Numerical Investigation of Combustor Inlet Temperature Effects on Emissions and Performance in Non-Premixed Ammonia-Fueled Micro-Gas Turbines

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Abstract

Ammonia combustion offers a carbon-free energy solution but faces challenges with high NOx emissions, especially at elevated air temperatures. This study uses CFD simulations to examine the effect of combustor inlet temperature (CIT) on a 20-kW staged rich-lean, non-premixed ammonia combustor. Raising CIT from 500 K to 1050 K at an equivalence ratio of 0.12 increased outlet temperature by 33% and NOx emissions by 50%, while reducing unburned NH_3 and H_2 by 90% and 27%. Findings support optimized, low-emission ammonia-fuelled turbine design.

Introduction

Combustion remains essential in industrial applications such as power generation and manufacturing. Although fossil fuels currently supply 80% of global energy, they are major contributors to carbon emissions and climate change [1]. Improving combustion efficiency alone cannot meet climate targets; a shift to renewable energy is required [2]. However, renewables face challenges like intermittency and infrastructure limitations. Some processes still require high-temperature combustion, making hydrogen a promising alternative [3]. Ammonia, with high hydrogen content and existing infrastructure, is gaining attention as a carbon-free fuel and hydrogen carrier [4] [5] [6]. It can be cracked into hydrogen or used directly in combustion systems such as micro gas turbines (MGTs), which offer decentralized, low-emission energy solutions [7]. Research has shown ammonia can achieve reasonable electric efficiency [8] [9] [10], and techniques like steam injection help reduce NOx emissions [11] [12]. However, ammonia's low flame speed [13] requires dual-fuel strategies, blending with hydrogen or methane improves stability but can introduce flashback [14] [15] or increase CO_2 and Nox [16]. Experimental studies confirm that stable ammonia flames are achievable, and NO emissions can be minimized under rich conditions. Strategies like staged combustion, optimized injection, and selective catalytic reduction (SCR) further reduce emissions [17] [18] [19] [20] [21]. This study extends prior work by analysing how combustor inlet temperature (CIT) affects ammonia combustion, focusing on flame stability, unburned species, and emissions using CFD.

Methodology

The MTT-EnerTwin is a 21-kW recuperated micro gas turbine using a non-premixed, rich-burn combustor optimized [21] for ammonia fuel. Operating at an overall equivalence ratio of 0.12, it runs at 240,000 rpm with 1.13 g/s fuel flow, 1050 K air inlet temperature, and 3.0 bar pressure (Figure 1) [11].

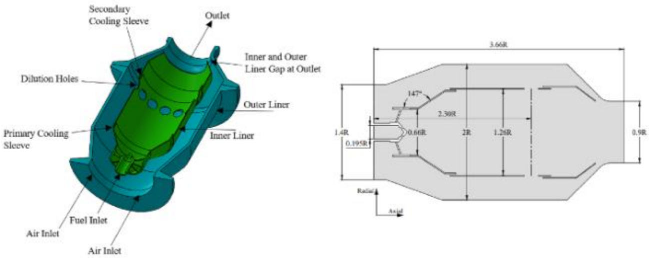

Figure 1. Three-dimensional model of the non-premixed swirl combustion chamber and the dimensions of its central cross-section (computational domain).

This study varied the air inlet temperature from 500 K to 1050 K to evaluate its impact on emissions, efficiency, and combustion stability, keeping the fuel inlet at 300 K. It employed a realizable RANS k–ϵ turbulence model and used Stagni et al.'s optimized kinetic mechanism [24], which includes 31 species and 203 reactions. This mechanism accurately models ammonia oxidation, NO formation, and reburn chemistry across different equivalence ratios and temperatures, ensuring reliable combustion simulation and emission prediction in ammonia-fueled systems.

Results and discussions

This study explores how combustor inlet temperature (CIT) affects emissions and performance in a non-premixed ammonia-fuelled micro gas turbine (MGT) using CFD simulations. CIT values from 500 K to 1050 K and various overall equivalence ratios (OERs) were analysed, with OER = 0.12 and 0.3 selected for detailed study due to safe outlet temperatures [25]. Results showed that increasing CIT raises combustor outlet temperature (COT) by 33% and expands the flame region, enhancing combustion stability and heat release, as demonstrated in Figures 2.

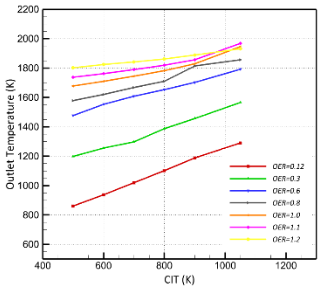

Figure 2. Combustor outlet temperature and distribution for various CITs and OERs

Increasing CIT significantly improved fuel oxidation and combustion efficiency. At CIT = 1050 K and OER = 0.12, unburned NH_3 and H_2 decreased by 90% and 27%, respectively (Figure 3a, 3b), while combustion efficiency increased by 85% (Figure 4). However, NOx emissions rose with CIT, especially under lean conditions, due to higher oxygen availability (Figure 3c). Richer mixtures reduced NOx but compromised efficiency.

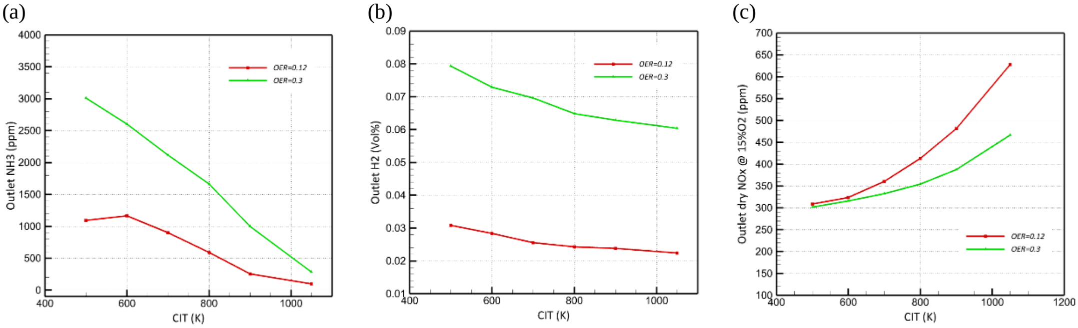

Figure 3. Concentration of (a) ammonia, (b) hydrogen and (c) NOx in the outlet of the combustion chamber for different CITs and OERs=0.12, 0.3

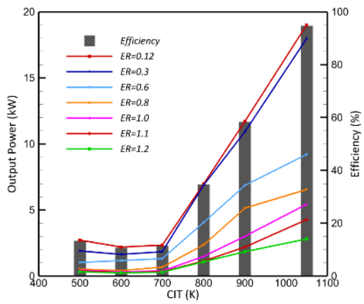

Figure 4. Combustor output power and efficiency at different combustor inlet temperatures (CITs) for various OERs.

Conclusion

This study examined the effect of Combustor Inlet Temperature (CIT) on emissions and performance in a staged rich-lean, non-premixed ammonia-fueled micro gas turbine using CFD simulations. Increasing CIT from 500 K to 1050 K at an equivalence ratio of 0.12 improved combustion efficiency by 85% and raised outlet temperature by 33%. Unburned NH_3 and H_2 were reduced by 90% and 27%, indicating enhanced fuel utilization. However, NOx emissions increased with CIT. While higher equivalence ratios were limited by excessive temperatures, OER = 0.12 provided optimal results. Future work should integrate NOx mitigation strategies and experimental validation for sustainable ammonia combustion.

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