Technological and economic assessment on hydrogen energy conversion systems based in gas turbines

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October 2021

Abstract

In order to contribute to the ongoing development of hydrogen technology, this study investigates the possibilities of hydrogen combustion and current status for hydrogen gas turbine technology. The study considered the model of combustion chamber in order to simulate the formation of emissions during combustion of selected fuels and fuel mixture of $CH_4 - H_2$. Such parameters as adiabatic flame temperature, laminar flame velocity and concentration of emission has been investigated with regard to the equivalence ratio ranging between 0.5 and 3.5. Furthermore, the study provides a techno-economic analysis of hydrogen and gas turbine technology, focusing on the environmental impact resulting from the implementation of hydrogen technology and estimation of costs of the micro-gas turbine installation with electrolyzer. The sensitivity analysis of green hydrogen costs indicates the importance of oxygen revenues and its sales in order to obtain low green hydrogen prices. Moreover, the impact of electrolyzer cost and its efficiency has been studied with respect to the price of renewable hydrogen and the utilization factor of the electrolyzer.

Keywords: hydrogen, gas turbine, emissions, low-NOx combustion

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Resumo

A fim de contribuir para o desenvolvimento contínuo da tecnologia do hidrogénio, este estudo investiga as possibilidades de combustão do hidrogénio e o estado actual da tecnologia das turbinas a gás de hidrogénio. O estudo considerou o modelo de câmara de combustão a fim de simular a formação de emissões durante a combustão de combustíveis seleccionados e mistura de combustíveis de $CH_4 - H_2$. Parâmetros como a temperatura adiabática da chama, velocidade da chama laminar e concentração da emissão foram investigados no que diz respeito à relação de equivalência que varia entre 0.5 e 3.5. Além disso, o estudo fornece uma análise técnico-económica da tecnologia de turbinas a gás e hidrogénio, centrando-se no impacto ambiental resultante da implementação da tecnologia do hidrogénio e na estimativa dos custos da instalação da micro turbina a gás com electrólise. A análise de sensibilidade dos custos do hidrogénio verde indica a importância das receitas do oxigénio e das suas vendas, a fim de obter preços baixos do hidrogénio verde. Além disso, o impacto do custo do electrolisador e a sua eficiência foi estudado no que diz respeito ao preço do hidrogénio renovável e ao factor de utilização do electrolisador.

Palavras-chave: hidrogénio, tecnologia de turbinas a gás, emissões, baixo NOx combustão

Introduction

Due to rapidly growing population and energy demands there is a strong need to curb emissions. Therefore an alternative energy sources and technologies are needed in order to substitute depleting fossil fuels that contribute strongly to negative environmental impacts and are a major source of carbon dioxide emissions. Hydrogen has been recognized recently as possible alternative to conventional fuels and energy vector of great potential. Hydrogen a carbon free, most abundant element, which has been recognized thanks to its properties which from the point of thermodynamics make it an attractive fuel. Together with gas turbines, which is a mature, robust technology a hydrogen can be a key to energy transition and very promising intermediate solution, enabling smooth adaptation od current energy system to future objective of Net Zero policy aiming to reduce the emission to the minimum. However very promising, hydrogen gas turbine is still an emerging technology which suffers high NOx, high combustion temperatures and stability issues when running on higher hydrogen contents. This results from the extraordinary nature of hydrogen, which is a challenging fuel in handling and combustion within gas turbines. However, showing great potential, this technology has not been commercialized yet, due to previously mentioned limitations, but also due to hydrogen infrastructure which still is not developed enough to meet the demands and energy production for a worldwide scale. Moreover, hydrogen gas turbine technology to be sustainable and environmentally friendly ought to run on so called green hydrogen, thus hydrogen produced with the use of renewable energy sources. By far hydrogen is mostly produced by steam methane reforming. Hydrogen produced by means of electrolysis covers only 4% of total hydrogen production, and not even this share comes exclusively from renewable sources. The major limitation of green hydrogen production is its still its elevated price in comparison with other hydrogen production methods. Nevertheless, this technology most probably will experience a broad roll-out

State-of-the-art

Even tough, not yet commercialized, this technology has already been proven to be achievable. Some leading gas turbine manufacturers proposed and validated stable gas turbine technology ready to achieve emission meeting the limits and stable combustion of high hydrogen contents. Such producers as Siemens, General Electrics, Mitsubishi Heavy Industries (MHI) and Kawasaki Heavy Industries (KHI) succeed in achieving pure or almost 100% hydrogen combustion, providing at the same time stable power plant operation and low NOx limits. Nevertheless, in case of each of this pilot projects it was necessary to introduce major changes to the turbomachinery or combustor system or use of novel solutions capable of accommodating such high hydrogen contents without damaging the power plant unit and without the performance penalty. Currently it is estimated that the conventional gas turbine system is capable of admission of around 5-15% of hydrogen by volume blended with natural gas without any changes done to the power plant [3][4]. This is achieved for modern combustors where most of them employ the Dry Low NOx premixed combustion or diffusion combustion methods with systems allowing for achieving low NOx such as water injection or post combustion flue gas treatment in form of Selective Catalytic Reduction methods (SCR). The technologies especially recognized by leading gas turbine manufacturers and employed for high-hydrogen content fuels or 100% hydrogen combustion include such technologies as Multi

Nozzle Quiet Combustor – a diffusion combustor proposed by GE which mitigated the risk of flashback, autoignition and other combustion instabilities however results in NOx or around 25ppm. Presented by KHI the Micro-mix Dry Low NOx combustor employs hundreds of miniaturized premixed flames, which allows for low NOx operation, without the necessity of water injection which additionally reduces the efficiency and thus worsens the fuel economy. This technology thanks to the cross-flow mixing, and miniaturized flames reduces the reaction time and residence time in the flame region, at the same time mitigating the flashback risk and providing low NOx operation. Another solution utilized for high hydrogen-content fuels is so called Multi-Cluster Combustor recognized by MHI, which can be employed either for premixed or non-premixed combustion and currently capable of running on 30% hydrogen targeting to pure hydrogen combustion in the nearby future. Generally most of the combustion techniques employ either diffusion or premixed combustion regime where each of this technologies shows different advantages and methods of achieving stable low NOx combustion.

Objectives

This study focuses on the gas turbine operation principles, depicting the limitations and possibilities of pure hydrogen combustion and fuels blends, addressing the possible alternatives and methods of achieving stable low NOx combustion. In this work mechanism of emission formation has been studied together with simulation of idealized well-stirred reactor model in order to present the different fuels characteristics and the formation of emissions. Furthermore, the study provides brief analysis on the environmental impact of hydrogen gas turbine technology and techno-economic assessment of micro-gas turbines coupled with electrolyzer unit. In the last part the sensitivity analysis has been performed showing the dependencies between green hydrogen cost and the electrolyzer unit depending on its efficiency and cost, as well as green hydrogen cost after including the revenues coming from oxygen sales.

Main concepts

Hydrogen combustion results in high laminar flame speeds, which is around 8 times higher when compared with methane combustion. Additionally, the adiabatic flame temperature of hydrogen reaches temperatures up to around 2300K and even 3600K for oxy-combustion, which is much higher than considering conventional fuel combustion [8][9]. One of the three main NOx formation mechanism is Thermal NOx also known as Zel'dovich mechanism, next to the Fuel and Prompt NOx. Therefore, the hydrogen combustion results in such a high emissions. Moreover, the hydrogen combustion promotes the instabilities in form of flashback and blowout which can be result inter alia of hydrogen's high reactivity or high laminar flame speed which in consequence may lead to the combustor degradation or even destruction of turbine unit. Additionally, water pollution should be taken into account, as the hydrogen technology is experiencing rapid development and introduction of such high contents of water into the system might result is negative environmental consequences. Water vapour in 60% contributed to the global warming, and is strongly dependent on the temperature. When combined with other species in the atmosphere results in acid rains after condensation, that impact human health, flora and fauna, agricultural areas and they contribute to deterioration of buildings. Special attention shall be paid to hydrogen gas turbines used in aircraft application. Unlike in case of stationary units, there is no possibility of adding condensation units, since the weight reduction and space saving is of paramount importance when speaking about aircraft application.

Combustion of hydrogen results in approximately 2.55 times more water vapor being produced when compared to conventional jet fuel. A simple estimation showed that a Portuguese fleet consisting in 150 aircrafts operating on hydrogen would produces even 4,43 mln tons of H_2O annually [10].

Reactor simulation

The simulation of the combustion of various fuels has been The analysis was performed using the Well Stirred Reactor (WSR) model in order to simulate the combustion using the “GRI mech 3.0” mechanism implemented in the Cantera suite. A WSR provides a idealization of primary zone of a gas turbine and allows for the analysis of the combustion and emissions. The reactor simulation enabled the investigation of various fuels combustion, namely: hydrogen, $CH_4 - H_2$ blend, ammonia and methane. The results have been assessed against the changing equivalence ratio Φ in the range of 0.3 – 3.5 in order to present the emissions and adiabatic flame temperature (AFT) characteristic for these fuels. Moreover, the flame speed of hydrogen and methane has been compared.

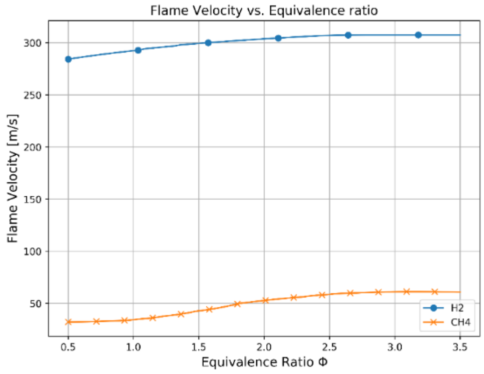

Figure 1 Flame velocity vs. Equivalence ratio of hydrogen H_2 and methane CH_4, combustion at T=1650K, P=1atm.

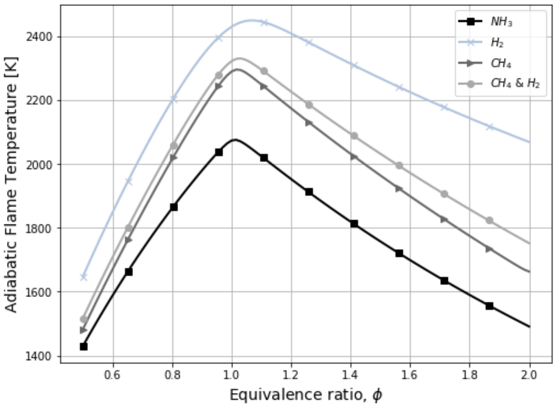

Figure 2 Adiabatic flame temperature for various fuels combustion in air at T=300K, P=1 atm.

Presented in the Figure 1 and Figure 2, obtained values for hydrogen differ significantly from remaining fuels. On the other hand it demonstrates the possibility of employing fuel blends in form of hydrogen-methane blend that would combine the features of both of those fuels such like increased laminar flame speed, increased flammability limits, lower adiabatic flame temperature, higher reaction rate and thus improved performance and fuel economy. Moreover, higher flame speed contributes to better flame stabilization and flame anchoring which might also have a positive impact on combustor design. Ammonia has been recognized as an attractive alternative for pure hydrogen since it contains fuel bound hydrogen, but it is much easier in handling. However ammonia additionally contains fuel bound nitrogen which later results in Fuel NOx species being formed. NH_3 AFT compared to CH_4 is around 200-300K lower, thus $NH_3 - H_2$ blends is a solution improving again the combustion dynamics and therefore combining the desired features of both fuels. The study by Hussein et al. shows that the lowest values of unburned ammonia and higher flame temperatures were achieved for the $NH_3 - H_2$ blends between 40-60% reducing at the same time NOx fraction in the exhaust gas [11]. Presented in the Figure 3 results show that the highest contribution comes from NO in case of hydrogen combustion. It has been observed that the NOx peaks around the equivalence ratio of unity which is strongly connected with the adiabatic flame temperature for stoichiometric mixtures combustion. On the other hand the behaviour of CO being formed results in the CO species experiencing graduate increase after passing the equivalence ratio of 1 being the result of incomplete combustion, combustion dynamics and showing strong correlation with oxygen content in the combustion process.

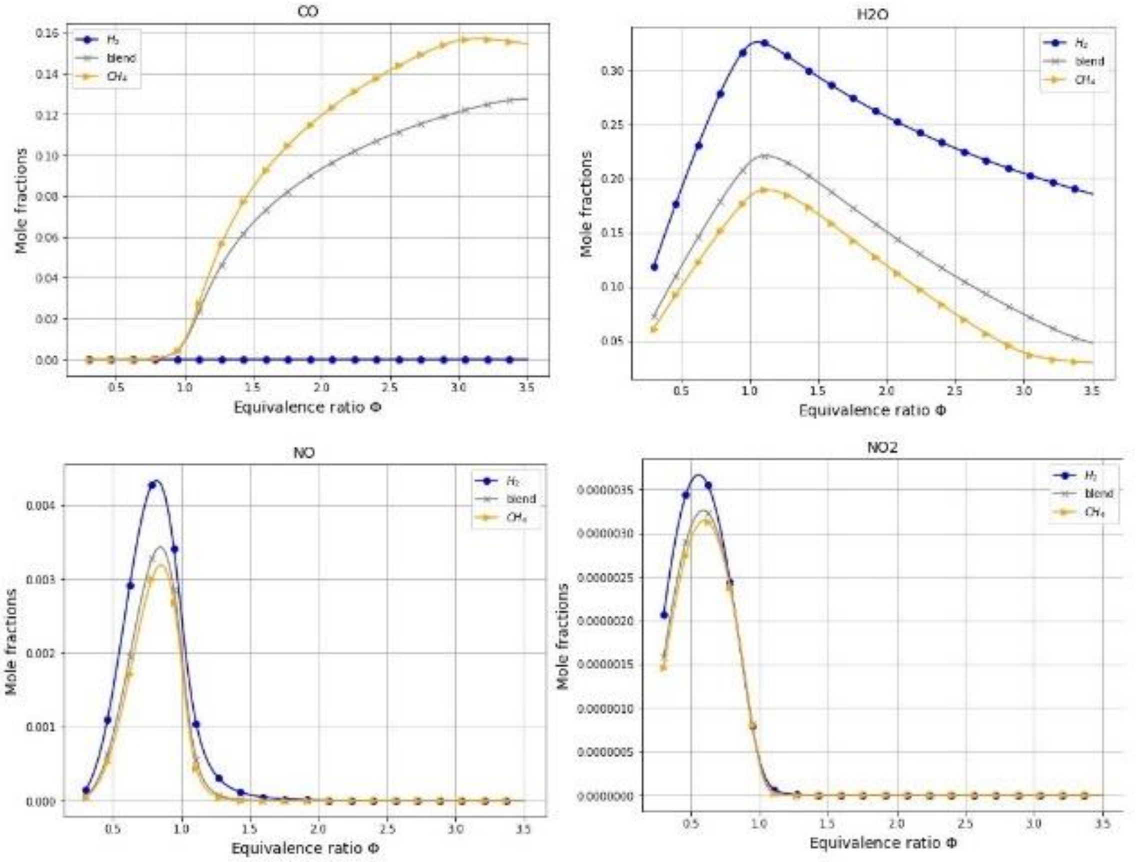

Figure 3 Emission formation, combustion of hydrogen, methane and hydrocarbon blend at T=300K and P=1 atm.

Techno-economic analysis

The economic evaluation has been performed for 30kW micro-gas turbine Capstone C30 coupled with 50kW electrolyzer Teledyne HM-200, which production of hydrogen matches the GT consumption ranging around 24kg of fuel per hour. It has been estimated that that the discounted payback time of this kind of installation would take slightly more than 3 years, without fuels costs being included in the analysis. This would be satisfied for the micro-power plant operating with the utilization factor of 4000h and assuming the energy selling price of 0,2 €/kWh. The estimated operational and maintenance costs each year are 3% of the total initial investment and the discount rate of 7%. However, for this conditions the Net Present Value of the project results to be negative meaning that the project is not feasible or would not result in any profits, but losses. On the other hand the same power plant would have to operate at least 13 years or assuming the selling price at the level of around 0,3 €/kWh. Since fuel costs component state for around 60 % of total investments regarding gas turbine power plant [12] , the analysis of the green hydrogen cost has been performed. The formula presented below proposed by Rui Costa Neto, allowed for calculation of the green hydrogen costs assuming the cost of renewable energy needed to perform the electrolysis process in order to produce hydrogen, being 30 €/MWh. Further the utilization factor of the renewable power plant and electrolyzer taken for the calculation assumes 10 years of continuous operation, which corresponds to alkaline electrolyzer performance, together with its efficiency of 70% [14]. The sensitivity analysis has been performed for three cases assuming: varying electrolyzer capital cost (CAPEX), varying electrolyzer efficiency and finally including the revenues coming from sale of oxygen for varying prices per kg of O_2.

$$Cost\ of\ green\ H_2 \left[\frac{€}{kg}\right] = \left(\frac{electr.cost \left[\frac{€}{MWh}\right]}{1000} + \frac{CAPEX\left[\frac{€}{kW}\right]}{t} \cdot \frac{1}{ha} \right) \cdot \frac{H_2\ LHV}{eff} - \ O_2\ revenue\ [\frac{€}{kg}]\ \cdot 8$$

The highest impact can be observed when considering the revenues from the oxygen production and sale. It has been observed that including the revenue of 2 € per 1 kg of O_2 would result in the same price of green hydrogen of around 2 €/kg H_2 for the reference without including oxygen selling however the utility factor of electrolyzer then would have to be at least 4500 h/annually while with O_2 by-product the same price is reached for the electrolyzer operating only 500 h/annually. It has a great impact since, resulting from stoichiometry, the production of each 1 kg of H_2 corresponds to 8 kg of O_2 production. With higher selling price of oxygen the hydrogen cost could even reach the negative value. The increase in electrolyzer efficiency also results in dropping green hydrogen cost. This analysis therefore proves that there is a strong potential in future green hydrogen production on worldwide scale. Moreover, this could be possible as the electrolyzer CAPEX is predicted to drop even to 200 €/kWh over next decades. The same situation refers to renewable energy, which with technological development and growing efficiency of the installation could result in decreasing prices per kWh. Additionally this study depicts the importance of oxygen sales and the impact those revenues have on the green hydrogen cost. Growing demand for hydrogen going together with demand for oxygen shows a great potential for future hydrogen production sites and the worldwide development of hydrogen economy.

Conclusions

Hydrogen recently has been recognized as a valuable fuel and energy vector offering wide range of possibilities of its implementation within the existing energy system. Due to hydrogen's extraordinary properties and no contribution to climate change there is a growing interest in hydrogen technology and creation of global hydrogen network and infrastructure. By far the biggest limitation for green hydrogen production on a global scale and sufficient to cover the energy demand is its high price compared to other hydrogen feedstock and methods of production. Gas turbines, as a mature, well-developed, robust technology able to provide vast amounts of energy is considered an attractive solution for the upcoming shifting towards hydrogen economy. Not only would it allows for hydrogen accommodation in the existing energy system, but also it would result in decreased CO_2 emissions and better allocation on energy surplus coming from renewable sources and thus it would contribute to better grid balancing. Existing gas turbine units are capable of admitting hydrogen volumes up to 15 %.

This is an important fact, which together with the projected hydrogen injection into the gas grid, would be of great importance and would contribute to smooth energy transition. The main limitation preventing this solution to be fully commercialized are the technical and economic issues connected with utilizing hydrogen as a gas turbine fuel. In order to commercialize this technology and run a gas turbines on 100 % hydrogen, there is a strong need in NOx emission reduction along with reduction of green hydrogen costs and technology scale-up in order to provide enough fuel for gas turbine to meet the energy demands and environmental limitations. The challenge in finding emission equilibrium and optimum point to reach low emission of different species results from the different reaction kinetics and thus residence time necessary for the conversion of each of different species. The big impact on the emission formation has the equivalence ratio being the fuel-to-oxidizer ratio to its stoichiometric equivalent. Equivalence ratio defines whether the fuel mixtures is lean, therefore composed of higher amount of oxidizer than fuel or rich where the situation is reverse. This factor is strongly connected with the combustion temperature and therefore the formation of emissions. Moreover, the water emission resulting from combustion of high-hydrogen content fuels should be taken into account. Additionally the study shows that that this solution offers a wide range of application from micro-gas turbine units up to industrial units and aircraft application.

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