TECHNOLOGY INSIGHTS

AMMONIA AND HYDROGEN FUEL BLENDS FOR TODAY'S GAS TURBINES: COMBUSTION CONSIDERATIONS

THE TECHNOLOGY

As potential fuels for gas turbine (GT) combustion, hydrogen and ammonia independently have combustion challenges compared to natural gas. However, ammonia-hydrogen fuel blends show promise for mitigating some of these issues. To accommodate these blends, extensive research efforts will be needed to develop commercially available, low-NOx GT combustors for new and retrofit applications.

THE VALUE

Flexible, low-NOx GTs capable of producing power from low-carbon fuels, such as hydrogen and ammonia, could enable natural gas assets and infrastructure to be leveraged as a resource for decarbonization.

LCRI'S FOCUS

The Low-Carbon Resources Initiative (LCRI)[1] is exploring opportunities for research, development, and demonstration of low-carbon fuels for GTs, including optimized hydrogen-ammonia blends.

INTRODUCTION

To meet worldwide decarbonization goals and policies, the existing "workhorse" gas turbine combined-cycle (GTCC) fleet—more than 2800 F-class engines worldwide—could soon be called on to burn low-carbon fuels. Most industry research about low-carbon fuels in GT engines and duct burners (located in the heat recovery steam generator) has been focused on hydrogen [1]. But ammonia, because of its higher volumetric energy density and greater ease of liquefaction for transport and storage [2], has also garnered attention as both a "hydrogen carrier" and fuel in its own right.

Hydrogen and ammonia have more combustion challenges compared to natural gas, and existing combustor systems require significant modifications to accommodate them as mixtures or in their pure forms. Current research [3] shows that burning ammonia-hydrogen blends might help mitigate some combustion-related issues that occur when these gases are burned individually. However, lowering levels of nitrogen oxides (NOx) in combustion emissions comparable to current levels achieved with natural gas fuel remains a key issue. Consequently, more research efforts are needed to develop, demonstrate, and scale up dry, low-NOx (DLN)[2] combustion systems for burning ammonia-hydrogen blends in GTs.

AMMONIA AND HYDROGEN DELIVERY

There are many technical and economic questions related to delivering hydrogen and ammonia to existing GT combustors, and options for delivering ammonia and hydrogen blends to the GT would be site-specific and driven by cost. Although detailed feasibility analyses are outside the scope of this technical brief, the following are potential options:

- Separate deliveries of ammonia and hydrogen to the plant by way of pipeline or truck/rail with an on-site blending system
- Ammonia delivery to the plant by pipeline or truck/rail with on-site conversion of the ammonia to the desired hydrogen-ammonia blend using catalytic conversion or "cracking"
- Ammonia delivery to the plant by pipeline or truck/rail with on-site production of hydrogen (electrolysis) and on-site blending

Box 1

1 The LCRI is a joint project between the Electric Power Research Institute and Gas Technology Institute. More information on the project can be found at www.lowcarbonLCRI.com.

2 Today's state-of-the-art, high-efficiency GTs use dry, low-NOx (DLN) combustors designed for burning natural gas; their emissions of NOx and CO are extremely low. These systems rely on the thorough mixing of air and fuel prior to injection into the combustion chamber (that is, premixing), resulting in a uniform blend throughout the flame zone. Because this strategy eliminates the localized hot region of a non-premixed flame, DLN combustors can produce significantly less NOx without relying on steam/water injection.

FUEL FUNDAMENTALS

The ideal combustor has several key design characteristics to optimize safety, operational flexibility, emissions, and durability. These characteristics are highly dependent on the combustion-related properties of the chosen fuel or fuel blend.

Blending ammonia with hydrogen shows promise in alleviating some of the design challenges associated with combustion of pure hydrogen in GTs. Key combustion-related properties for methane—the dominant GT fuel—as well as hydrogen, ammonia, and hydrogen-ammonia blends are provided in Table 1 as a point of reference.

Key takeaways are summarized as follows:

- The flame speed of hydrogen is eight times higher than that of methane and 42 times higher than ammonia's. The fast flame speed of hydrogen—and associated risk of flashback and autoignition, the unintended propagation of the flame and combustion upstream—presents the biggest technical obstacle in designing hydrogen-fueled turbines. For DLN air-fuel combustion systems—the power industry standard—flashback and autoignition can cause hardware failures in the fuel injectors, mixing vanes, and combustor liners.

  Hydrogen-ammonia blends in the range of 30%-70% to 50%-50% by volume [5] have flame speeds similar to methane. At these speeds, the risk of flashback and autoignition is reduced. Due to market pressure to reduce carbon dioxide emissions, the current DLN systems might be required to burn various blends of fuels, starting with natural gas (methane) and transitioning to blends of natural gas with ammonia and/or hydrogen. Each change in fuel blending ratios will require detailed evaluation and potential design modifications to the combustor hardware to achieve safe and reliable operation.

- The flame temperature for ammonia is about 8% lower than methane, whereas hydrogen is about 8% higher. Therefore, blends of ammonia and hydrogen yield flame temperatures similar to methane, as shown in Table 1. Lower hydrogen content in the fuel blend will decrease the flame temperature and help to mitigate thermal NOx, which is dependent on the gas temperature. These lower flame temperatures also help to decrease materials degradation-related challenges associated with pure hydrogen.

- The volumetric lower heating values (LHVs) of hydrogen and ammonia are approximately 30% and 40%, respectively, of methane. Because the volume flow rate sets the size of the plumbing, both hydrogen- and ammonia-based blends will require larger piping, valves, and instrumentation or be operated at higher supply pressures than standard natural gas (methane) systems. The commitment to burn ammonia-hydrogen blends would require existing GT-based power plants to modify and upgrade the hardware and controls as well as training the staff regarding new fuel safety, handling, and operations procedures.

- *Lean blowoff* or *blowout* (LBO) refers to situations where the flame is physically "blown out" in the combustor at different GT operating conditions. These LBO events are quite abrupt and can lead to sudden, severe increases in CO emissions, changes in flame stabilities, and resulting physical damage to the hardware. Variations in the flame speed, flame temperature, and LHV of each fuel will influence the LBO and require specific GT design considerations to effectively operate and maintain DLN combustion systems.

  Compared to natural gas, burning pure ammonia shows a significant decrease in flame stability and a greater tendency for LBO (especially at lower power operation), leading to a loss of GT operational flexibility and power turndown capabilities. Hydrogen, on the other hand, has a significantly reduced tendency for LBO at lower power operation. Blending hydrogen with ammonia will significantly stabilize the flame and decrease the tendency for LBO at low GT power settings, improving power turndown capabilities compared to operation on ammonia alone.

- The exhaust gas composition varies significantly across the alternative fuels. In particular, the water content in both hydrogen and ammonia exhaust is significantly higher than that of methane. At typical baseload conditions burning one fuel for F-class machines,[3] the combustor exhaust gas water content is 8% for methane, 13% for hydrogen, and 15% for ammonia (all by volume). This alters the specific heat of the post-combustion gases, which influences the relationship between the firing temperature and heat rate. Higher water content leads to a higher specific heat of the post-combustion gases and a greater heat load on primarily the turbine hot section vanes and blades, leading to increased metal temperature and decreased part life.

Table 1. Comparison of fuel properties (% by volume)

	Methane (100%)	Hydrogen (100%)	Ammonia (100%)	30% Hydrogen/ 70% Ammonia	50% Hydrogen/ 50% Ammonia
Flame Speed (cm/sec)	37	291	7	30–50	< 100
Flame Temperature (°C)	1950	2110	1800	1868	1954
Lower Heating Value (MJ/kmol)	800	240	323	300	285

3 These calculations were performed at an equivalence ratio that would provide 2420°F (1327°C) adiabatic flame temperature at 750°F (399°C) combustor inlet temperature and 15 atmospheres of pressure (typical baseload conditions for F-class machines).

Combustion properties—such as flame speed, flashback, emissions, and LBO—are interconnected and directly dependent on the physical dimensions of the combustor. Design approaches that individually address challenges resulting from these fuel properties can conflict with each other (see Table 2), so design trade-offs must be made to optimize the safety, operational flexibility, emissions, and durability of the overall GT design.

Retrofitting the current GT fleet with design modifications described in Table 2 to accommodate burning ammonia-hydrogen blends will require rig testing and field site demonstrations of each specific GT combustor design to confirm the GT performance and safe operation. The current DLN combustor designs offered by GT original equipment manufacturers (OEMs) have been optimized for burning natural gas. For example, a DLN combustor burning natural gas should be long enough to promote good turndown with LBO margin and low CO emissions, but it must also be short enough to maintain low NOx emissions. The combustor must also have good premixing capability to produce low NOx emissions, but premixing upstream of the combustor should be limited to mitigate flashback and autoignition. These types of design trade-offs and iterations will be required for transitioning from natural gas to low-carbon fuels, such as ammonia-hydrogen blends.

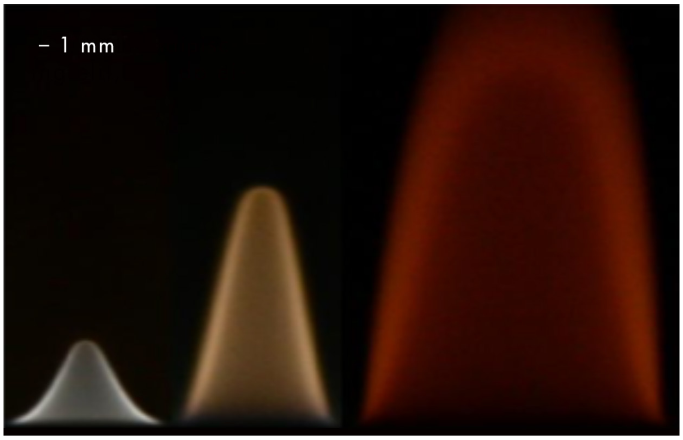
Table 2. GT and combustor design trade-offs

Design Objective	Operational Outcome
Ideal combustor for minimizing risk of autoignition and flashback	• Shorter premixing distance to reduce autoignition risk. • Optimal premixing with correct throughput velocity removes potential for flashback.
Ideal combustor design for minimizing NOx production	• Short combustor for decreased residence time. • Uniform mixing of fuel and air to eliminate localized high-temperature spots.
Ideal combustor design for LBO and CO emissions	• Long combustor for increased residence time. • Regions of enriched mixing for strong anchoring of the flame. • Good power turndown emissions, but it must also be very short.
Design approach for mitigating impacts of overheating due to higher exhaust gas water content	• Reducing the firing temperature by up to 100°F to account for the higher heat rate. • Alternatively, hot section redesign, including application of new metal and thermal barrier coatings, enables the GT to operate at the originally designated firing temperature.

The GT DLN combustor of the future will likely have a greater degree of adjustability, introducing a variety of lengths, residence times, and fuel-air mixing techniques into the design that can be adjusted for various constraints resulting from different operating profiles and fuel blends. This adjustability will likely be accomplished through more complex fuel injection strategies to manipulate fuel-air mixing and homogeneity, flame stability, and emissions control.

RESEARCH AND DEVELOPMENT ACTIVITIES

The 1960s saw considerable R&D for the application of ammonia as a fuel for GTs [6], which confirmed the inherent issues from the relatively slow ammonia chemical reaction rate as reflected in the laminar flame speed (see Figure 1). This early work also discovered that the dissociation of approximately 30% of the ammonia to hydrogen resulted in more beneficial combustion properties. Unfortunately, the resulting NOx emissions were on the order of hundreds to thousands of ppmv (at 15% O_2, dry) due to the fuel-bound nitrogen in the ammonia.



(a) (b) (c)

Figure 1. Instantaneous laminar flame images of (a) 20-80, (b) 50-50, and (c) 80-20 ammonia-hydrogen blends by volume [4] (The expanding shape of the flame is an indication of the slow burn rate of ammonia.)

More recent work by Okafor [7] and Medina [3] indicate that sub-50-ppmv (15% O_2, dry) NOx is possible for ammonia-hydrogen fuel blends. The lower NOx levels are achieved by changing the mixing and staging of the fuel into the combustor. Additional studies and rig tests are required to identify effective fuel injection locations within the premixing swirlers and in different axial and circumferential locations in the combustion chamber (can, can-annular, or annular) that will suppress the formation of free radicals that enable the formation of NOx from burning ammonia blends. These design techniques need to be optimized to potentially achieve 10–20 ppmv (15% O_2, dry) to meet the current low emissions limits for GTs (see Box 2).

POST-COMBUSTION NOx CONTROL

Most GTCC units in the U.S. fleet incorporate selective catalytic reduction (SCR) systems for post-combustion NOx control. These systems use ammonia as a reagent and are designed to handle GT engine outlet (that is, SCR inlet) NOx levels in the range of 10–25 ppmv (at 15% O_2, dry) with the GT firing natural gas. They are generally capable of providing 90% NOx reduction with less than 5-ppmv ammonia "slip" as a byproduct. This allows GTCC units to comply, in some cases, with NOx permit levels as low as 2 ppmv at the stack. There is some margin built into most SCR designs; however, if the SCR inlet NOx level significantly exceeds the design point for natural gas fuel, the costs to modify the SCR system to meet NOx and ammonia permit limits weigh against the advantages of burning hydrogen or an ammonia-hydrogen blend.

Box 2

To date, OEM efforts to accommodate low-carbon fuels have focused on hydrogen and hydrogen-methane blends. Several major OEMs are striving to have their GT DLN designs ready to operate on up to 100% hydrogen by 2030 [8]. This shift is driven by carbon reduction objectives and anticipated growth in production of low-carbon hydrogen. Blending ammonia with natural gas or hydrogen does not appear to be a current priority for the GT OEMs. The application of ammonia and ammonia-hydrogen blends as GT fuels that took place in the 1960s [6] was largely abandoned and has only recently received limited renewed interest due to worldwide momentum toward reduction of carbon dioxide emissions. To date, research on combustion of ammonia-hydrogen blends in GTs has largely been confined to the academic community, and development has been limited to laboratory-scale hardware.

CONCLUSIONS AND NEXT STEPS

Although firing blends of hydrogen and ammonia in GTs might help to reduce combustion-related challenges that occur when using these fuels in their pure forms, extensive development, testing, and demonstration are required to design commercially available, low-NOx GT combustors (for new and retrofit applications) to accommodate ammonia-hydrogen blends. All aspects of design, operation, control, and maintenance of a GT burning ammonia-hydrogen will need to be confirmed to fully introduce these types of blends into production.

A key objective of the LCRI [3] is to accelerate the development of promising technologies related to low-carbon energy carriers, such as hydrogen and ammonia. In the context of GTs, this could include the following tasks:

- Confirm the viability of using ammonia as a carbon-free energy carrier for large-scale GT power generation (Frame F, G, H, J). Demonstrate the beneficial combustion properties of ammonia-hydrogen blends, and determine the optimized mixture fraction of each fuel.
- Enhance existing analytical models of ammonia-hydrogen combustion through collaboration with global research groups and organizations to seek pathways to minimize the formation of NOx, control combustion dynamics, and increase LBO and flashback operational limits.
- Conduct ammonia-hydrogen combustion experiments in sub-scale rig tests to confirm the results of the analytical modeling simulations, and finalize evaluation by conducting full-scale combustor rig testing using a single can assembly from a F-class GT at actual operating conditions (match mass-flow, temperature, and pressure).
- Prepare a test plan for actual field testing of a full-scale F-class GT at an LCRI member location.

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ACRONYMS

CO	carbon monoxide
DLN	dry, low-NOx
GT	gas turbine
GTCC	gas turbine combined-cycle

LBO	lean blowoff or blowout
LCRI	Low-Carbon Resources Initiative
LHV	lower heating value
NOx	nitrogen oxides
OEM	original equipment manufacturer
R&D	research and development
SCR	selective catalytic reduction

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