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AMMONIA GAS TURBINES (AGT): REVIEW

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ABSTRACT

Ammonia can potentially become a breakthrough chemical for power generation, cooling, storage and distribution of energy through hydrogen. Gas turbines are potential candidates for the use of the resource in an efficient way that will enable commissioning of combined cycles to power communities around Europe and around the world while serving as sources of heat and chemical storage. Therefore, development of these systems will bring to the market a safer, zero carbon fuel that can be used for multiple purposes, thus decentralizing power generation and increasing sustainability in the communities of the future whilst positioning the developing and manufacturing companies as global leaders of a new generation of energy devices.

Therefore, this review highlights attempts and ongoing research to use this chemical as a viable energy vector for power applications, emphasizing the challenges that ammonia gas turbines have faced over the years and details of current research conducted across the globe to allow implementation and commercial deployment of micro, small, medium and large systems for power and propulsion purposes.

INTRODUCTION

Chemical storage of energy can be considered via hydrogen or carbon-neutral hydrogen derivatives. Ammonia is one such example, which has been identified as a sustainable fuel for mobile and remote applications. Similar to synthesised hydrogen, ammonia is a product that can be obtained either from fossil fuels, biomass or other renewable sources such as wind and photovoltaics, where excessive electrical supply may be converted to chemical storage via hydrogen (Zamfirescu and Dincer, 2008). Some advantages of ammonia are its low cost per unit of stored energy, relatively high volumetric energy density, maturity of handling and distribution practice, and good commercial viability (Bartels, 2008; Metkemeijer and Achard, 1994). Alternative storage technologies such as Lithium batteries or Redox cells (Zamfirescu and Dincer, 2008; Bartels, 2008; Metkemeijer and Achard, 1994) are unlikely to be capable of providing the required capacity for grid-scale energy storage. Pumped hydro and methods such as compressed gas energy storage are constrained generally by geological limitations to their deployment (Wilkinson, 2017). Thus, ammonia presents itself as a good candidate to serve as long-term energy storage medium.

Ammonia (NH_3) recovered by harvesting of renewable sources is carbon-free and has no direct greenhouse gas effect. Moreover, it has an energy density of 22.5 MJ/kg, comparable to some fossil fuels; can be readily liquefied by compression to 8 bar; and, a reliable and proven infrastructure already exists – today around 180 million tons of NH_3 are produced and transported annually (Banares-Alcantara et al, 2015).

However, a viable energy system based on ammonia faces four primary barriers:

1. High-efficiency, carbon-free ammonia synthesis,
2. High-efficiency, low emission, power generation from small to utility-scale size,
3. Public acceptance through safety regulations and appropriate community engagement,
4. Economic viability for full global deployment compared to other technologies.

Barrier (1) is important because today's ammonia production methods are heavily reliant on fossil fuels. Since this is a challenging area that still requires considerable research, this barrier is left as a separate concern not encompassed within this review. Barrier (2) above is also critical, since most developments to date have focused on improving small- to medium-scale devices such as reciprocating engines, and have not effectively addressed the issue of emission reduction, most notably NOx. Moreover, power output from such units is relatively modest, typically in the range of 0.1 – 1.0 MW. Finally, Barriers (3) and (4) have played an important role even in these small devices, restricting the deployment of engines, i.e. in transport or small-scale energy production. However, these last barriers are out of the scope of this work.

It is important to emphasise that ammonia is complementary to the delivery of the "Hydrogen Economy", through essentially easing transportation and storage of the hydrogen molecule. Hence, there should be no conflict with the Hydrogen community. Development of new devices and techniques that can use green ammonia (i.e. hydrogen indirectly) can accelerate the adoption of the Hydrogen economy through:

1. *Reducing Emissions*. Being carbon free, ammonia offers the possibility of fuelling gas turbines, fuel cells and engines without direct CO_2 emissions. If the energy (and raw materials) used to synthesise the ammonia come from renewable sources, the cycle can be made carbon-free. NOx is the main pollutant from ammonia power-generation, and this remains a challenge.
2. *Improving Security of Supply*. Ammonia can be synthesised from abundant raw materials, namely hydrogen (in water) and nitrogen (in air). Ammonia is already produced and transported globally in considerable quantities, and is therefore a practical fuel which can be delivered to power-generators across a range of scales. With the capability of providing grid-scale energy storage, ammonia facilitates the increasing exploitation of renewable sources, and most notably has the potential to address challenges posed by variable, intermittent renewables power generators prevalent in the UK and Europe, i.e. wind, marine and solar.
3. *Reducing Costs of Energy*. The capital costs of ammonia energy storage are comparable or better than those for compressed air and pumped hydro but without the associated geological constraints, and substantially lower than other electro-chemical technology options such as batteries (Posada et al., 2016). Moreover, considerable infrastructure already exists for the transportation and storage of ammonia, along with well-established safe handling procedures, reducing the need for investment in infrastructure and training (Dincer and Zamfirescu, 2016).

Therefore, ammonia can become an important part of the energy mix, especially for the recovery of stranded energy and its storage over long periods (>1 month). However, highly efficient recovery of this energy can only be delivered with novel techniques, such as Ammonia Gas Turbines. For that, current and past research has advocated to unravel the technical and fundamental challenges of burning ammonia in such devices.

USE OF AMMONIA IN GAS TURBINES

Past work

Initial research on the development of ammonia fuelled gas turbine combustion systems during the 1960's (Verkamp et al. 1967; Pratt, 1967; Newhall and Starkman, 1966). Those studies demonstrated that ammonia's ignition energy was considerably higher compared to fossil fuels due to the low reactivity of ammonia. Moreover, at stoichiometric conditions, the quenching distance for ammonia-air was 3.5 greater than for propane, with ammonia burning at narrower equivalence ratio ranges (Pratt, 1967). However, it was also found that dissociation of ammonia could produce faster flames which could have similar properties to some hydrocarbons. Thus, it was concluded that 28% dissociated NH_3 could be used as a substitute fuel in gas turbine combustion systems sized for hydrocarbon fuels. Further experiments have demonstrated that the fundamental problem with ammonia-air as a turbine fuel is the relatively slow chemical reaction rate, giving a laminar burning velocity of ~6-8 cm/s (Li et al, 2014). As airflow is reduced to allow sufficient residence time for the reaction to progress, diminished Reynolds number effects lead to less turbulence and hence less effective mixing. This in turn decreases combustion efficiency (Newhall and Starkman, 1966).

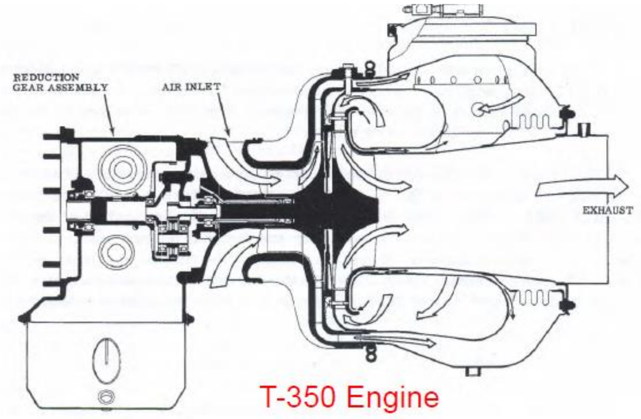
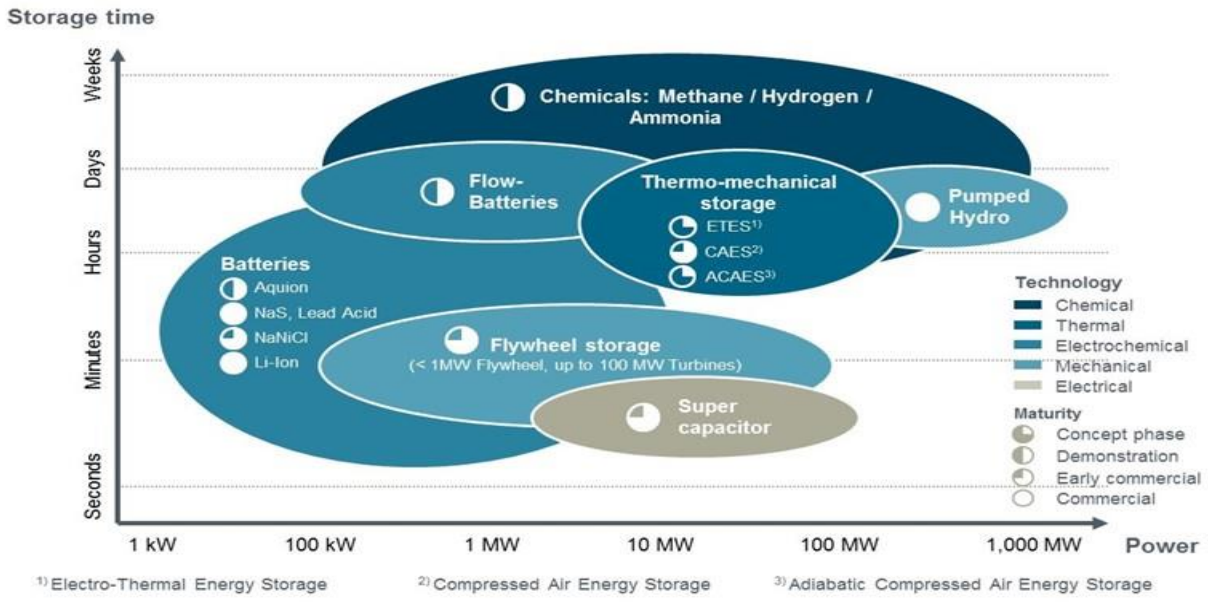


Figure 1. T-350 Engine, Solar (Karabeyoglu and Evans, 2012)

In the 1960's, Solar and UC Berkeley investigated a 250HP T-350 single can ammonia burner turbine (Karabeyoglu and Evans, 2012). Performance of the engine using vapour NH_3 was found to be similar to JP-4. In 1991, the Italian power generator ENEL undertook a research program that included ammonia for power generation. Their conclusions led to good power production that was unfortunately shadowed by the high emission of NOx (Balestri et al, 2004). Grcar et al. (2005) combined experimental and modelling investigations of ammonia chemistry in a hot combustion environment below adiabatic flame temperatures. The final products of NH_3 oxidation remained sensitive to mixing even at temperatures below those of self-sustaining flames. At these low temperatures NH_3 oxidation occurred in a premixed reaction zone, while at sufficiently high temperatures saw the development of a non-premixed reaction zone that produces significantly less NO than the equivalent premixed system developed.

Pioneering studies were undertaken during the middle of the 20th century by NASA, who identified through their XLR-99 program the need for "combustor enhancers", i.e. hydrogen, kerosene, fossil fuels, etc. during start-up and idle for their propulsion engine (Ganley and Bowery, 2010). According to some documents and "in field" research (Seaman and Huson, 2013), Reaction Motors, the company that took over the XLR-99 program, decided to use ammonia on their Viking engine (XLR-10). The



rationale behind the use of ammonia and liquid oxygen (LOX) was the need for a stable fuel with good volumetric energy density, easy to store, working in the required temperature range, with cooling properties and also potential for hydrogen engine development. However, due to the lack of motivation and no clear understanding of the need for using ammonia and the need for gravimetric energy density based fuels, the programme stopped. During the period that the project ran, the X-15 aircraft was developed. The aircraft, a powerful device commissioned by NASA, set unofficial world records in speed and altitude (Seaman and Huson, 2013). It would not be until the beginning of the XXI century that public work on ammonia gas turbines (AGTs) would be published again.

Current work

Several organizations, later detailed in this review, have recognized the importance of ammonia as energy storage for power applications. Ammonia, being a chemical that can be stored for long periods (i.e. even years) can be a promising, cheap and malleable energy vector for distribution of hydrogen. Thus, compared to other technologies, it presents high possibilities to play an important role for large-scale power generation through recovery of stranded sources, Figure 2.

More recently, a number of different approaches have been followed to use ammonia as a flexible fuel in gas turbines, with most of them finding that emissions are the main concern of such technologies. SPG Advanced Propulsion and Energy (Karabeyoglu and Evans, 2012) is one of the few companies claiming the development of commercial systems. They have presented through series of conferences that the main challenges for the development of a reliable technology are: a) Lower flame temperatures and slower kinetics of NH_3; b) unstable combustion; c) reliable ammonia vaporization to improve efficiency; d) pre-cracking of the molecule required to increase flame speed and burning ratios.

Initial characterization of swirl stabilised combustion of ammonia with other molecules was briefly analysed at the University of Iowa by Meyer et al (2011) in a 40kW burner, with nozzles, swirl stabilisers and a self-sustained heat exchanger. Stabilisation was achieved using different swirlers with different concentrations of ammonia, hydrogen and methane. For those experiments where ammonia and hydrogen were mixed, it was found that the use of a flame holder increased the combustion efficiency, with a demonstrable reduction in NOx emissions.

The Fukishima Renewable Energy Institute (FREA), has developed fuel flexibility platforms to burn liquid and gaseous NH_3 produced from renewable sources, i.e. wind and solar, in combination with kerosene and methane in a 50 kW micro-gas turbine. For liquid ammonia, diffusion combustion has been employed in the prototype by-fuel combustor due to its flame stability and it has been demonstrated that the equipment can be run using ammonia-kerosene blends at different concentrations (Iki et al, 2015). The gas turbine was initially started with kerosene, which was eventually replaced by ammonia producing an output power of 17 and 21kW with 38% and 30% decrease of kerosene by supplying NH_3, respectively. However, the production of NOx increases considerably based on the amount of ammonia injected, reaching levels of up to 600 ppmV. The NOx emissions challenge for ammonia fuelled turbines has been investigated since the first development of the technology. Some of the best solutions are the use of selective catalytic converters (SCR) to reduce the unwanted emissions produced by the micro-gas turbine (Iki et al, 2014; Iki et al, 2015; Iki et al, 2017).

Recent studies carried out by the research group at Tohoku University have determined that pure ammonia can also be used for micro gas turbine power applications (Somarathne et al. 2018) with low NOx emissions without SCR. Further results (Kurata et al, 2017) showed that new combustor configurations are required to increase the residence time of the fuel, thus enabling combustion efficiencies as high as 95%. Moreover, injection strategies using new injectors showed low nitrogen oxide emissions under rich fuel conditions reaching concentrations ~40ppm at high inlet temperatures.

In general, the group led by Prof Kobayashi has been highly prolific in the study of ammonia-based combustion, with analyses that go from the previously mentioned experiments to complex numerical simulations of their gas turbine combustion systems. Some of these simulations (Somarathne et al, 2018) denote the fundamental patterns of NO production at various equivalence ratios. The studies emphasized that the reduction of OH radicals, product of the increase of pressure in the combustion chamber, has a high impact on the formation of the contaminant, Figure 3. Thus, it is expected that lower NOx emissions will be produced at higher pressures, i.e. in more representative systems used for large-scale powergen.

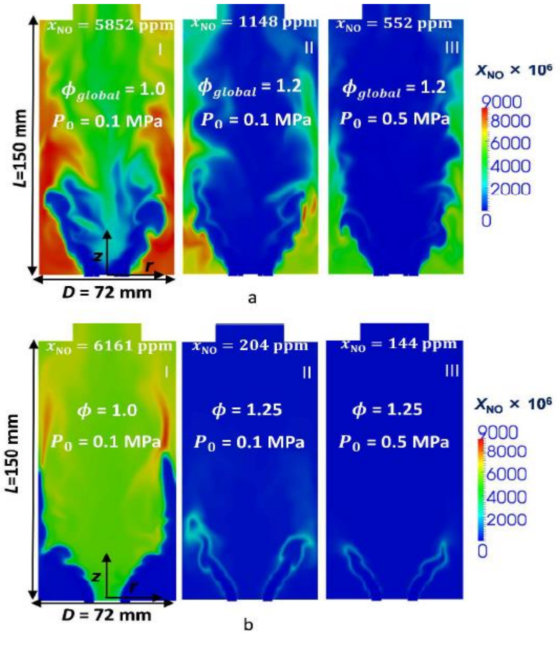


Figure 3. NO distribution in terms of global equivalence ratio and pressure. a) Non-premixed; b) Premixed (Somarathne et al, 2018).

Other potential beneficiaries of the undertaken research on ammonia-fueled devices include industries where ammonia is already available and could be considered as fuel for co-firing applications in low-pressure furnaces and self-production of energy via gas turbines. Co-firing could be achieved using this “brown” ammonia to support power production in high-energy intensive components. With that aim, companies and groups around the world are currently investigating the development of new gas turbine combustion systems capable of providing medium to large power outputs with low emission rates by combining this by-product ammonia with other available fuels produced in-situ.

For example, ammonia has been used for energy recovery in low pressure furnaces in China (Teng, 1996) and can be co-fired with other process gases such as Blast Furnace Gas (BFG), Coke Oven Gas (COG), etc. in a similar fashion for extra power generation in large facilities that currently flare the chemical. Jojka and Slefarski (2018) presented some investigation with low ammonia content (from 1 to 5%) in methane flames. Overall values of NO concentration derived from experimental and numerical studies, showing good correlations for rich fuel conditions. Conversion factors of NH_3 to NO achieved the lowest value equal to 40.4% in a rich mixture with 5% ammonia content. However, the NH_3 conversion to NO is not complete and trends are not linear, thus requiring further research and more detail analyses of the chemical reactions incurred under these regimes.

Further work (Ito et al, 2016) has detailed the exhaust gas compositions of a particular burner under atmospheric pressure and fuel lean conditions in combination with fossil fuels. It has been demonstrated that as the equivalence ratio increases, unburnt species such as NH_3, CO and total hydrocarbons decrease in contrast to NOx and that the burner achieves combustion efficiencies above 97% for ammonia-mixing-ratios below 50%. It has been reported that it has been difficult to achieve low emissions and high combustion efficiency in a single-stage combustor, and hence a two-stage combustion systems (rich-lean or lean-burn with secondary ammonia supply) have been conceptualized, with theoretical studies suggesting low NOx and unburnt gas species emissions while maintaining high combustion efficiencies (Ito et al, 2016; Onishi et al 2017).

Valera-Medina et al (2015, 2017a) presented a series of studies using a generic swirl burner that was fed using ammonia and methane at different concentrations. The results showed the complexity in stabilizing premixed ammonia blends, denoting a particular pattern of oxygen consumption that was followed by flame speed reduction, suffocating the combustion process and eventually leading to flame push-back into the combustion chamber with an inherent aeration. NOx and CO were considerably low at high equivalence ratios >1.10, depicting a region of chemically reactive balance between methane and ammonia combustion, Figure 4.

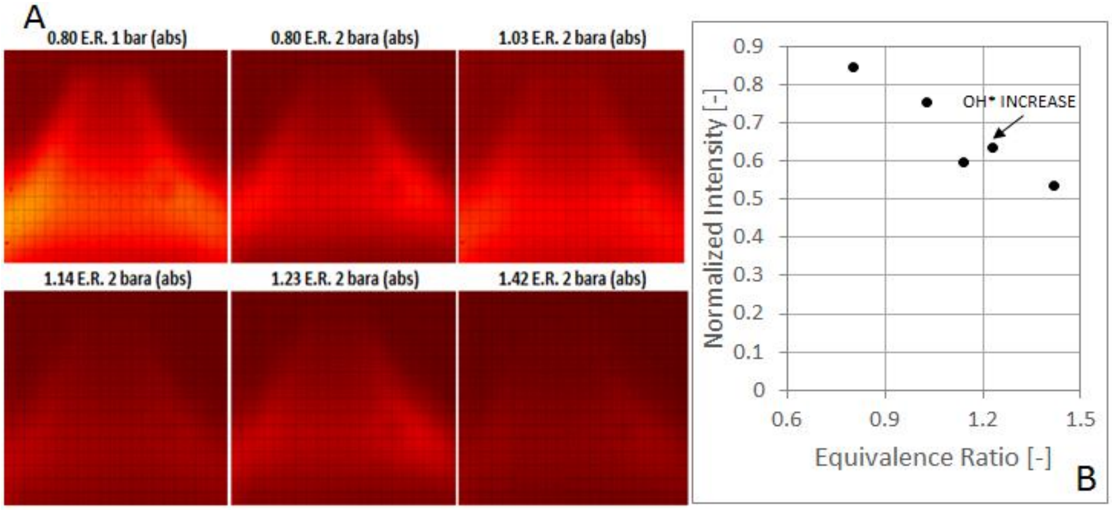


Figure 4. A) OH* chemiluminescence, mean values out of 200 images. B) Normalized intensity of mean values at 0.84 E.R. at 1 bar (absolute). (Valera-Medina et al, 2017a).

Xiao et al (2016) produced data to determine the potential of using reduced chemical kinetic models for the study of ammonia/methane blends for power generation. The base mechanism was the well-known Konnov's mechanism. Five reduced mechanisms were assessed and compared to experimental data and finally tried in a 2D gas turbine combustion simulation. Results showed that several of the reduced mechanisms utilized in the study performed reasonably well in combustion simulation trials under gas turbine conditions, suggesting that a reduction to 48 species and 500 elementary reactions can provide good results for those studies using more complex meshes and industrially relevant operating conditions. Further numerical models are under study using advanced reduction techniques for chemical kinetics models (NAFGM, LES with reduced mechanisms, etc.) to set new guidelines for further development of AGT systems running on ammonia/methane.

Ammonia combined with other molecules has inherently progressed to blending with hydrogen. The program conducted at Cardiff University was initiated setting a blend of 50%-50% ammonia/hydrogen, which demonstrated a narrow operability range (Valera-Medina et al, 2017b). Those trials followed a reduction in hydrogen to 40% H_2 (%vol) which still proved to be unstable. By contrast, a 70%NH_3-30%H_2 (%vol) blend demonstrated stable combustion behaviour, and so was selected for use throughout further studies. Experimental characterizations have been undertaken at a HHV power output ~39.3kW under various conditions. Initial tests carried out under atmospheric pressure were also conducted at 3 different inlet temperatures (288±5 K, 400±7 K and 484±10 K). To support the study and determine progression of species, improved chemical kinetic models have been incorporated to CHEMKIN-PRO for the analysis of Chemical Reaction Networks (CRN), representative of recirculating flames found in swirling flows. Recirculation strength was approximated from previous experimental campaigns using similar burners (Valera-Medina et al, 2013). The model was calibrated to the experiments in order to determine heat losses that mainly accounted to the primary combustion zone. Mass flow rates and chemical composition were set as in the experiment under atmospheric pressure conditions. The chemical kinetic model proposed was mostly based on recent work performed by Mathieu under high-pressure conditions (Xiao et al, 2017).

Figure 5 shows the findings of the experimental campaign, denoting the change in OH intensity across different equivalence ratios. The results were combined with CHEMKIN-PRO reaction modelling, providing evidence that OH radicals directly impact on the production of NOx emissions, Figure 6. However, NH_2 amidogen radical was also notoriously high in the post-combustion zone, decreasing the concentration of nitrogen oxides in this region. One key finding was the enhancement of the reaction $NH_2+NO \rightarrow H_2O+N_2$ at rich conditions, which occurs when hot ammonia is present in the post-combustion zone at elevated inlet temperatures.

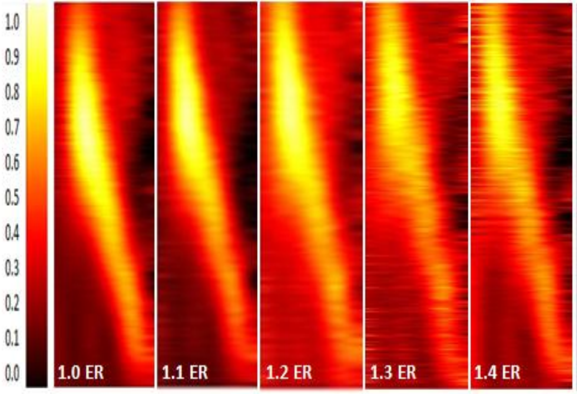


Figure 5. Deconvoluted Abel OH Chemiluminescence at various equivalence ratios. Ammonia/hydrogen. (Valera-Medina et al, 2018)

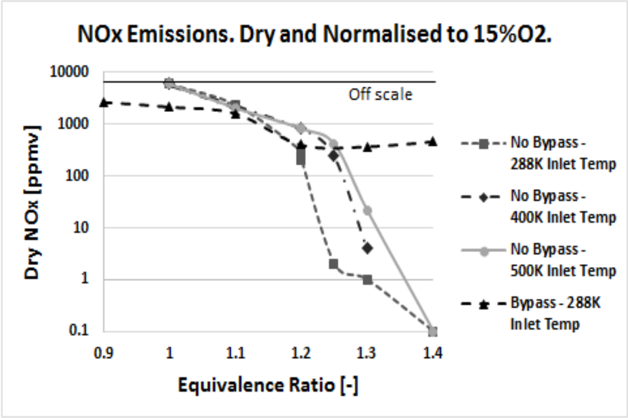


Figure 6. Dry NOx Emissions. (Valera-Medina et al, 2018)

Low emissions were observed at high equivalence ratios, as expected. However, increase in inlet temperature had also a high impact on NOx emissions as a product of higher flame temperatures (thus thermal NOx), Figure 6. Nevertheless, emissions at 1.25φ demonstrated to be in the range of 1-50ppm (%vol), potentially viable under current legislation.

The influence of elevated pressure was also explored up to 0.185MPa. Premixed operation at higher pressures required a fuel pre-heating vaporiser (to ensure NH_3 supply pressure was greater than combustor pressure). Sampled NOx concentrations were reduced by a near order of magnitude across the specified range, as shown in Figure 7 (experimental markers are superimposed on the equivalent CHEMKIN-PRO modelled line). An increase in pressure was also predicted to give a rise in unburned NH_3 concentration, with experimental trends broadly agreeing with modelled results, as demonstrated in Figure 8. Note – unburned NH_3 data could not be captured at 0.184MPa due to experimental runtime limitations from fuel evaporation.

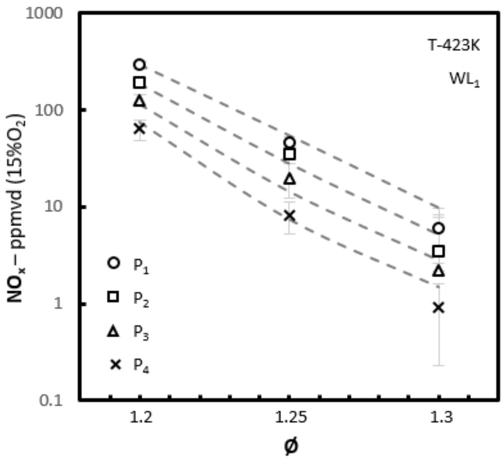


Figure 7. Experimental (markers) and modelled (lines) NOx concentrations against φ at elevated pressure. P1=0.105MPa; P2=0.131MPa; P3=0.158MPa; P4=0.184MPa. (Pugh et al, 2018)

The reduction in NOx formation with pressure, Figure 7, is small from the numerical NH_3/air flame compared to the experimental results obtained herein. This was attributed by the authors to the influence of OH in NH_2 oxidation, alongside the role of HNO in NO production, and used to explain why their results demonstrated a reduced influence at φ=1.25 (Pugh et al, 2018).

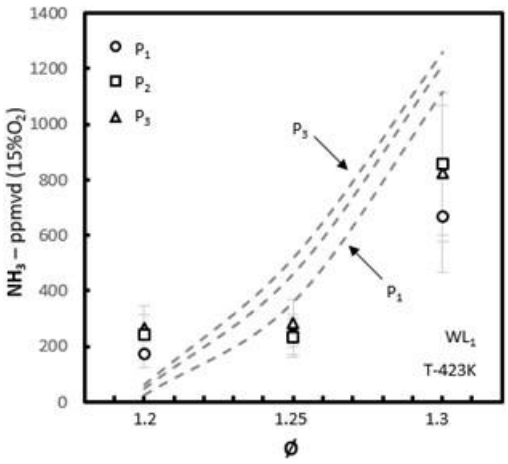


Figure 8. Experimental (markers) and modelled (lines) NH_3 concentrations against φ at elevated pressure (as in Figure 9). (Pugh et al, 2018).

Reactant humidification is also an effective process for controlling NOx production through the combined influence of reduced flame temperature, alongside enhanced O consumption through the reaction $O+H_2O \leftrightarrow OH+OH$ to limit $N_2+O \leftrightarrow NO+N$. In Pugh et al work (2018) the efficacy of employing humidification for NOx reduction was also studied, increasing H_2O fraction to ~10%mol. Reduction of emissions was observed as a combination of both decrease in temperature (~150K) and extra NH_2 radicals in the post-combustion zone. Therefore, humidified conditions are currently under the scope of research of the group at Cardiff University. An operational point was specified at medium pressure (0.184MPa) with injection of secondary air to give favourable NOx and NH_3 fractions of ~32ppm (vol%, 15%O2) and ~50ppm (vol%, 15%O2). The system is currently under development for future work enabling enhanced mixture control with secondary humidity, and operation at significantly higher pressure.

Exploring the potential application of these blends in industrial systems, an industrial Rolls-Royce Allison 501-KB5 gas turbine has also been studied by Valera-Medina et al (2018) as one of the major concerns from industrial partners is the feasibility and efficiency of these systems for real application in gas turbines. Thus, for model validation, the same input parameters utilised during the test campaign of a reference gas turbine plant (Centrax, 2012) were applied, with error values within the range of experimental uncertainty for the operating conditions considered. Moreover, the values of pressure drop in the compressor and the combustion chamber were also quantified, as well as the polytropic efficiencies of the compressor and turbine, the combustion efficiency and mechanical efficiency. An inlet temperature of 567K and 9.67 bar pressure are adopted for all calculations performed.

Calibration results confirmed good agreement with the underpinning data, with relative errors for the power and cycle efficiency both below 1%. When the model was used to compare the efficiency of the ammonia/hydrogen cycle, the first step was to ascertain power output at which the analysis needed to be performed. Due to model restriction on fuel flowrate due to the calibration limit, 0.367kg/s was set as the inlet fuel condition for the ammonia/hydrogen cycle. A fuel-rich condition was predefined to ensure lower NOx emissions, consistent with experiments, with a corresponding total air mass flowrate of 2.260 kg/s into the combustion chamber, resulting in an equivalence ratio of 1.20.

In order to compare such a system with current, high performance available technologies, a Dry Low NOx (DLN) condition operating at 0.65 equivalence ratio and using methane was used for comparison purposes. Thus, with a total fuel mass flowrate of 0.207 kg/s and an air flowrate of 5.480 kg/s into the combustion chamber, analyses were performed. A total air mass flowrate from the compressor was set at 14.99 kg/s, with a thermal power of 10.3 MW in both cases.

As expected, initial analyses demonstrated that the reduced quantity of air (~15% of total air throughout) fed into the combustor for the ammonia/hydrogen blend to keep rich fuel combustion, together with turbine inlet temperatures of only 850K - a consequence of the excessive dilution that occurs after the primary combustion zone product by the remaining air coming from the main compressor - led to a cycle efficiency of only ~ 9.77%. Results for the cycle including the DLN methane-fuelled combustor, predict efficiencies of about 19.36%, i.e. since the system was designed to run at higher fuel flowrates, with air in the combustion primary zone accounting ~37% of the total available air flowrate, thus producing turbine inlet temperatures of 1155K.

Although it is clear that efficiencies can be increased by reducing dilution into the turbine, the model cannot be calibrated for these parameters, and a new set of calibration data is required to enable calculations under these conditions. Moreover, it is evident from the previous analyses that although this particular ammonia/hydrogen blend has potential for low emissions combustion, generators running on these blends need to be re-designed to ensure that higher efficiencies through greater flue gas temperatures and/or mass flowrates are attained.

Finally, Ammonia using oxycombustion has also been approached numerically (Xiao et al, 2018), Figure 9. Results have demonstrated that NO emissions slightly increase with the increase of oxygen content mainly due to the increase of flame temperature, whilst under 17bar conditions the NO emissions remain barely unaltered from 21% to 40% oxygen content. It is obvious that increasing pressure has a large inhibiting effect on the NO emission under oxygen enriched conditions. Actually, under highly pressurised environments the NO emissions predicted by all the mechanisms are less than 7ppm under all oxygen enriched conditions. This indicates an advantage of utilizing NH_3 blends (in this study analyzed in combination with CH_4) under oxygen enriched conditions in gas turbines with low NOx emissions for real operation conditions at high pressure.

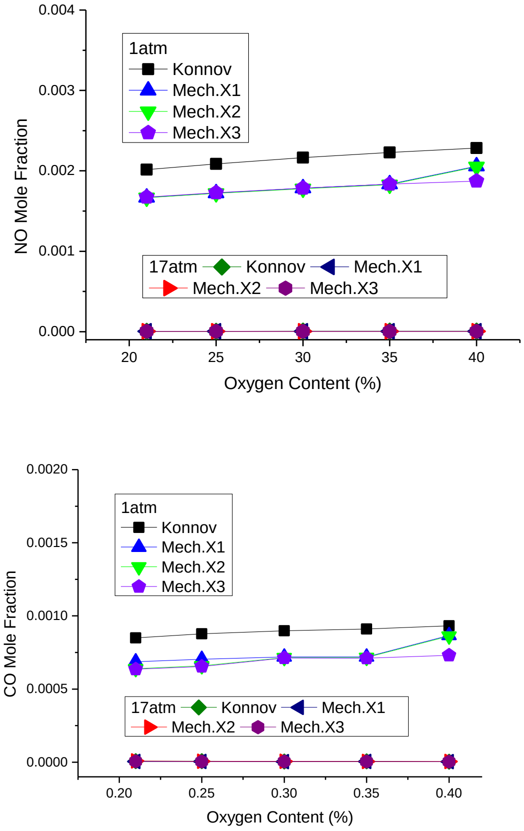


Figure 9. Ammonia/methane blends with oxycombustion. Oxygen increases the production of NO, with limited impact on CO emissions. (Xiao et al, 2018).

Industrial Interest

Companies such as NUON have also started ambitious programs to develop their capabilities in terms of ammonia fired systems. The most notable is the “Power-to-Ammonia” program in which NUON collaborates with TU Delft, Proton Ventures, OCI Nitrogen, AkzoNobel, ISPT and the University of Twente (ISPT, 2016; Proton Ventures, 2017). The NUON project perceives ammonia as a “superbattery” that stores excess renewable power at large scale over long periods. The new Magnum-plant in Eemshaven, officially opened in 2013, is proposed to be converted into a green ammonia fuelled facility instead of a coal plant, thus reducing CO_2 emissions considerably (Brown, 2017; Lavery, 2016).

Moreover, it has recently been announced (Brown, 2017) that Chugoku Electric Power Company has conducted a series of trials at its Mizushima power plant in July 2017, where ammonia was added to the 155MW coal-fired plant at a rate of 450 kg/hr. The company confirmed that the addition of the ammonia did not cause the plant's power efficiency to reduce. On the basis of energy content, the ammonia added represented 0.6-0.8% of total fuel. At this ratio, a decrease in carbon dioxide emissions was observed. The Chugoku demonstration has been the first where ammonia has been burned in a commercial power plant in Japan.

In Norway, a new project has been set between Siemens, Statoil and NTNU (Norway) to start unravelling the thermoacoustic characteristics of ammonia blends with hydrogen for gas turbine combustion systems. Similar work is under review in the UK with companies such as Siemens, TATA, Yara and C-Job Naval that are supporting applications led by Cardiff University and Trinity College Dublin for the recognition of stability profiles in complex fuel injection schemes.

Research into the use of ammonia for large power generation in support of decarbonising high carbon-producing processes is still ongoing. Of particular interest are the ill-defined kinetic processes that occur at high power outputs using various blends of ammonia with gases such as methane and hydrogen. More specifically, at equivalence ratios between 1.05 to 1.25 an increase in reactivity and overproduction of OH species has been observed, suggesting recombination of molecules that require further understanding and research to reduce the time to deployment ammonia power generation at a commercial scale. Therefore, the interest from industry grows continuously, and it is expected that by 2030 large-scale systems are running across the world whilst powered using ammonia as a fuel.

CONCLUSIONS

Ammonia, a carbon-free chemical that can be recovered from stranded renewable sources or by-product streams, is a component that has currently been assessed numerically, experimentally and industrially for its use as fuel in gas turbine systems. Ranging from micro to large devices, ammonia seems to have the required ingredients to support the transition to a Hydrogen Economy, providing cost effective storage and transportation of hydrogen.

In terms of combustion performance, groups around the world are continuously working towards the development of new strategies to use ammonia as a fuel that enables stable combustion with low NOx emissions. Experimental trials and numerical calculations have employed pure ammonia, ammonia/fossils and ammonia/hydrogen to elucidate methods of stabilization/decontamination for various operating regimes. Results are encouraging, as most of the findings demonstrate that there are conditions, injection strategies, flow stabilization patterns and operability regimes that cleverly combined can bring down nitrogen oxides whilst stabilizing these ammonia flames in what seems to be the foundations of new devices that will form part of the global energy mix of the future.

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