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HYDROGEN-FIRED GAS TURBINES AND THE IMPACTS ON HEAT RECOVERY STEAM GENERATORS

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ABSTRACT

Investigating the impacts of increasing hydrogen (H_2) content in natural gas (NG) fuel in the gas turbine (GT) and supplementary firing on the Heat Recovery Steam Generator (HRSG), either with or without exhaust gas bypass system, requires careful attention to specific design aspects. Firing H_2 has potential impacts on NO_x emissions, exhaust volume flow, and water content.

To maintain NOx emission levels, the Selective Catalytic Reduction (SCR) needs enlargement. In new power plant construction, a larger spool duct should be considered to accommodate 100% H_2. Existing units may experience increased flue gas pressure drop, necessitating the consideration of duct and casing sizing, heating surfaces, internal gas flow distribution, and acoustic provisions in HRSG design.

The increase in water dew point is minimal up to 50%-vol H_2 content, but above this, condensation effects should be studied in existing installations with case by case solutions.

Due to the different heat transfer properties of the exhaust gas from H_2 combustion, the HRSG steam power output for a given heating surface might be different than that of natural gas. Especially for new plants, the HRSG can be designed to cope with a mixture or 100% hydrogen fired GT and will not be a limiting factor, taking into account the right measures suggested in this paper.

NOMENCLATURE

Symbols

CH_4	Methane
CO_2	Carbon dioxide
H_2	Hydrogen
H_2O	Water
NG	Natural gas
NOx	Nitrogen oxides

Abbreviations

CCPP	combined cycle power plant
CHPP	combined heat power plant
FW	feed water
GT	gas turbine
HRSG	heat recovery steam generator
ISO	ISO conditions (15°C @ 101.3 kPa)
LHV	lower heating value
NFPA	National Fire Protection Association
OEM	original equipment manufacturer
RH	relative humidity
SCR	selective catalytic reduction
WHRU	waste heat recovery unit

1 INTRODUCTION

Global pressure to reduce the use of traditional fossil fuels and the emission of green-house gases such as CO_2 is enormous. The worldwide emissions of CO_2 and other greenhouse gases will have to decline to reduce the effects of global warming. Consequently, the whole energy equipment sector is taking action. One of the key efforts in reducing CO_2 emissions from electricity generation is to replace the use of natural gas with hydrogen (H_2). The various gas turbine Original Equipment Manufacturers (OEMs), (1) as well as utilities and other users of gas turbines, are currently investigating the impact of firing H_2 in gas turbines and have committed to a development roadmap that allows gas turbines, both existing and new, to be able to fire up to 100% H_2 by 2030. Mixing H_2 with natural gas will result in an immediate CO_2 emission reduction. Figure 1 shows the non-linear relationship between increasing the hydrogen content (%vol) in natural gas fuel mixture and the resulting CO_2 emissions (in vol%). The most significant CO_2 savings are gained from replacing the last ~ 20% natural gas with the mixture of H_2 when expressed as volume fraction.

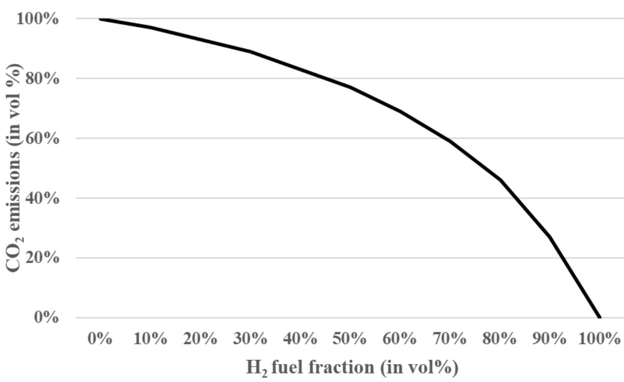

Figure 1. CO2 emissions (in vol%) as a function of increasing H2 content (in vol%) in the fuel mixture.

2 IMPACT OF H2 FIRING ON HRSG PERFORMANCE AND DESIGN

Switching from natural gas (mainly methane, CH_4) to H_2 does not only impact the GT but also the other components of Combined Cycle Power Plants (CCPP) or Combined Heat and Power Plant (CHPP). Although a significant fraction of the global gas turbine fleet is utilised in CCPP's or CHPP's, little focus is given to the effect of burning H2 on complementary equipment such as the HRSG.

This paper gives insight into the impacts and consequent design changes for the HRSG when H_2 is used as the primary fuel for the gas turbines and for supplementary firing inside the HRSG. NEM Energy (2) has investigated HRSG related technical challenges associated with H_2 firing. As the main component directly connected to the GT, the HRSG needs a special focus in the investigation, since H_2 firing will impact its design in many different aspects, such as:

1. Higher NO_x emissions in the exhaust gas, impacting the size and cost of Selective Catalytic Reduction (SCR);
2. Higher exhaust volume flow and exhaust gas inlet temperature;
3. Increased water content in the exhaust gas, leading to higher risk of water condensation in the cold end;
4. HRSG performance and gas pressure drop related impact;
5. Burner system related technical challenges, in case of supplementary firing (SF);
6. Safety aspect, related to potential H_2 accumulation in the HRSG in case of a GT trip.

The following sections discuss the risks and possible mitigation measures for the impacts of using H_2 in the GT and for supplementary firing from a HRSG supplier perspective.

2.1 Higher NOx emissions in the GT exhaust gas

During combustion, the local flame temperature and flame speed of hydrogen are contributing factors to NOx formation. Higher flame temperatures are favourable for production of nitrogen oxides (NOx). Combustion of H_2 may lead to higher flame temperatures than natural gas due to the higher heat of combustion of H_2. Current tests show that gas turbines running on 100% hydrogen will produce more NO_x than those running on natural gas. (3).

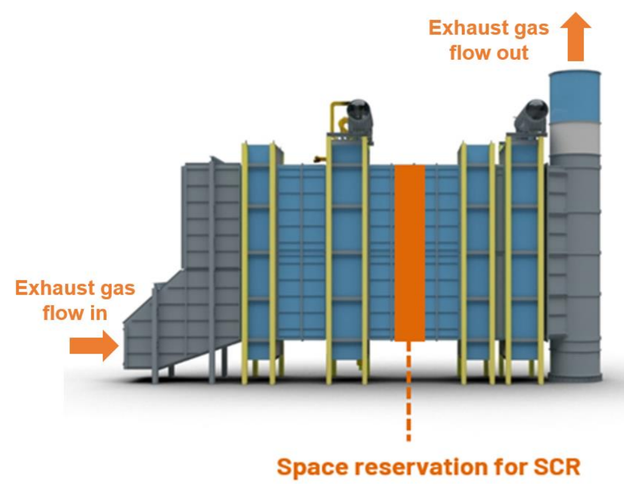

Figure 2. Location of the SCR system within the HRSG.

The higher NOx emissions directly affects the sizing of the SCR system. Figure 2 shows the typical location of such an SCR system inside the HRSG. As seen from the figure, any adaptations after installation will be challenging due to space constraints. Thus, in preparation for a future GT H_2 burning scenario, a larger spool duct needs to be considered in the design of any new build installations. Furthermore, many existing power plants have supplementary firing systems installed either in the inlet duct of the HRSG or between the high-pressure superheater modules. Increasing H_2 ratios in the combustion fuel of such burners will also likely increase the NOx emissions and impact SCR performance.

2.2 Higher Exhaust Volume Flow And Exhaust Gas Inlet Temperature

Firing H_2 also adds extra volume to the exhaust gas flow compared to firing natural gas. Combustion reactions for both fuels are the following:

$$CH_4 + 2\ O_2 \rightarrow 2H_2O + CO_2$$
$$4H_2 + 2\ O_2 \rightarrow 4H_2O$$

CH_4 has a LHV of 49895 kJ/kg = 798.3 kJ/mol and H_2 has a LHV of 120087 kJ/kg = 240.2 kJ/mol. The higher energy density of hydrogen per mass still results in a much lower energy density per mol. Since the compressor of the GT will suck in the same volume flow of air, practically independent of the type of fuel that is fired, and the same amount of energy needs to be added (this is a good approximation to achieve the same turbine entry temperature), it means that 3.324 times the amount of CH_4 (in mols) need to be added in the form of H_2 in case of 100% H_2 firing. Typically, for a modern GT about 4% of the molar flow of air is added as CH_4, this will then increase to 13.3% in case of 100% H_2 firing. The molar mass of the flue gas drops from 28.3 g/mol (100% CH_4 firing, 60% RH @ ISO) to 27.2 g/mol (100% H_2 firing, 60% RH @ ISO). A curious phenomenon now occurs: switching from 100% CH_4 firing to 100% H_2 firing the mass flow of flue gas decreases by 1.3% while the volume flow of flue gas increases by 2.5%.

For new HRSG units, design parameters such as the sizing of the duct and casing, heating surfaces, internal gas flow distribution within the HRSG and acoustic provisions need to be analyzed when designing the unit for H_2 firing.

2.3 Increased water content in the exhaust gas flow

Another important consideration is that the water dew point of the flue gas increases when firing H_2 in the GT. This implies that condensation in the HRSG cold end will occur at a higher temperature.

Most combined cycle power plants run on natural gas, whose exhaust gas has a water dew point around 47-50°C. As shown in Table 1, mixing hydrogen with natural gas would result in increased water content (and increased water dew point, consequently) in the exhaust gas. It can be easily observed that with an H_2 content below 50% the increase in water dew point is minimal, while it becomes significant moving towards 100% hydrogen firing.

Table 1: Water dewpoint by fuel type and/ or mixture*

		NG	30% H_2	100% H_2
H_2O content	Vol%	10.3	10.7	16.7
Dew point	°C	47.0	48.0	57.0
HRSG min. reqd. FW inlet temperature	°C	x	x+1	x+10
*Based on 400MW frame GT simulations				

When designing a new installation, it is therefore necessary to adapt the insulation system to avoid accumulation of liquid water resulting from hydrogen firing. Hydrogen firing will require the adaptation of the heating surfaces for condensate recirculation i.e., increasing the incoming condensate temperature to avoid water condensation on the coldest tubes. For existing installations this is only possible to a limited extent (or not at all) and an engineering study needs to be performed to find a solution to this issue, customized for the specific site conditions. If existing installations have a cold casing design, checks might need to be performed on the casing wall temperature to minimize condensation between the insulation and the inside of the casing walls. Such checks will help prevent corrosion on the casing surface.

2.4 Effects on HRSG performance and gas side pressure drop

Converting an existing combined cycle power plant fired with natural gas to a H_2 fired one with additional constraints such as maintaining the same GT back pressure, design temperature and pressure of the HRSG pressure parts, one can expect a slight decrease of performance of the bottoming cycle. This can be attributed to the decrease in mass flow and change in specific heat of the flue gas. For a given heating surface, this implies a decrease in heat transfer and consequently less steam production. However, the reduction of steam production is in the order of 1-2% and hence has minor impact on the HRSG

Besides, the increased water dew point could also have a negative impact on performance, as additional thermal energy needs to be used to recirculate the condensate to a higher temperature. For new installations, due to the larger volume flow of flue gas, the gas side pressure drop in H_2 fired plants will be slightly higher than for natural gas units, resulting in a slightly lower GT output. It is important to note that any performance impacts on the HRSG is coupled to the operation of the GT and the CCPP.

2.5 HRSG burner design for H_2 firing

This section discusses the impact of using H_2 as a fuel for supplementary firing in HRSG burners of both existing and new build HRSGs.

Existing power plants

The transformation of an existing NG-fired supplementary burner system into a H_2-ready system capable of accommodating various blends of NG and H_2 presents several technical challenges. The challenges include but are not limited to:

A. Change in properties and supply pressure of H_2
B. Increased flame radiation of H_2
C. Higher combustion velocity of H_2
D. Increase in NO_x emission.

The challenges listed above can be mitigated by design adaptations such as: (i) adjusting the size of the fuel gas skid to ensure optimal supply gas pressure, (ii) installing shielding plates on the castings and modifications/ replacements of burner runners to deal with the increased radiation of H2, (iii) modifications such as adding slots in castings or relocating burner runners to adapt for higher flame velocity of H2 and (iv) studying the impact of increased NOx emissions on the performance of the SCR.

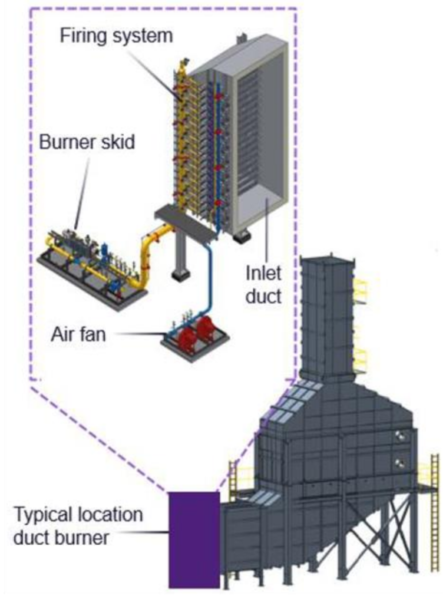

Figure 2. Typical duct burner system and location in HRSG/WHRU

Overall, the design adaptations required to transition from an NG-fired supplementary burner system to a H_2-ready system must be carefully studied on a case-by-case basis to ensure optimal operation and performance of the system.

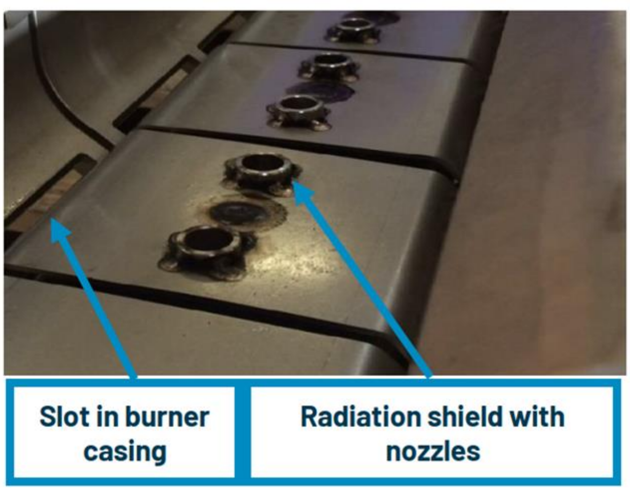

Figure 3. Typical example of radiation plates and slots for hydrogen firing on DJC grid burner.

New built power plants

When designing a new power plant, it is common for the facility to have a H_2 roadmap that outlines the planned H_2 operating scenario. For instance, the GT may initially operate on 100% natural gas or a low percentage of H_2 blend, with the H_2 percentage gradually increasing until reaching 100% in the future.

The HRSG must now accommodate two design points and all intermediate operating conditions, making the design of the HRSG more challenging. While certain components can be modified to adapt to the increased H_2 blend, this is not the case always. Certain integral components, such as the heating surfaces, cannot be altered. Therefore, design compromises must be made thereby affecting performance to some extent.

In principle, it is feasible to design a supplementary firing system capable of firing H_2 and NG blends in any ratio ranging from 0%-100% to 100%-0%. However, specific technical considerations should be considered such as important differences between H_2 and NG combustion with respect to velocity, flame radiation, and NO_x emissions.

When using a single fuel control skid for H_2/NG blend, the sizing of the piping will be determined by the flow of H_2 gas. This means that the fuel velocity will be relatively low when firing NG and relatively high when firing H_2. If the available pressure is sufficient, vortex flow meters are recommended for accurate fuel flow measurement. The design of flue gas and burner ducts should consider the high combustion velocity of H_2. To prevent damage to the manifold caused by flame radiation, shielding plates should be installed. Moreover, the higher NOx emissions resulting from increasing H_2 ratios in the combustion fuel should be considered when sizing the SCR system.

By thoroughly addressing specific technical considerations, it is possible to realize the design of a new power plant with the capability to accommodate H_2 and NG blends in different ratio.

2.6 Safety Considerations due to H_2 firing

Last, but certainly not least, are the safety aspects that apply when firing H_2 in the gas turbine. This is specifically applicable when a gas turbine trip occurs. Such an event could, for instance, cause an accumulation of H_2 gas in the 'attic' of the HRSG, especially for horizontal units (Refer Figure 5). Design evaluation of the HRSG casing and attic and additional measures for optimal venting, can be applied as risk mitigation actions in accordance with NFPA and other applicable guidelines of local authorities.

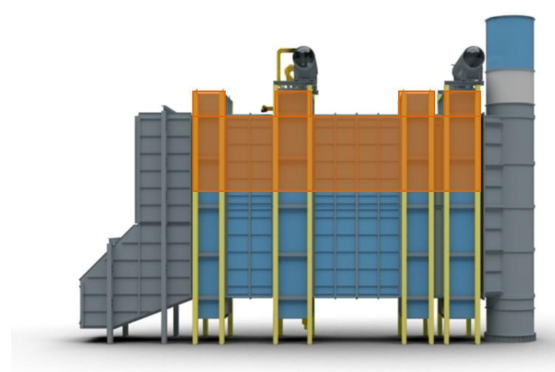

Figure 4. The 'attic' region of a typical horizontal HRSG unit.

However, the same accumulation pattern as natural gas is expected for H_2 since both the gases are less dense than air. Therefore, it is expected that no additional or different provisions are required, based on compliance with NFPA guidelines (4).

3 H_2-READINESS CERTIFICATION

In the meantime, a clear definition of H_2 readiness for a combined cycle power plant has been defined and a certification guideline is available (5) prepared by TÜV SÜD. The guideline is used as a basis for independent third party certification for various new plant configurations and to evaluate the hydrogen readiness of a CCPP.

The guideline was created for the following goals: (i) to capture the influence of change in fuel supply from NG to H2 in all relevant components and systems, (ii) to define the requirements of a H_2 readiness concept for a new build power plant and (iii) to list the evidence to confirm the correct implementation of the concept. The impact of H_2 firing on CCPP is divided into focus areas such as the fuel gas supply, GT, HRSG, explosion protection etc. Based on the boundary conditions such as expected operating time until transition, a scale is used to qualify the capability of the plant components to use H_2 as either 'H_2-capable', 'Retrofit required', 'Replacement required' or 'Obsolescence'.

A certification process is carried out for the three phases of a power plant:

(i) H_2- Readiness Concept Certificate
(ii) H_2- Readiness Project Certificate
(iii) H_2- Readiness Transition Certificate

NEM Energy BV is already awarded the H_2-Readiness Concept Certificate from TÜV SÜD. HRSG complementary components such as the exhaust gas bypass system, transition piece to inlet duct, burner system for supplementary firing, SCR and CO catalysts (sourced from 3rd party suppliers) are also included in the certification. As a next step, the H_2 readiness certification of a specific plant in realization phase will confirm that the plant (initially running on natural gas) has been built according the H_2 readiness concept of the bidding phase. Here, the final design of the HRSG supplier is provided as input.

4 CONCLUSION

In conclusion, the HRSGs will not be a limiting factor for the use of hydrogen in gas turbines and using H_2 or NG/ H_2 blends as fuel for HRSG supplementary firing in a burner system is technically feasible. For new plants, the HRSG can be designed to cope with a mixture, or 100% hydrogen fired gas turbine. Such designs can be called hydrogen ready (H_2-Ready) and is included in NEM Energy's product offerings. H_2/NG ratios need to be provided at the start of a project to implement the adaptations for the new boilers or burners. There are various challenges in making existing HRSG's capable of running on high levels of hydrogen and maintaining the design performance and emission (primarily NOx) levels.

Most of the burner suppliers working with NEM possess the competency to design burner installations firing H_2 or refinery gas (with high amount of H_2). Since specific site and operating conditions play a role, project specific investigations need to be performed starting in the project bidding phase. These investigations can be done under the supervision of NEM specialists/key persons, and in close contact with the burner supplier(s).

Although many different fuels have been utilized in GT power plants, there is limited industry experience burning 100% hydrogen. NEM Energy is well equipped to solve these challenges and is supported the in-house research and development team that is investigating this topic further. HRSGs already have a significant contribution to decarbonization by increasing energy efficiency of power generation through heat recovery. H_2 ready HRSGs can be an integral part of the energy transition and contribute further to mitigate climate change.

ACKNOWLEDGEMENTS

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