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Opportunities, Advances and Challenges of Hydrogen micro Gas Turbines

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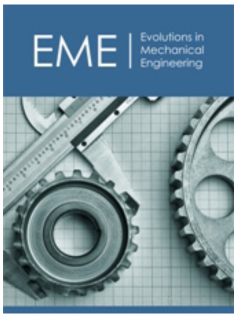

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Abstract

When green hydrogen becomes more prevalent for the buffering of renewable energy, one way to utilize this hydrogen is to use it in a small gas turbine. The units proposed in this article would be part of a flexible, modular, scalable, robust, easily maintainable and economically viable solution for large-scale grid balancing, small-scale combined heat and power and ultra-low emission transportation.

Introduction

According to the World Energy Outlook 2019 by the International Energy Agency [1], the expansion of electricity generation from wind and solar PV will help renewables overtake coal in the power generation mix by the mid-2020s. By 2040, they will even provide more than a quarter of the total worldwide electricity generation, with hydropower and nuclear making up about another quarter.

This increase in low-carbon energy sources is great news for global CO2-emissions, but the current electricity grid operators will be less happy with these forecasts. To ensure stable grid operation it is imperative that it stays at a constant frequency; 50Hz for most of Afro-Eurasia and 60Hz across the Americas. Think of the electricity grid as a tank of water, where the height of the water is the grid frequency level and the electricity production and consumption are the water in- and outlets, respectively. To keep the frequency constant, electricity supply and demand have to be in perfect balance at all times. In a conventional grid, if the demand should rise or fall (because of factories starting up or people starting to cook), the large powerplants could still follow those relatively slow demand fluctuations by ramping up or decreasing their electricity production.

Nowadays, however, with an increasing amount of weather dependent renewable energy sources, the electricity supply can change so quickly that conventional powerplants can barely follow. These fluctuations can be so steep that even fast-starting natural gas-fired gas turbines have to be pushed to their limits. The obvious solution is to store the excess electricity when demand is low and inject it back into the grid when demand increases. This is already being done, mainly by the use of large pumped hydro storage plants. However, for the rapid fluctuations a modern, renewable energy fed grid, these storage plants are becoming more and more inadequate.

Batteries can be seen as an alternative storage technique. However, they have two main downsides. Firstly, they can only store energy for a certain amount of time, usually only a few days. Secondly, their energy density is very low. The best lithium-ion batteries store less than 0.2 kilowatt-hours per kilogram. To illustrate the problem with a concrete example; in 2018 the typical U.S. household used about 213 kilowatt-hours per week according to the US Energy Information Administration (EIA) [2]. That would mean that you would need a 1066 kg (2350lb) battery, assuming you wanted to store enough electricity to run everything in your house for a week and the battery could hold its charge for that long. This means that current battery technology would only be suitable for short-term and small-scale grid balancing through electricity storage. One possible way to flatten out these fluctuations is by increasing the size of the electricity grid and thereby covering a diverse spectrum of climates.

Unfortunately, overhead AC power lines and the necessary HVDC long-range interconnections are difficult to realize due to their high cost and the possible geopolitical problems with competing national priorities for energy supply security. However, there is already a continent-spanning, interconnected, energy grid, the gas grid. A gas grid is much more cost-effective than an electricity grid. For the same investment a gas pipe can transport 10 to 20 times more energy than an electricity cable. The only downside is that natural gas is a carbon-based energy carrier.

Green Hydrogen

This is where hydrogen comes in. More specifically, green hydrogen. Green hydrogen is hydrogen produced by electrolysis using (excess) renewable electricity. It can be transported using the natural gas grid and can be stored in salt caverns and depleted gas field to balance out seasonal mismatches in supply and demand of energy. As for the cost, recent studies carried out by DNV-GL and KIWA in the Netherlands concluded that the existing gas transmission and distribution infrastructure is suitable for hydrogen with minimal or no modifications [3].

After electrolysis, storage and distribution, the green hydrogen must be re-electrified. This can be done most efficiently in a small- to medium scale local Combined Heat and Power (CHP) unit to produce electricity and heat directly were it is needed, instead of in a conventional, large power plant. Both in densely populated, urban, highly grid connected markets, which require supply reliability and peak shaving abilities [4,5], as in rural, more isolated grids, with typically high costs for grid connection and increasingly abundant renewable energy production [6,7], decentralized energy production is already commercially viable. This re-electrification in a CHP system can be achieved by using three different technologies: Reciprocating Internal Combustion Engines (RICE), micro Gas Turbines (mGT) and Fuel Cells (FC).

Decentralized Energy Systems

In these decentralized energy applications, diesel gensets (RICE) are currently the most widely used option [8,9]. However, mGTs have a few distinct advantages when compared to RICEs. A gas turbine has only one moving (rotating) part, which leads to lower noise and vibrations levels and decreased wear on the components. This leads to much lower operational and maintenance costs because the maintenance intervals are larger, and the maintenance interventions are less invasive, especially during the half-way major overhaul. The mGT also has the possibility for multi-fuel applications, opportunities for lower emissions (especially Nitrous Oxides or NO_x) and a cleaner exhaust [8]. When it comes to the comparison with FCs, mGTs are advantageous in many ways; they have a much higher power density, a far longer service life, the combustion process requires a less high hydrogen quality and they do not require nearly as much expensive rare earth metals [10]. However, the main disadvantage of mGTs compared to FCs is their lower electrical efficiency. A 100kWe FC unit typically has an electrical efficiency of 50 %, while a current, natural gas burning mGT with the same power output only reaches 30% [11]. This explains their small market share in the small-scale CHP market [6,12]. Currently, RICEs dominate the small-scale CHP market [13], and only a small number of mGTs (with an electrical output ranging from a few kW to 400kW and electrical efficiencies going from 15% to 30%) are commercially available. These units typically operate according to the recuperated Brayton cycle see Figure 1 and they usually burn gaseous fuels (mostly natural gas). However, some are also capable of using liquid fuels like diesel, when they are equipped with a different, specific combustor.

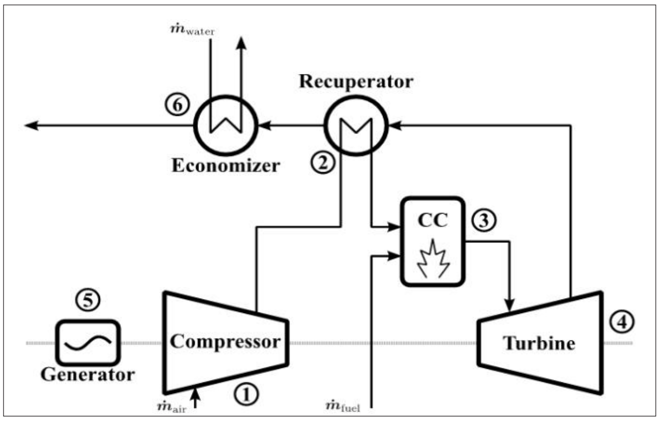

Figure 1: The mGT is a typical recuperated Brayton cycle, consisting of a radial compressor (1) and turbine (4), a low-NO_x burner (3), a recuperator (2) to increase the efficiency and a high-speed generator (5). Since most mGTs are used in CHP applications, the thermal power is produced in an economizer (6) [11].

The Hydrogen Micromix Combustion Chamber

Additionally, and more relevant to our R&D, none of these units can run on pure hydrogen. This is related to two major challenges of hydrogen combustion: its higher flame velocity and temperature. Especially its higher flame velocity can lead to a problem called flame flashback. This is when the flame velocity is higher than the air flow velocity, causing the flame to suddenly propagate upstream, leading to possible damage of the nozzle. The higher flame temperature also causes higher nitrous oxide (NO_x) emissions when compared to hydrocarbon fuels. Most nitrous oxides are formed when air is exposed for a relatively long time to high temperatures, literally oxidizing the nitrogen in the air mainly to NO. Designing a low-NO_x, stable hydrogen combustor has therefore been at the core of our research. Furthermore, higher turbine inlet temperatures (TIT) cause additional costs in either CAPEX, OPEX or both. Current commercially available machines have a TIT of 950 °C, due to the temperature limitations of an all-metallic turbine. The use of ceramic materials for the turbine rotor would allow for a higher

TIT, resulting in a considerable thermal efficiency increase [14].

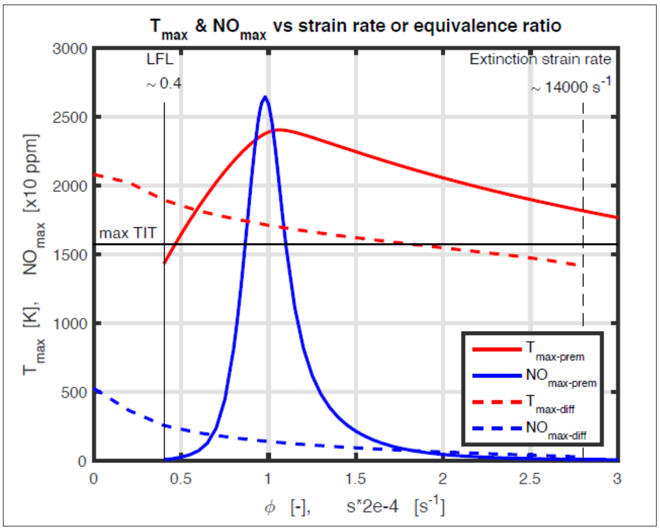

Figure 2: Fundamental laminar adiabatic maximum temperatures and NO emissions, premixed as function of equivalence ratio and non-premixed (diff) as function of applied strain (LFL=lean flammability limit).

Fundamentally, there are two types of major combustion modes. On the one hand, one could look for a design with premixing the fuel and the oxidizer before combustion and on the other hand, supplying them separately and letting the mixing occur in the primary combustion zone. As can be seen in Figure 2, both combustion modes have different characteristics for the maximum temperature and NO formation with respect to a fundamentally laminar adiabatic evaluation. However, the influence of turbulent flow provides a lot of additional complexity. From the figure, it can be concluded that both combustion modes have their optimal operating regions.

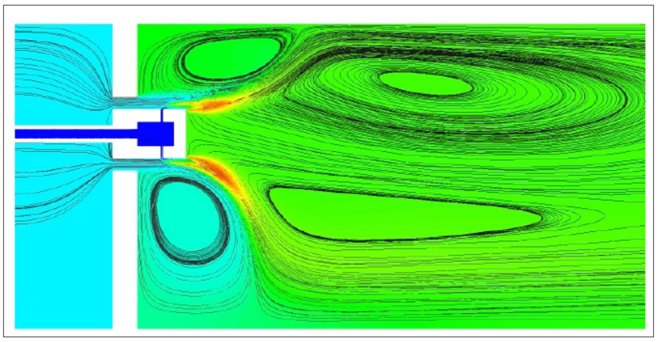

Figure 3: The micromix principle, temperature and streamlines.

These fundamental problems may be solved by using a multitude of combustion modes in combination with a selection of possible flow (or mixing) opportunities. The non-premixed mode is quite classical and mostly used for propulsion applications because it is less prone to sudden flame-out. The premixed mode is used more in stationary gas turbines, in the last decennia particular under lean fuel conditions, mitigating combustion temperatures and consequently NO_x (and dangerous CO) emissions as well as combustion speeds. Recently the micromix concept [15] has gained a lot of popularity, at least at lower TRL levels. It is a combination of a non-premixed combustion of many laminar flames, reducing the size of the high temperature zone and thereby reducing the high temperature residence time (Figure 3).

The Hydrogen Micro Gas Turbine Units

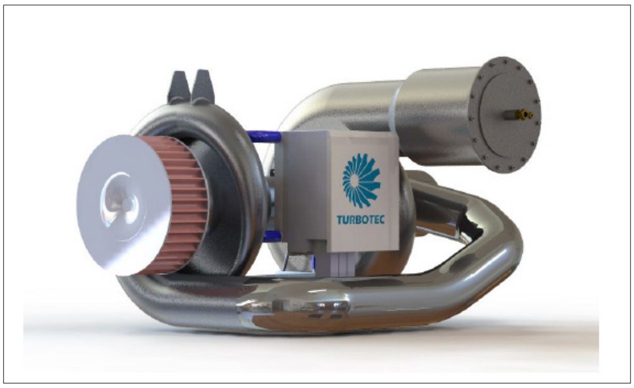

Figure 4: The TURBOTEC HyTG-100.

Since a hydrogen gas grid is obviously quite some years ahead of us, any commercially viable use of a small hydrogen fueled gas turbine will have to be in a mobile application, where hydrogen is already available, like a Fuel Cell Electric Vehicle (FCEV). That is why we have developed two small hydrogen gas turbine designs: the TURBOTEC HyTG-100 and the TURBOTEC HyTG-550. The TURBOTEC HyTG-100 (Figure 4) is a light-weight hydrogen fueled gas turbine generator, suitable for light hybrid-electric helicopters, airplanes and drones. The engine offers 100kW (134hp) of electric power and can also be used as a marine or offshore generator, as a range extender in a large electric vehicle or in a CHP unit.

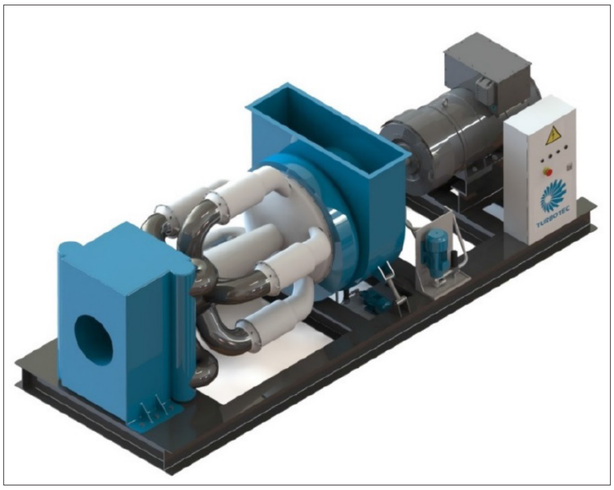

Figure 5: TURBOTEC HyTG-550.

The TURBOTEC HyTG-550 (Figure 5) is a hydrogen fueled gas turbine, designed as a marine propulsion and generator unit, and offers 550kW (737hp) of electric power. It can also be used as a stationary genset in a CHP setup, if the hydrogen is available on-site. This modular unit can fit in an 18ft. high cube (9'6") shipping container. This modular hydrogen gas turbine generator unit can be parallelized to get the desired power output in a larger hybrid-electric system.

For mobile applications like marine or aviation propulsion, the main issue holding back hydrogen solutions is the storage. Hydrogen is a gas at room temperature and pressure and needs to be compressed or cryogenically liquified to store it in a compact form. Another way to store hydrogen in a liquid form is to chemically bond it to another substance, such as CO_2 or N_2 to create methanol or ammonia respectively. Independent of how the hydrogen is stored, a gas turbine can turn it into electricity and heat. Therein lies one of its main advantages, fuel flexibility. Getting a hydrogen gas turbine to burn methanol, ammonia or any other liquid, gaseous or even solid fuel (if a gasifier is available) is realized by modifying or changing out the combustor, while leaving the rest of the machine the same. Furthermore, a single combustor that will be able to burn a wide range of fuels (either gaseous or liquid) will also be available within a few years, further increasing the gas turbine's fuel flexibility.

Conclusion

Including all advantages stated in this article as well, we see a hydrogen gas turbine as a flexible, modular, scalable, robust, easily maintainable and economically viable solution for large-scale grid balancing, small scale combined heat and power and ultra-low emission transportation. The future will depend on widely conducted research and TURBOTEC will play a part in it.

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