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## **HYDROGEN FOR GAS TURBINES – A TECHNICAL OVERVIEW**

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## **ABSTRACT**

With the global interest in carbon emissions reduction, industrial gas turbine (GT) original equipment manufacturers (OEM), aftermarket equipment/engineering companies, and operators are looking to augment and ultimately replace natural gas fuels (NG) with clean burning hydrogen ( $H_2$ ). However, augmenting and replacing NG with  $H_2$ , particularly at higher volume concentrations, presents some unique challenges. Properties such as diffusivity, flame speeds, and flame temperatures are significantly higher for high  $H_2$  fuels, and such differences can require changes in design and operation of combustion systems.

This paper provides an overview of technical issues pertaining to the use of  $H_2$  fuels in GTs. First, key characteristics of  $H_2$  flames and combustion are discussed. This discussion demonstrates that  $H_2$  fuels, particularly at high volumetric concentrations, differ considerably from the NG fuels commonly used today. This paper also highlights the impact of  $H_2$  fuel usage on GTs with a particular focus on the combustion systems. Because of the unique flame properties of  $H_2$ , GTs will require novel combustion systems that can tolerate higher flame speed and reduced autoignition delay times. Impacts of  $H_2$  fuel on auxiliary systems are also discussed. Though the mass-energy density of  $H_2$  is very high, the volumetric energy density of  $H_2$  is approximately one-third of NG volumetric energy density. As such, systems like fuel piping and fuel conditioning systems may need considerable modification or even replacement when  $H_2$  fuel is utilized. The paper concludes with a brief discussion of emerging technologies that utilize  $H_2$  fuels.

## **KEY WORDS**

Hydrogen combustion, Gas Turbine, Oxides of Nitrogen (NOx), Micromix



## **1 WHY HYDROGEN FUELS?**

With the global interest in carbon emissions reduction, industrial gas turbine (GT) original equipment manufacturers (OEM), aftermarket equipment/engineering companies, and operators are looking to augment and ultimately replace natural gas fuels (NG) with clean burning hydrogen ( $H_2$ ). However, augmenting and replacing NG with  $H_2$ , particularly at higher volume concentrations, presents some unique challenges. For example, mixing and combustion properties such as diffusivity, flame speeds, and flame temperatures are significantly higher for high  $H_2$  fuels. Such differences can present some challenges in the design and analysis of combustion systems.

A considerable amount of information has been published in recent years and in the early 2000s about the use of  $H_2$  and  $H_2$ -blended fuels in GT applications. A few key points are reiterated here to highlight the current motivations driving the development of  $H_2$  combustion systems.

Perhaps key among the motivating factors is that of reduced or no carbon emissions in the combustion process. With the global push toward decarbonization, there is a strong push from OEMs and operators to reduce or eliminate  $CO_2$  emissions from their GT-driven processes. Utilizing  $H_2$  fuels is one of the means toward this end. Figure 1, adapted from Goldmeer [1], demonstrates the reduction in  $CO_2$  emissions as a function of  $H_2$  volume content for a fuel blend of methane ( $CH_4$ ) and  $H_2$ . When considered on a volumetric basis, the relationship between  $H_2$  content and  $CO_2$  emission reduction is nonlinear. For example, a 50% reduction of  $CO_2$  emissions – an appreciable reduction that achieves the near term domestic emissions reduction targets [2] – would require approximately 75%  $H_2$  content by volume. Nevertheless, if a pure  $H_2$  fuel is utilized, then there are essentially no  $CO_2$  emissions at the exhaust stack. This is the primary motivation for much of the current development work within the GT industry.

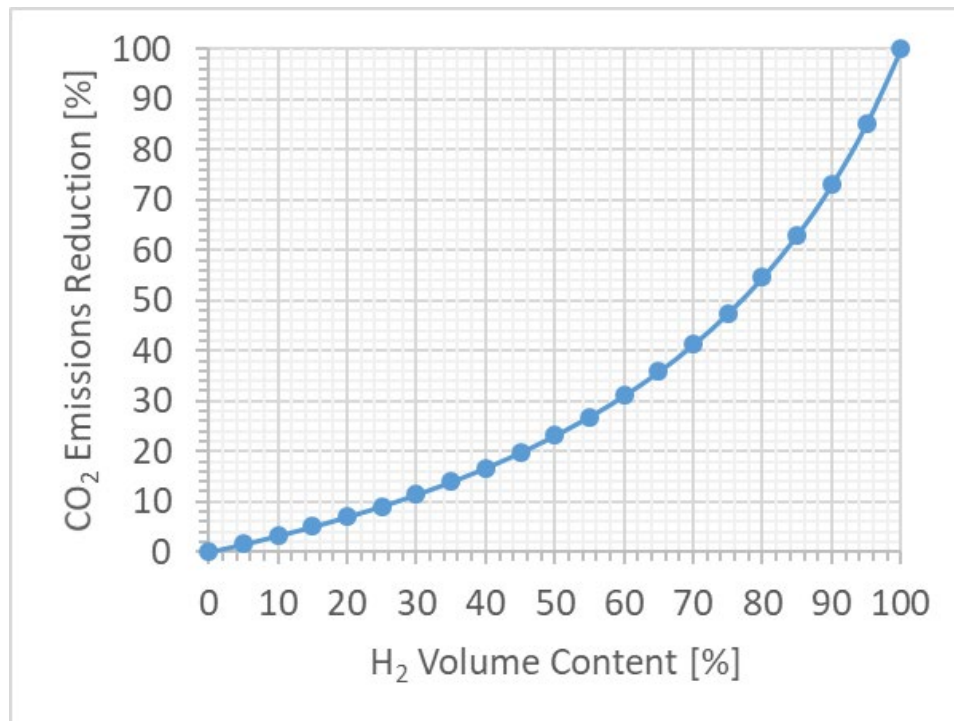


FIGURE 1: CO<sub>2</sub> emissions reduction as a function of H<sub>2</sub> volume content for a CH<sub>4</sub>/H<sub>2</sub> fuel blend (adapted from [1])

## 2 H<sub>2</sub> FUEL FUNDAMENTALS

CO<sub>2</sub> emissions are not the only factor that must be considered. Emissions of nitrogen oxides (NO<sub>x</sub>) also result from the combustion process and have the potential to increase with H<sub>2</sub> fuels due to the higher flame temperatures. Zandaryaa and Buekens [3] illustrate the temperature dependency of various NO<sub>x</sub> production mechanisms (see Figure 2). In the case of a pure H<sub>2</sub> fuel, there would not be any fuel contribution to NO<sub>x</sub> production (i.e., no nitrogen-bearing compounds in the fuel) but the thermal NO<sub>x</sub> and, to a lesser extent, the prompt NO<sub>x</sub> (i.e., NO<sub>x</sub> generated at the flame front by free radicals from the combustion process) tend to increase with increased flame temperatures. Cowell et al. [4] indicate that for conventional or diffusion type combustion systems, NO<sub>x</sub> emissions can increase roughly 90% for a pure H<sub>2</sub> fuel compared to typical pipeline-quality fuel gas. It should be noted that this increase does not take into account design modifications or other measures to abate the increased NO<sub>x</sub> production.

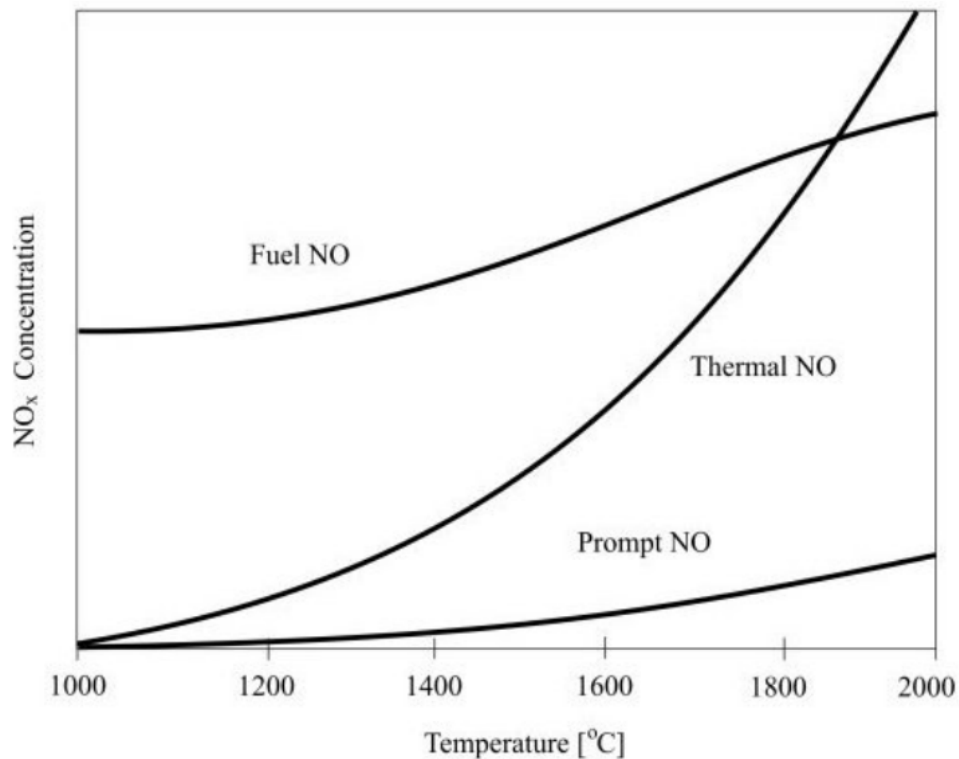
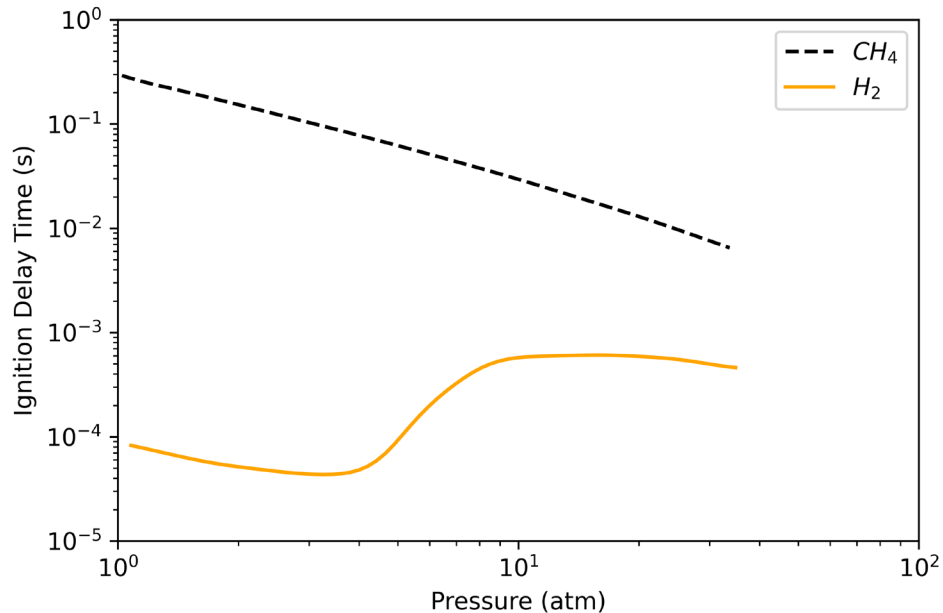


FIGURE 2: NO<sub>x</sub> emissions from various production pathways tend to increase with increased flame temperature [3].

Though increased NO<sub>x</sub> emissions in diffusion burners can be controlled with water injection schemes and/or after-treatment, most of the current industry focus is on the development of lean pre-mixed or micromixed designs that yield very low NO<sub>x</sub> concentrations compared to diffusion burners. In general, lean pre-mixed and micromixed designs rely on the lower flame temperatures that can be achieved with lean equivalence ratios to minimize NO<sub>x</sub> production.

However, the flame properties of high-H<sub>2</sub> fuels, namely auto-ignition delay time and flame speed, make lean-premix and micro mix designs a real challenge. Chemical kinetics mechanisms (i.e., models that detail the various chemical reactions and reaction rates of the combustion process) are often used to determine properties like auto-ignition delay and laminar flame speed. One such model was used to plot (Figure 3) the auto-ignition delay for pure H<sub>2</sub> and CH<sub>4</sub> at 827°C and equivalence ratio ( $\phi$ ) = 0.7 (adapted from Brower et al. [5]). It is clear that

ignition delay for  $H_2$  is orders of magnitude lower than  $CH_4$ , which means ignition can occur prematurely in the premixing chamber causing significant damage to the combustor.



*FIGURE 3: The auto-ignition delay time calculated for pure  $H_2$  is orders of magnitude less than for pure  $CH_4$ . Analysis conditions are 827°C and  $\phi = 0.7$ , (adapted from Brower et al. [5])*

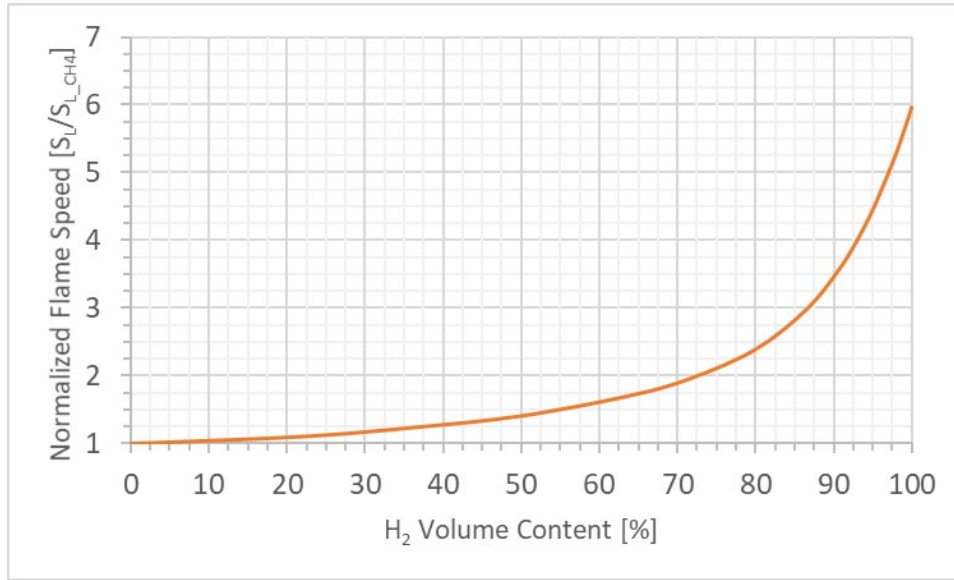
The flame speed of  $H_2$  and high- $H_2$  flames follow similar trends where flame speeds are considerably faster than for NG fuels. Figure 4 shows the calculated normalized laminar flame speed for mixtures of  $H_2$ - $CH_4$  at lean fuel/air ratios, pressure of 25 atm., and a constant flame temperature of 1477°C (adapted from Brower et al. [5]). At low concentrations, the effect on flame speed is minimal. At high concentrations, the  $H_2$  content increases flame speed several times over. This has severe implications for flame holding and flashback. Faster flames travel upstream more easily, causing combustion near the fuel injection. This can also damage sensitive components and lead to very high NO<sub>x</sub> if not controlled.

Simulations and modeling of pure and blended hydrogen gas turbine combustors are becoming increasingly popular as new fuel injection nozzles are designed. [6–8] The challenge for designers is to capture the key flame characteristics without excessive computational cost.

Many GT OEMs report that existing lean pre-mix systems can tolerate some amount of  $H_2$  content (generally in the 30% to 50% range). At lower concentrations the impact on auto-



ignition delay and flame speed are modest and can be handled in a system operating at design flow rates (i.e., velocities and residence times within the injector). However, these same systems cannot operate at higher concentrations of  $H_2$  because of auto-ignition delay time and increased flame speed essentially guarantee flashback issues or combustion within the nozzles. Perhaps the greatest engineering challenge is to design systems that permits some amount of fuel flexibility where the  $H_2$  content is variable (a very likely scenario in the path toward decarbonization).



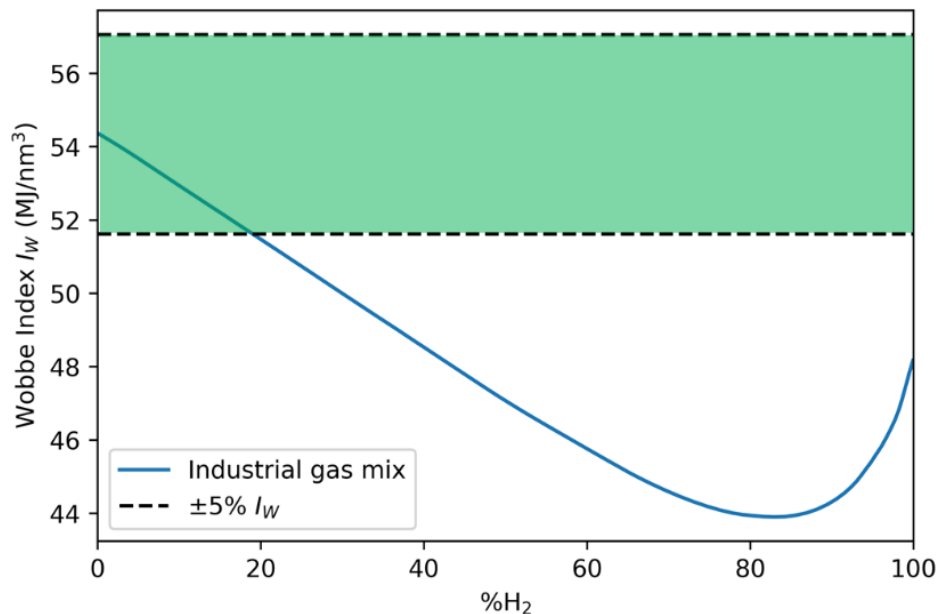
*Figure 4. The laminar flame speed of a  $H_2$ - $CH_4$  mixture with respect to volumetric concentrations of  $H_2$ .  $\phi < 1.0$ , pressure = 25 atm., constant flame temperature of 1477°C (adapted from Brower et al. [5])*

A very practical consideration is the impact of  $H_2$  concentration on a fuel's Wobbe Index. By definition, the Wobbe Index is the ratio of a fuel's higher heating value to the square root of the fuel's specific gravity; capturing both energy content and flow impacts.

$$I_w = \frac{HHV}{\sqrt{SG}} = \frac{HHV}{\sqrt{\frac{\rho_{fuel}}{\rho_{air}}}}$$



In application, two fuels with identical or very similar (e.g., within  $\pm 5\%$  of nominal) Wobbe indices are generally interchangeable within a given piece of equipment (e.g., a stove burner or a gas turbine). It is common for gas turbines manufacturers to specify a Wobbe index range for fuels. Figure 5 depicts the Wobbe index for a natural gas fuel with variable  $H_2$  volume content. The shaded area provides a  $\pm 5\%$  variation of the nominal case (i.e. the 100% natural gas case). At  $H_2$  concentrations above 20% vol, the Wobbe index is no longer within the given limits. Depending on Wobbe limits, burner redesigns are likely necessary for many gas turbines. Additionally, the Wobbe index on its own is necessary, but not sufficient, to describe fuel compatibility. That is to say, common problems with hydrogen fuel like autoignition and flashback may still cause problems even if the Wobbe index is within the acceptable range for the combustor.



*Figure 5. Variation of Fuel Wobbe Index with  $H_2$  Content*

In addition to some of the fundamental considerations given up to this point, consideration must also be given to the safety aspects of  $H_2$  fuels and fuel blends. Figure 6 compares the flammability limits, explosion limits, and ignition energy for  $H_2$ , gasoline, and





natural gas [9]. Notice that both natural gas and gasoline have narrow flammability limits compared to those of hydrogen, which is flammable in concentrations from 4 to 74%. Also striking is that the energy required to ignite a H<sub>2</sub>-air mixture is an order of magnitude less than that of natural gas and gasoline. An additional worthwhile comparison not captured in Figure 6 is to Jet-A fuel. At atmospheric pressure and temperature conditions, Jet-A has flammability limits between 0.7% and 5.0% with an ignition energy of 0.2 mJ [10]. The wide flammability and explosion limits coupled with the low ignition energy requirement all point to the necessity of handling H<sub>2</sub> fuels with appropriate safety measures in place.

	<b>Hydrogen</b>	<b>Gasoline Vapor</b>	<b>Natural Gas</b>
Flammability Limits (in air)	4-74%	1.4-7.6%	5.3-15%
Explosion Limits (in air)	18.3-59.0%	1.1-3.3%	5.7-14%
Ignition Energy (mJ)	0.02	0.20	0.29
Flame Temp. in air (°C)	2045	2197	1875
Stoichiometric Mixture (most easily ignited in air)	29%	2%	9%

*Figure 6. H<sub>2</sub> flammability limits exceed those of natural gas and other common fuels [9].*

### **3 H<sub>2</sub> FUELS IN GAS TURBINE COMBUSTION SYSTEMS**

Moving beyond the fundamental properties of H<sub>2</sub> fuels, the specific impact on gas turbine combustion systems is now considered beginning with conventional burners. Conventional burners (or diffusion burners) are those that mix the fuel and oxidizer directly downstream of the injectors (see Figure 7). These types of combustion systems have a long history of operating with high-H<sub>2</sub> and even pure H<sub>2</sub> fuels with great success. For example, refinery waste gas (approximately 30% vol H<sub>2</sub>), coke oven gas (COG) (approximately 60% vol H<sub>2</sub>), and various other

industrial process gases with  $H_2$  content up to 100% have operated in conventional burners for decades with good success. These types of systems are generally installed in industrial locations where these high- $H_2$  fuels are a waste product of the particular industrial site and thus, readily available.

Some of the fundamental differences discussed previously, such as flame speed, are *less* impactful in the conventional burner architecture because the fuel and oxidizer are not premixed. As such, nozzles are less susceptible to the damage of flashback.

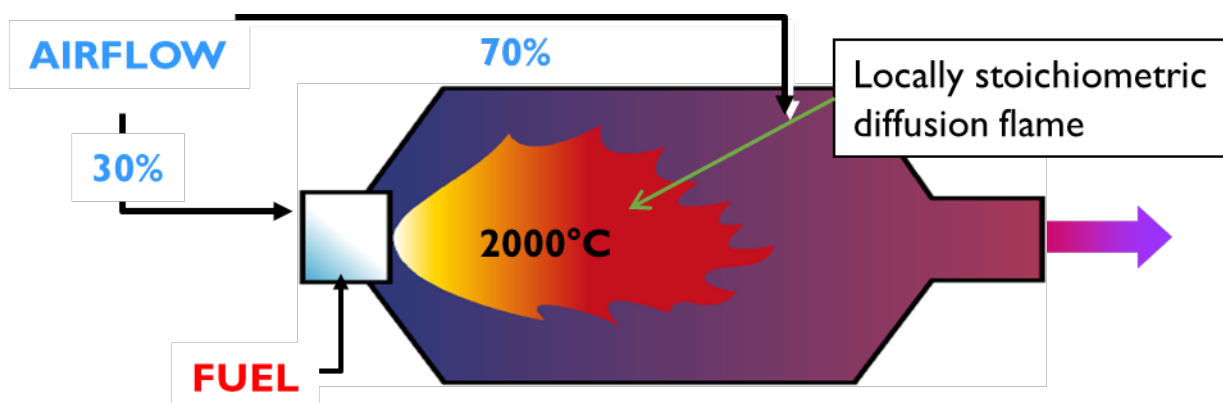


Figure 7. Diffusion or Conventional Burners Mix Fuel/Oxidizer immediately downstream of the nozzle.

Though these systems have operated successfully for decades with  $H_2$  fuels, they still have some drawbacks; key among which is their propensity for higher  $NO_x$  production with the addition of  $H_2$ . Conventional burners often yield locally stoichiometric conditions (i.e., high flame temperature) at the flame front and thus relatively high  $NO_x$  (see Figure 8). With the addition of  $H_2$ , stoichiometric flame temperatures increase (see Figure 6) and yields increased thermal  $NO_x$  production. To mitigate the higher  $NO_x$  produced from conventional burners, various abatement systems are installed to either cool the combustion or treat the combustion products: selective catalytic reduction (SCR) systems, water or steam injection, and various others.

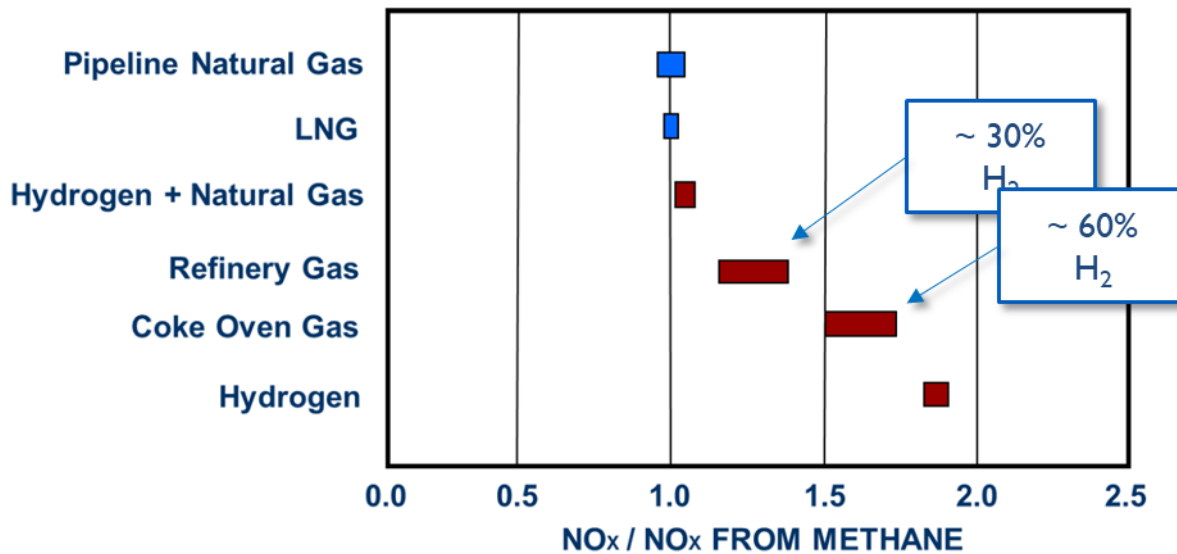


Figure 8. NOx Production in Conventional Burners [4]

To reduce the NOx production of conventional/diffusion combustion systems, lean premixed combustion systems were developed. Lean premixed systems (often denoted as dry low emissions (DLE), dry low NOx (DLN), and various other trade names) use various methods to mix the fuel and oxidizer upstream of the combustion chamber (Figure 9). Furthermore, the mixture ratio is lean which reduces the overall combustion temperature. Targeting lean fuel/air ratio results in lower combustion temperatures and thus lower thermal NOx production compared to stoichiometric conditions (see Figure 2 and Figure 10). Note that in Figure 10, there is an ideal operating region that minimizes NOx, carbon monoxide (CO), and unburned hydrocarbons (UHC). Stable operation in this region is, at least in high-level terms, the goal of lean-premixed combustion systems.

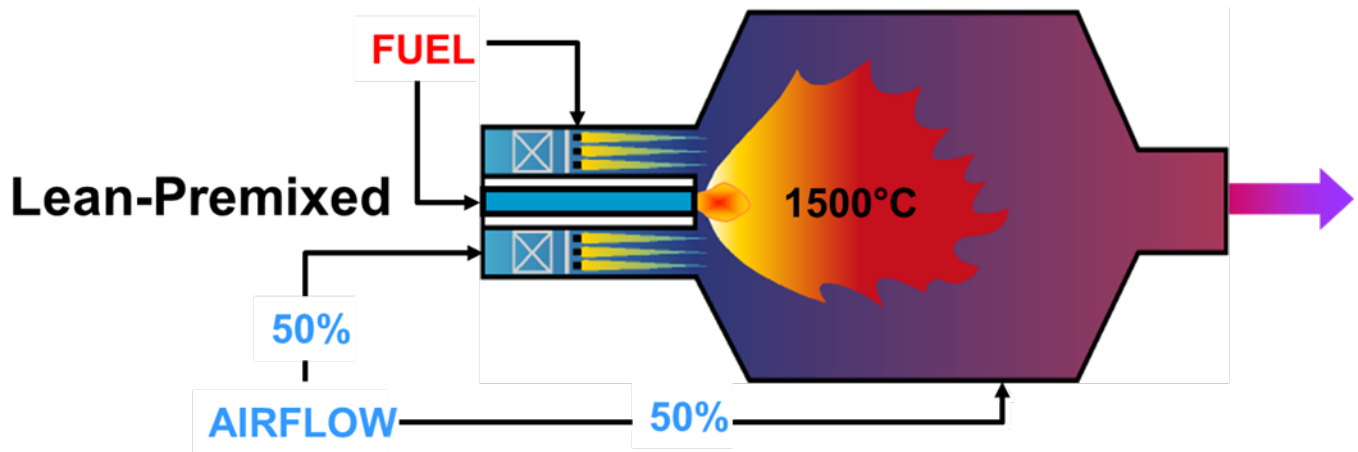


Figure 9. Lean Pre-Mixed Burner Designs mix Fuel and Oxidizer upstream of the combustion chamber to reduce the Primary Zone Temperature

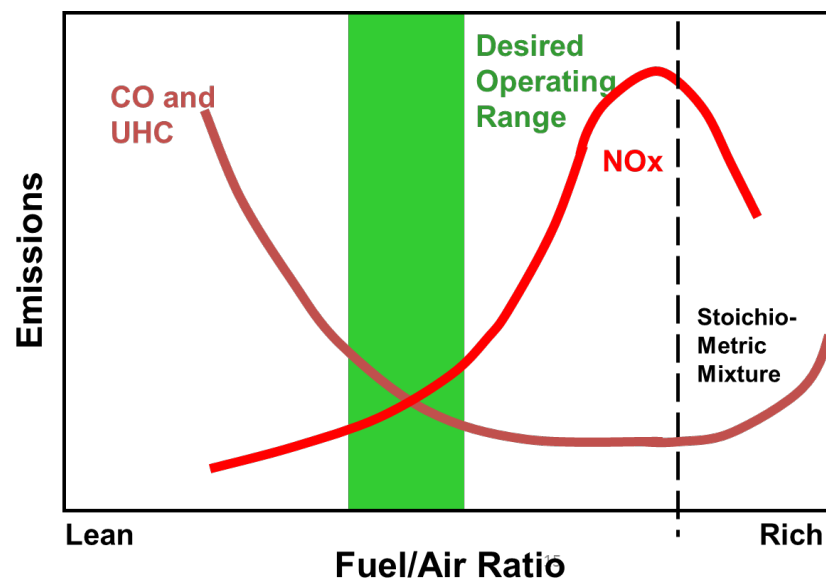


Figure 10. Lean Fuel/Air Ratios Result in Lower NOx Compared to Stoichiometric Combustion

Unlike conventional combustion systems, the stability of lean pre-mixed combustion systems can be quite sensitive to the addition of  $H_2$  beyond some threshold value. In particular, the increased flame speed that occurs with the addition of  $H_2$  can be quite detrimental to lean pre-mixed systems and lead to flashback. Referring to Figure 4, it can be observed that the laminar flame speed ( $S_L$ ) at 20%vol  $H_2$  is only marginally higher than the pure natural gas case. However, as these concentrations increase the flame speeds increase considerably such that, at



100% H<sub>2</sub>, the laminar flame speed is six times greater than the NG flame speed. In such conditions, the flame can propagate backward (i.e., flashback) into the nozzle and lead to considerable damage within the combustion system.

It should be noted that flow conditions within the nozzle/combustor are turbulent and the turbulent flame speed ( $S_T$ ) is the actual quantity of interest. However, quantifying  $S_T$  is not straightforward. Scaling laws that exist for natural gas cannot be generally applied to H<sub>2</sub> thanks to the increased diffusivity. For the sake of this discussion, it can generally be assumed that  $S_T \gg S_L$  and  $S_T \propto S_L$ . Generally, the trends observed with  $S_L$  are also reasonable for the much faster  $S_T$ .

Together, the increased flame speeds as well as the decreased autoignition delay times make high-H<sub>2</sub> operation in existing lean pre-mixed systems very difficult. As shown in the first portion of this paper, moderate concentrations of H<sub>2</sub> do not alter combustion/fuel properties significantly. As such, many manufacturers have successfully demonstrated operation with NG-H<sub>2</sub> mixtures in the range of 20 to 30%vol H<sub>2</sub> (note that concentrations differ considerably based on manufacturer, model, and specific installed equipment). To move beyond these concentrations, there is a significant amount of development work focused on micromixing approaches.

In general, the design philosophy behind the micromixer designs is to 1) mix the fuel and oxidizer rapidly 2) mix it *well* so as to avoid stoichiometric combustion (i.e., richer zones of the mixture) and 3) eject the fuel/air mixture out of the nozzle and away from the wall before it ignites. As the name suggests, these goals have pushed designers to relatively small and often intricate nozzles.

A few examples of published burner designs that rely on some or all of these design philosophies are shown in Figure 11 and Figure 12. The Mitsubishi [11] multi-cluster design shown in Figure 11 utilizes coaxial jets to rapidly mix the fuel and air. The “homogeneous mixing achieves low NO<sub>x</sub> combustion” [11]. Another example of a micromix design is shown in Figure 12. The researchers [12,13] utilized a *jet in cross-flow* mixing scheme, where a jet of H<sub>2</sub> fuel is

injected perpendicular to the air flow, to achieve the rapid mixing. In this case, the researchers report  $\text{NO}_x < 10$  ppm in their rig tests using 100%  $\text{H}_2$  fuel [13].

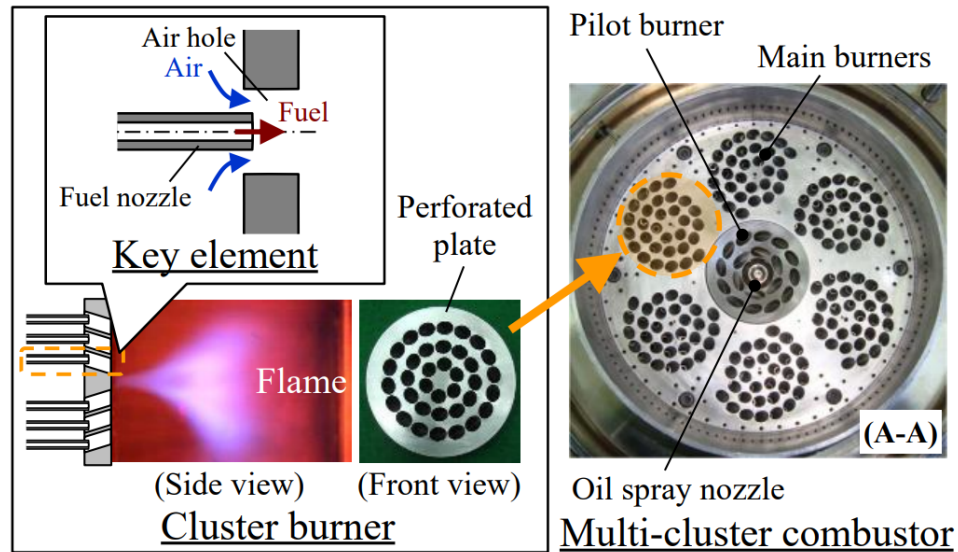


Figure 11. A multi-cluster combustor designed/tested by Mitsubishi Hitachi Power Systems, LTD is [11]

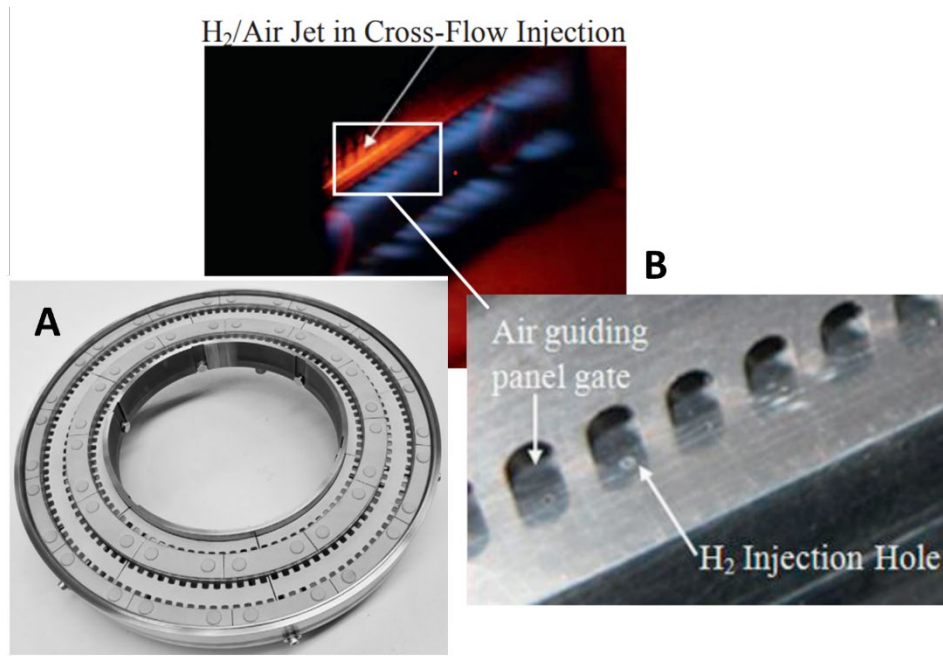


Figure 12. A micromix burner (A) [13] and associated micromix test article (B) [12] that uses a jet in cross-flow mixing scheme.



## 4 IMPACTS ON PACKAGE AND AUXILIARY SYSTEMS

The use of H<sub>2</sub>-blends impacts more than just the GT combustion system. Many of the auxiliary systems and package components are also impacted. Though H<sub>2</sub> has one of the highest *mass* heating values, the very low *volumetric* heating value of H<sub>2</sub> impacts fuel systems considerably. Figure 13 plots the volumetric and mass heating values for a variety of common GT fuels. Observe that H<sub>2</sub> mass heating value is the highest on the plot at nearly 120 MJ/kg, approximately 2.2X greater than pure methane at 55 MJ/kg. However, the *volumetric* heating value is only 10 MJ/m<sup>3</sup> compared to the 35 MJ/m<sup>3</sup> for methane.

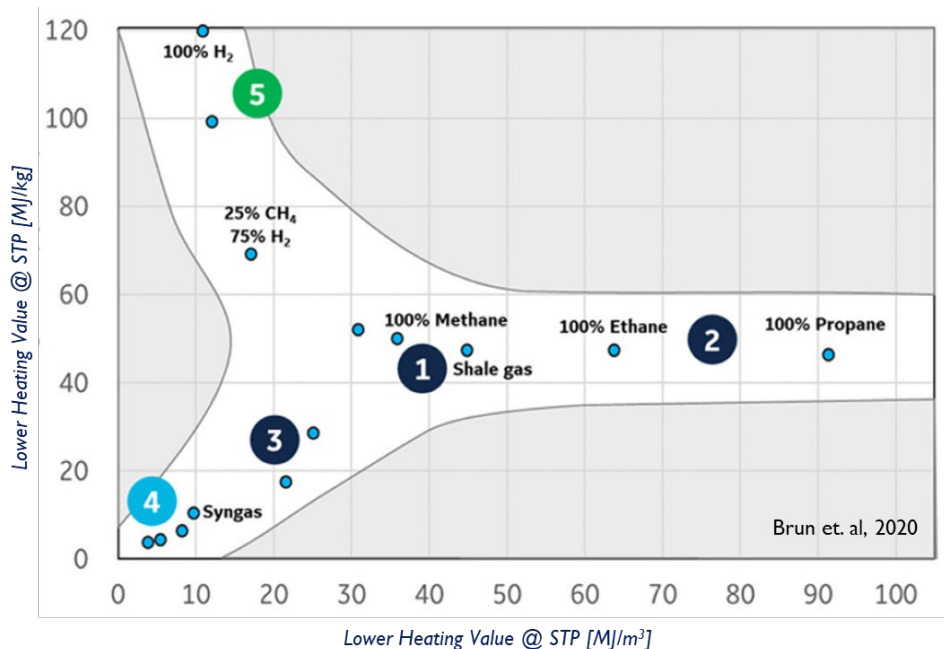


Figure 13. H<sub>2</sub> has the highest heating value on a mass basis but one of the lowest heating values on a volumetric basis [14].

To illustrate this impact, the authors performed a thermodynamic calculation a 234.3 MWe combined cycle power plant with a heat rate of 6,261 kJ/kWh. Fuel conditions are assumed to be 50°C and 2.19 MPa. Figure 14 plots the fuel mass and volume flows as a function of H<sub>2</sub> mass fraction. It is clear that while the total mass flow decreases with the addition of H<sub>2</sub>, the volumetric flow increases significantly once 50% mass fraction is achieved. Such drastic volume increases will certainly impact fuel systems. For equivalent fuel passages, flow velocities





increase significantly. These are among the first components that need to be redesigned to accommodate high- $H_2$  fuels.

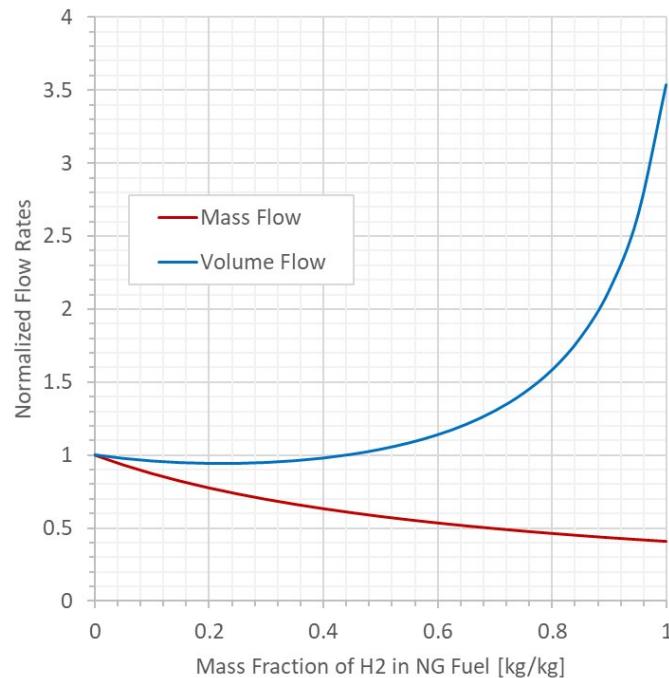


Figure 14. To maintain an equivalent thermal energy input to a particular gas turbine, the mass flow will decrease with the addition of  $H_2$ . However, the volume flow will increase significantly at mass fractions of 50% and more.

Some additional considerations are noted here but not discussed in great detail within this paper. Many of these topics are active areas of on-going research as industry looks to introducing  $H_2$  into NG systems.

With the use of  $H_2$ , **material compatibilities** must be considered. For example,  $H_2$  embrittlement in a variety of materials is well established. Many such materials are currently used in piping networks that are being considered for  $H_2$  transport and storage. Replacing systems with stainless steel or other compatible materials certainly presents a significant cost impact. Additionally, the compatibility and functionality of seals, valve seats, and elastomeric components also needs to be considered. To the authors' knowledge, there is still a significant amount of active research to identify impacts of  $H_2$ -NG blends on the materials used in transport pipelines. In the GT application, material compatibilities are most likely to impact the fuel system components but not the combustion or hot gas path components. Once the  $H_2$  is burned, the combustion products do not carry the same material compatibility concerns.





It should be noted that while  $H_2$  embrittlement may not be a concern in the hot gas path,  $H_2$  does produce a higher concentration of water vapor in the exhaust compared to NG. With the higher water vapor concentration the exhaust specific heat ( $c_p$ ) is increased and will impact heat transfer (i.e., blade cooling) [15] and, subsequently, blade life [16].

In addition to the material compatibility issues, the increased volumetric flow rates required with  $H_2$  will also impact the **sizing of fuel piping, valves, orifices, and conditioning systems**. As shown earlier, a fuel system sized to deliver a certain volume flow of NG would need to handle approximately 3X the flow rate if pure  $H_2$  was used. The increased flow requirement impacts everything in that fuel system including compression systems. Alternatively, it is possible to deliver  $H_2$  at ~3X pressure and maintain similar volume flows. However, this will require more compression power, appropriate pressure rating for piping and associated equipment, as well as impact the injection conditions at fuel nozzles. Regardless of the approach, the use of  $H_2$  or high  $H_2$  blends will necessitate significant modification to fuel systems.

A few additional fuel system complications are likely to exist during the development and commercialization time frames: **fuel flexibility** and **start-up**. As mentioned previously, several development activities are focused on combustion systems that can operate with wider range of  $H_2$ -NG blends, ideally from 0% to 100%  $H_2$ . In application, a fuel system would need to handle this same wider range and associated volumetric flow variations. Also related is the start-up condition. Because of the potential challenges with failed starts and package ventilation, there may be some desire to start-up a GT using NG or some other fuel and then transition to the  $H_2$  fuel once steady operation is achieved.

Careful consideration must be given to the GT **package**. The  $H_2$  molecule is light and leakage and subsequent accumulations must be considered. Further, if there are failed starts, it is likely that purge cycles will need to be updated. Such considerations will also necessitate replaced or modified instrumentation rated for the  $H_2$  environment.



## 5 Conclusion

Undoubtedly, the use of  $H_2$  and  $H_2$ -blended fuels is certainly of great interest within the GT industry. The key motivating factor is the promise of reducing or eliminating carbon emissions in the combustion process. However, augmenting and replacing NG with  $H_2$ , presents some unique challenges that must be addressed. This paper focusses primarily on the challenges with GT combustion systems operating with high  $H_2$  blends. The pace at which OEMs and aftermarket manufacturers are developing and advancing  $H_2$  combustion systems is feverish. Still, to the authors' knowledge, there are no commercially available 100%  $H_2$  premixed or micromix combustion systems at the time of this publication, despite these tremendous development efforts.

Other, perhaps even greater, challenges exist beyond the combustion system. For example the  $H_2$  fuel generation and transport infrastructure that would be required to supply GTs does not currently exist in most instances. The technical and fiscal roadblocks for such infrastructure improvements, which seem formidable, will also need to be addressed before the  $H_2$  economy can be fully realized.

It should also be noted that  $H_2$  is not the only *horse in the race* toward a reduced or carbon-free economy. Other fuels like methanol, renewable natural gas, biodiesel, and  $NH_3$  are all being considered as alternative fuels for GT operation. At least a few of these fuels have the added benefit of easier transport and storage (i.e., in a liquid or saturated liquid state) compared to  $H_2$ . In addition to alternate fuels, other technologies to capture  $CO_2$  or even store energy through various means should also be considered.

In the authors' view, the regulatory environments along with social, fiscal, and geopolitical factors around the world are far too diverse to converge to a single technology solution moving forward. It seems more likely that several of these technologies, in addition to  $H_2$ , will find an application space in the future. Regardless of what that future mix of technologies ultimately turns out to be, the authors are convinced that gas turbines will continue to play a critical role.



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