Novel Humidified Ammonia/Hydrogen Gas Turbine Cycles

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Abstract

Medium-long term storage of energy to ensure availability on demand, as well as transportation to where it is needed - that is providing supply where there is demand - is truly a global grand challenge. Whereas hydrocarbon fuels have fulfilled this role very effectively for the past 150 years or more, zero-carbon chemical energy is likely to be the main contender in the future.

Ammonia is an example of zero-carbon chemical storage, as the molecule has been identified as a sustainable fuel for remote applications due to its high hydrogen content. Ammonia can be obtained either from fossil fuels or most renewable sources (wind, biomass, photovoltaics, marine) where stranded energy supply may be converted to chemical storage via hydrogen [1].

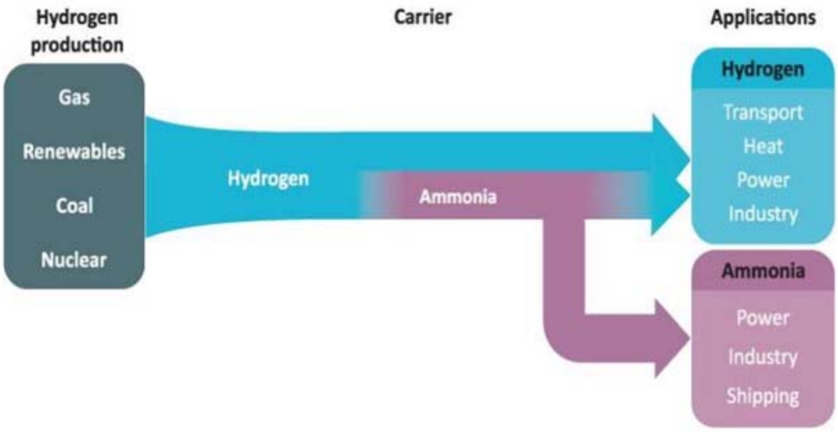

Figure 1. Hydrogen: Accelerating and Expanding Deployment, IEA [2]

However, some advantages of ammonia over hydrogen are its lower cost per unit of stored energy, i.e. over 182 days ammonia storage would cost 0.54 \$/kg-H2 compared to 14.95 \$/kg-H2 of pure hydrogen storage [3] and higher volumetric energy density (7.1–2.9 MJ/L). Ammonia has an energy density of 22.5 MJ/kg, comparable to other fuels (i.e. low ranked coal, 20MJ/kg; methanol, 22.7MJ/kg); can be easily liquefied at 8 bar, and has an existing proven & reliable infrastructure that transport ~180Mtons of ammonia annually [4]. Moreover, ammonia can transport more hydrogen (kg-H2/L) than liquid hydrogen itself [5], thus having a few orders of magnitude more delivered hydrogen than through injection to the natural gas grid. For that reason, the International Energy Agency has recognised the role of ammonia as an energy vector that can contribute with the decarbonisation of the planet in the short to medium term, Fig. 1.

It is important to emphasise the ammonia for power approach is regarded as complementary to the delivery of the "Hydrogen Economy" via hydrogenated nitrogen. Hence, the "Ammonia

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community" sees itself as part of the "Hydrogen community". However, ammonia based systems face four main barriers,
1. High-efficiency, carbon-free ammonia synthesis.
2. Clean, high-efficiency conversion to power at medium to utility-scale.
3. Public acceptance through safe regulations and appropriate community engagement.
4. Economic viability for full global deployment compared to other technologies.

Barrier (4) above is the one targeted for resolution in this work. Most developments to date have focused on improving small- to medium-scale engines without effectively addressing the issue of NOx emissions or efficiencies for cost effective energy production. While ammonia combustion in internal combustion engines has been demonstrated before, this is the first time ammonia/hydrogen combustion has been studied for its implementation in gas turbines. Moreover, further addition to the complexity of the fuel is the use of humidified conditions to raise efficiency levels, thus setting the foundations for the study of thermodynamic cycles that can competitively challenge current energy production systems. The concept, particularly exciting as it shows that novel technology can be deployed to provide a carbon-free storage and transportation vector for renewable energy, provides a guideline towards the development of new systems looking forward implementing large-scale devices for recovery of stranded sources via hydrogen storage through ammonia. One advantage of using ammonia for this purpose – in addition to being carbon-free – is that much of the infrastructure required to deploy ammonia energy storage already exists at scale: large-scale ammonia synthesis plants exist today, and can be readily adapted to receive hydrogen produced via electrolysis (from renewable power) rather than steam methane reforming (e.g. from natural gas); large scale ammonia storage facilities (typically 20,000 tonnes or more) and sea-shipping tankers are in commercial use today; and combustion is well-known as an energy-release processs for power generation purposes. Thus, the challenge with ammonia combustion is to perform it with appropriate emissions control and efficiently, purposes of the study carried out in this work.

A new numerical model of a physical cycle was developed to understand the impacts of combustion of ammonia-hydrogen blend in the gas turbine cycle. The numerical model that is applied for a basic gas turbine cycle considers the processes of non-adiabatic expansion and cooling in the turbine as a whole. The basic assumption of the method is the continual distribution of the cooling air along the gas turbine, with the computation of the expansion process of the combustion gases and cooling air separately. This method was selected as the 'reference method' [10]. For the developed numerical model, it was necessary to make adjustments to the reference model by introducing the effects of water vapor and fuel enthalpy impacts for correspondence to the actual gas turbine plant [11]. The high accuracy of the reference method was previously obtained trough verification based on the comparison of the developed numerical model predictions against the manufacturer's data for a reference gas turbine, with relative errors under 5% [12-14]. For analysis of ammonia-hydrogen combustion in the gas turbine cycle, a new numerical model was employed based on the reference model [10], which consisted of air compressor, combustion chamber and gas turbine, employing predicted values of inlet parameters, as below determined.

Combustion analyses using 1D simulation were conducted using a Chemical Reactor Network (CRN) model, which has shown to be viable for gas turbine simulations previously [6,7]. The reactor network has two clusters. The first cluster represents the swirling flame with a central recirculation zone (CRZ) whose recirculation was set at 20% of the product gases. Recirculation strength was approximated from previous experimental campaigns using similar burners [8,9]. The second cluster uses a single Plug Flow Reactor for post-flame processes along a 0.1 m duct. Simulations were conducted using CHEMKIN-PRO. As inlet conditions, the simulation was carried out using atmospheric and preheated temperatures as in the experimental trials. The model was calibrated to the NOx experimental values in order to determine heat losses that mainly accounted to the primary combustion zone. Then, having the model calibrated, further analyses were conducted on other species and posterior reactions through the post-flame zone.

The new mathematical model showed that combustion of humidified ammonia-hydrogen blends with a total supplied heat of 10.45 MW produces a total plant efficiency of 34%. This basic gas turbine cycle was inserted into a two shaft gas turbine plant facility. At the end of the cycle combustion products mainly consisted of N_2 and H_2O (about 95% of total composition). Then, a reversed Brayton cycle was assessed. Wet and hot exhaust gases at atmospheric pressure (from the first gas turbine outlet) are used for production of extra turbine power by expanding them to negative pressures. The gas mixture is still a high temperature fluid at the end of the second expansion, hence needing to be cooled. The gas mixture is cooled down by applying a special regenerative heat exchanger (HE). Steam is transformed to condensate and extracted from the mixture. The pressure of the gas is lower than the atmospheric and therefore it is compressed in the second compressor to atmospheric pressure. The two shaft concept is analysed in three different cases. In the first case the temperature of the compressed nitrogen is used to increase water temperature (for steam production) and preheating of the gaseous ammonia pre-combustion, Figure 2. In the second case, warm nitrogen is used for distric direct heating, Figure 3. In the third case, the expansion of ammonia (from liquid to gas state) is used for cooling the air which is further compressed in the first compressor. Gaseous ammonia is further heated by hot nitrogen, Figure 4.

All three analysed cases showed significant increase of total efficiency compared to the basic, one shaft gas turbine facility with efficiency of 34%. The first case total efficiency is about 60%, the second case is about 59% and the third case is 53%. Obtained values of total efficiency show a significant potential for the use of humidified ammonia-hydrogen blends in combined gas turbine facilities. It is clear that there is opportunity for efficient energy production using humidified ammonia-hydrogen blends in the novel cycles which consider lower dilution in the combustion sector, as well as cogeneration and trigeneration concepts.

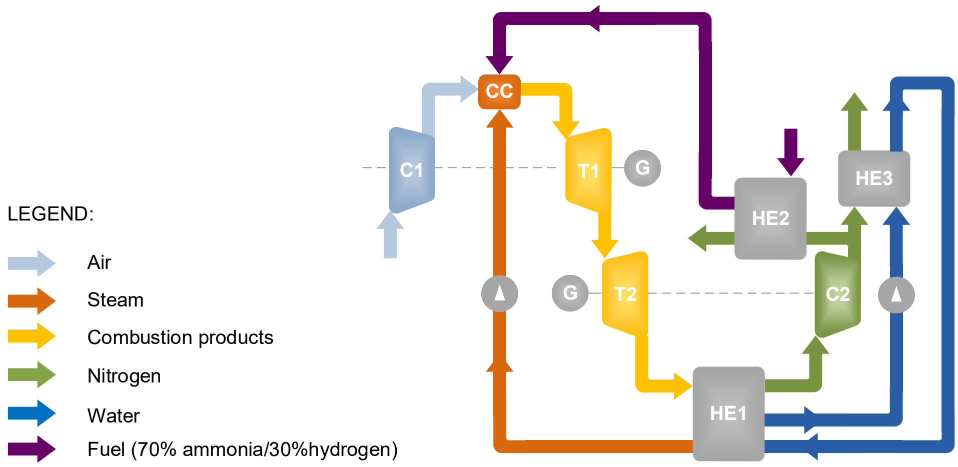

Figure 2. Two shaft concept for ammonia-hydrogen blend with Brayton and reverse Brayton cycle – case 1

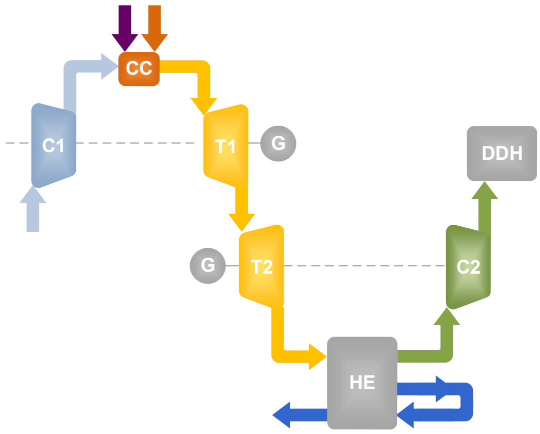

Figure 3. Two shaft concept for ammonia-hydrogen blend with Brayton and reverse Brayton cycle – case 2

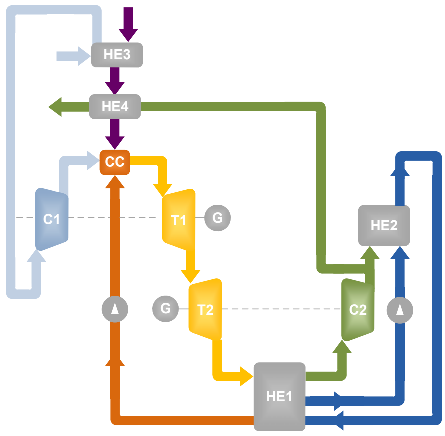

Figure 4. Two shaft concept for ammonia-hydrogen blend with Brayton and reverse Brayton cycle – case 3

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