4. Benovsky, P., Brunetti, I., Sigali, S., Leroy, C., Gheri, P., Cocchi, S., NOx Reduction Strategy in GE10 Hydrogen-Fuelled Heavy Duty Gas Turbine, GT2008-51270, Proceeding of ASME Turbo Expo 2008, June 9-13, 2008, Berlin, Germany.
5. Cocchi, S., Provenzale, M., Cinti, V., Carrai, L., Sigali, S., Cappetti, D., Experimental Characterization of a Hydrogen Fuelled Combustor with Reduced NOx Emissions for a 10 MW Class Gas Turbine, GT2008-51271, Proceedings of ASME Turbo Expo 2008, June 9-13, 2008, Berlin, Germany
6. Cocchi, S., Sigali, S., Development of a Low-NOX Hydrogen-Fuelled Combustor for 10 MW Class Gas Turbines, GT2010-23348, Proceeding of ASME Turbo Expo 2010, June 14-18, 2010, Glaskow, UK.
7. Cerutti, M., Cocchi, S., Modi, R., Sigali, S., Bruti, G., Hydrogen Fueled Dry Low NOx Gas Turbine Combustor Conceptual Design, GT2014-26136, `Proceedings of ASME Turbo Expo 2014,.June 16-20, 2014, Düsseldorf, Germany.
8. Tarenzi, M., Asti, A., Baldini, M., Carta, R., Giannini, N., NovaLT12 Hydrogen Fuel Capabilities, Pipeline Technology Conference 2021, March 15-18, 2021, online conference.
9. IEC 60079-20-1:2010-09, Explosive atmospheres – Part 20-1: Material Characteristics for Gas and Vapour Classification – Test Methods and Data.
10. ISO/TR 15916:2015, Basic Considerations for the Safety of Hydrogen Systems.
11. ASME B31-12, Hydrogen Piping and Pipelines, 2020.
12. NFPA 69, Standard on Explosion Prevention Systems, 2019.
13. San Marchi, C., Somerday, B.P., Technical Reference for Hydrogen Compatibility of Materials, Sandia Report, SAND2012-7321, September 2012.
14. Jewett, R.P., Walter, R.J., Chandler, W.T., Frohmberg, R.P., Hydrogen Environment Embrittlement of Metals, NASA CR-2163, March 1973.
15. Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants, API Recommended Practice 941, Sixth Edition, March 2004.
16. Jiang, T., Zhong, J., Zhang, X., Wang, W., Guan, K., Hydrogen embrittlement induced fracture of 17-4 PH stainless steel valve stem, Engineering Failure Analysis, Volume 113, July 2020, 104576
17. ASME B1.20.1 Pipe Threads, General Purpose, Inch, 2013 (R2018).
18. AIGA 033/14, Hydrogen Pipeline Systems, Asia Industrial Gas Association, 2014.
19. ISO 11114-2:2013, Gas Cylinders - Compatibility of Cylinder and Valve Materials with Gas Contents - Part 2: Non-Metallic Materials.
20. ISO 19880-5:2019, Gaseous Hydrogen - Fuelling Stations - Part 5: Dispenser Hoses and Hose Assemblies.
21. NFPA 12, Standard on Carbon Dioxide Extinguishing Systems, 2018.
22. Zabetakis , M.G., Flammability Characteristics of Combustible Gases and Vapors, Bulletin 627, Bureau of Mines, 1970.
23. IEC 60079-0:2017, Explosive atmospheres – Part 0: Equipment – General requirements.
24. NFPA70, National Electrical Code, 2020.
25. Marangon, A., Carcassi, M.N., Hydrogen - Methane Mixtures: Dispersion and Stratification Studies, 4th International Conference on Hydrogen Safety, September 12-14, 2011, San Francisco, USA.

26. Ibrahim, O.K., Vaagsaether, K., Bjerketvedt, D., Experimental Study of Light Gas Dispersion in a Channel, International Conference on Hydrogen Safety, September 21-23, 2019, Adelaide, Australia.
27. Hall, J.E., Hooker, P., Jeffrey, K.E., Gas Detection of Hydrogen/Natural Gas Blends in the Gas Industry, International Conference on Hydrogen Safety, September 21-23, 2019, Adelaide, Australia.
28. ISO 80079-36:2016, Explosive Atmospheres - Part 36: Non-Electrical Equipment for Explosive Atmospheres - Basic Method and Requirements.
29. Pedersen, L.D., Nielsen, K.K., Yin, C., Sørensen, H., Fossan, I., Modelling of Hot Surface Ignition within Gas Turbines Subject to Flammable Gas in the Intake, GT2017-64698, Proceeding of ASME Turbo Expo 2017, June 26-30, 2017, Charlotte, NC, USA.
30. Ungut, A., James, H., Autoignition of Gaseous Fuel-Air Mixtures Near a Hot Surface, IChemE, Symposium Series No. 148, 2001.
31. Babrauskas, V., Ignition of Gases, Vapors, and Liquids by Hot Surfaces, International Symposium on Fire Investigation Science and Technology, May 20, 2008, Cincinnati OH.
32. Morreale, C., Marengo, S., Migliavacca, G., Maggioni, A., H2 Ignition by Hot Surfaces: Safety Issues and Test Methods, Proceedings of the 18th World Hydrogen Energy Conference, May 16.-21. 2010, Essen.
33. Boeck, L.R., Meijers, M., Kink, A., Mével, R., Shepherd, J.E., Ignition of fuel–air mixtures from a hot circular cylinder, Combustion and Flame 185 2,65–277, 2017.
34. Melguizo-Gavilanes, J., Boeck, L.R., Mével, R., Shepherd, J.E., Hot Surface Ignition of Stoichiometric Hydrogen-Air Mixtures, International Journal of Hydrogen, Energy 42(11), 7393-7403, 2017.
35. Mével, R., Melguizo-Gavilanes, J., Boeck, L.R., Shepherd, J.E., Experimental and numerical study of the ignition of hydrogen-air mixtures by a localized stationary hot surface, Journal of Heat and Fluid Flow, 76,154-169, 2019.
36. Kuchta, J.M., Cato, R.J., Hot Gas Ignition Temperatures of Hydrocarbon Fuel Vapor-Air Mixtures, Report of Investigation 6857, Bureau of Mines, 1966.
37. Wolanski, P, Wojcicki, S, Investigation into the Mechanism of the Diffusion Ignition of a Combustible Gas Flowing into an Oxidizing Atmosphere, Proceedings of the Combustion Institute, Vol. 14, pp. 1217-1223, 1972.
38. Molkov, V., Saffers, J-B., Hydrogen Jet Flames, International Journal of Hydrogen Energy, 2012
39. Molkov. V., Makarov, D.V., Bragin, M.V., Physics and Modelling of Under-Expanded Jets and Hydrogen Dispersion in Atmosphere, Proceedings of the 24th International Conference on Interaction of Intense Energy Fluxes with Matter, 1-6 March 2009, Elbrus, Russia.
40. Bragin, M.V., Molkov, V.V., Physics of Spontaneous Ignition of High-Pressure Hydrogen Release and Transition to Jet Fire, International Journal of Hydrogen Energy, Volume 36, Issue 3, pp. 2589-2596, 2011.
41. Corsini, A., Delibra, G., Giovannelli, M., Lucherini, G., Minotti, S., Rossin, S. and Tieghi, L., Identification of Poorly Ventilated Zones in Gas-Turbine Enclosures with Machine Learning, GT2019-91198, Proceedings of ASME Turbo Expo 2019, Phoenix, Arizona, USA, 2019.
42. Corsini, A., Delibra, G., Giovannelli, M., Lucherini, G., Minotti, S., Rossin, S. and Tieghi, L., Prediction of Ventilation Effectiveness for LM9000 Package with Machine Learning, GT2020-14916, Proceedings of ASME Turbo Expo 2020, June 22-26, 2020, Virtual Conference.
43. Franquet, E., Perrier, V., Gibout, S., Bruel, P., Free Underexpanded Jets in a Quiescent Medium: a Review, Prog Aerosp Sci, 77, pp. 25-53, 2015.
44. Li, X., Chowdhury, B.R., He, Q., Christopher, D.M., Hecht, E.S., Validation of Two-Layer Model for Underexpanded Hydrogen Jets, International Conference on Hydrogen Safety, September 21-23, 2019, Adelaide, Australia.

45. Rian, K.E., Modelling and Numerical Simulation of Hydrogen Jet Fires for Industrial Safety Analyses – Comparison with Large-Scale Experiments, International Conference on Hydrogen Safety, September 21-23, 2019, Adelaide, Australia.
46. ISO 21789:2009 Gas turbine applications – Safety.
47. Lucherini, G., Minotti, S. and Michelassi, V., The Impact of Model Assumptions on the CFD Assisted Design of Gas Turbine Packages, ASME paper GT2019-90781, Turbo Expo 2019, Phoenix, Arizona, USA, 2019.