Recent advances in H₂ and NH₃ combustion for decarbonization of power generation and industry

Richard Marsh, Phil Bowen, Agustin Valera-Medina, Jon Runyon, Daniel Pugh, Anthony Giles, Burak Goktepe, Syed Mashrulk
Cardiff University, UK
• Ammonia has a narrow flammability range and is therefore generally considered non-flammable when transported.
• The minimum ignition energy of ammonia is 16 times higher than typical hydrocarbons.
• At this stage in development, research interest focusses on **co-combustion with more reactive fuels** (CH$_4$ and H$_2$).
Steps towards 100% Hydrogen Gas Turbines

Potential for gas composition variation

Flexibility will be key, but can these systems achieve 0 – 100%?

Figure 1. Fuel used on high efficiency gas turbines.

GE Energy Addressing Gas Turbine Fuel Flexibility GER4601 (05/11)
Jones, Goldmeer, Monetti,
Current State-of-the-Art

High H$_2$ (up to 100%) gas turbines are a reality today...

- Often requires diffusion flames with steam dilution to control emissions (e.g. NO$_x$) with efficiency penalty
- Dry low emissions (DLE) and dry low NO$_x$ (DLN) lean premixed burners limited to ~60% H$_2$
- Sequential and micromix burners show promise

In 2019, CTOs of Siemens, General Electric, Solar, Mitsubishi, Ansaldo, and MAN Energy Solutions committed to 100% H$_2$ GTs by 2030
Ammonia

Air Products announces $5bn renewable hydrogen to ammonia investment

By Matthew Farmer

Air Products Limited, a world leader in cryogenic technology, today announced a $5bn joint investment in a chemical production plant in Saudi Arabia powered by 4GW of renewable energy. The company will form a joint venture with Saudi-based ACWA Power and tech accelerator Nuseir to jointly fund a power-to-hydrogen-to-ammonia facility.
Ammonia as a traded chemical

• The global ammonia market size is anticipated to reach $76 billion by 2025.
• Current market amounts to 181 million tonnes, of which 10% is traded on the world market.
• The global demand for hydrogen is about 70 million tonnes (although about 30 MT is used to produce NH₃)
• As such NH₃ is one of the most widely produced industrial chemicals in the world.
• Ammonia is used mainly in fertilizer production.
• Normally produced from the cracking of natural gas, but direct synthesis from water is possible and this route can also be decarbonized.
Hydrogen densities in hydrogen carriers. Courtesy of Prof. Yoshitsugu Kojima, Hiroshima University.
Ammonia as a zero carbon fuel

• Ammonia can be used as fuel for gas turbine systems.
• Although, key challenges are:
  • Slow chemical kinetics
  • High NOx emissions
  • Safety issues due to toxicity
• New programs of research have been conducted to use ammonia as fuel for power generation in gas turbines.
• NH$_3$ can split during combustion into hydrogen and nitrogen/hydrogen radicals.
Options for NH$_3$ / H$_2$ deployment
Swirl stabilised premixed combustion of CH$_4$ / NH$_3$ blends

- Generic swirl burner at GTRC
- 61% NH$_3$ and 39% CH$_4$.
- Gas analysis to examine NO$_X$, CO.
- Comparison to chemical equilibrium modelling.
- Aim to establish optimum balance between fuel burn and NO$_X$.
- NO$_X$ production largely from fuel-bound nitrogen.
Exhaust gas analysis

- NO\textsubscript{X} can be reduced to sub 10ppm, but at the cost of CO.

- Initial investigations show no perfect operating condition where both NO\textsubscript{X} and CO can be held at acceptable levels in a single condition.

- Effect of pressure potentially allows for reduction in both species.

- Modelling shows underprediction in rich operation.

Swirl stabilised premixed combustion of NH$_3$ / H$_2$ blends, with H$_2$O (steam) addition.

- NH$_3$/H$_2$ ratio of 70/30%mol
- Gas analysis to examine NO$_x$, Unburnt NH$_3$/H$_2$.
- Comparison to chemical equilibrium modelling.
- Aims:
  - To establish optimum balance between fuel burn and NO$_x$.
  - To further investigate potential low NO$_x$ operation via steam dilution.

<table>
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<th>$\bar{\theta}$</th>
<th>$P_{1-4}$ (MPa)</th>
<th>$WL_{1-4}$ (g·s$^{-1}$)</th>
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<td>1.2</td>
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<td>0.184</td>
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Exhaust gas analysis

• Similar optimum operation point at around $\phi = 1.2 - 1.3$.
• Unburned $H_2$ clearly an issue.
• $NO_X$ reduction is achieved through a combination of reduced thermal formation in the flame zone and NO consumption in the post-flame zone.
• The relative increase in $NH_3$ at richer $\phi$ also leads to a significant increase in $NH_2$ in the post-flame zone, which enhances NO consumption.
Effect of operating pressure

![Graph showing the effect of operating pressure on NOx and NH3 emissions.](image-url)
• The NO\textsubscript{\chi} reduction is predicted to diminish as pressure is increased further, as demonstrated with modelled data at 0.4 MPa represented by the solid line.

• This suggests implementation at increased pressure could allow for leaner operation.

• The predicted reduction in NO\textsubscript{\chi} formation with pressure from the numerical NH\textsubscript{3}/air flame is small compared to the experimental results.

• This is attributed to the influence of OH in NH\textsubscript{2} oxidation, alongside the role of HNO in NO production.
Steam addition

• Beyond $\phi = 1.3$ operation, steam caused flame to become unstable and flicker.
• $H_2O$ addition ultimately leads to a greater relative decrease in flame zone NO fraction.
• Models also suggest a relative rise in NO consumption through $NH_2$ mechanisms, resulting from enhanced $NH_3$ decomposition
Conclusions

• Whilst the combined influences of pressure and H$_2$O both cause an increase in unburned NH$_3$, when offset against a change in $\varnothing$, the net effect is still a reduction.

• Hence leaner operational $\varnothing$ can be employed to reduce unburned fuel fractions without a NO$_x$ penalty.

• Our ongoing research is examining staged combustion. Subsequent injection of oxygen in the post-flame zone can potentially oxidise the residual unburnt fuel and intermediates.