Experimental Investigation of the Effect of Steam Dilution on the Combustion of Methane for Humidified micro Gas Turbine Applications

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Introduction

Water introduction in the micro Gas Turbine (mGT) cycle is considered the optimal route for waste heat recovery and flexibility increase of such small-scale Combined Heat and Power (CHP) units [1]. However, humidification of the combustion air in a mGT affects combustion stability, efficiency and exhaust gas emissions. This can lead to a non-stable, incomplete combustion, which will affect the global efficiency negatively. Additionally, CO emissions will increase. The non-stable, incomplete combustion might result in an engine shutdown due to a flameout.

To study the impact of humidification on the combustion of methane in a humidified mGT, we performed combustion experiments in an atmospheric, variable-swirl, premixed combustion chamber. In this study, we focused on the Lean Blowout (LBO) limit and CO emissions of methane combustion. By measuring the LBO limit, we tried to predict how the fuel control of the mGT needs to be changed in order to get a stable combustion under humid conditions. CO emission levels were measured to show the influence of the steam dilution on the exhaust emissions. Out of these results, guidelines for combustion in humidified mGTs were be formulated. In addition to the experimental results, simplified chemical kinetic simulations concerning the CO emission values have been added to this study.

Methodology

The focus of the presented work was the investigation of the effect of steam dilution on the LBO limit for methane combustion at different swirl numbers and steam fractions. For the combustion experiments, an atmospheric, variable-swirl, premixed burner with a circular cross section (Figure 1), was used in combination with an electric steam generator. For LBO-limit determination, following procedure has been used: First, a rich mixture (equivalence ratio close to 1) was ignited.

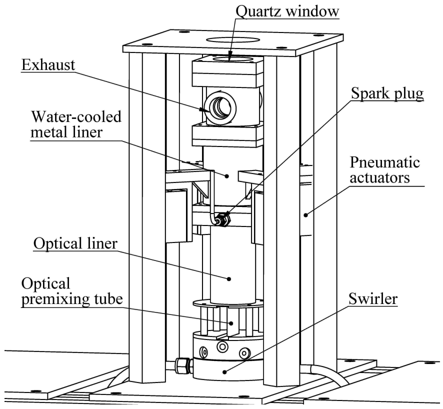

Figure 1: The variable-swirl burner, at the labs of the Thermal Power Engineering division of the Department of Energy Sciences of Lund University, Sweden, has an optical access to study the flames [2].

After ignition, the equivalence ratio was reduced slowly by gradually reducing the methane fuel flow rate. After each change of fuel flow rate, it was maintained constant for at least 3 minutes to stabilize the flame and to allow the combustion chamber to reach thermal equilibrium. During this period, CO emissions were also captured. The fuel flow rate was reduced until blowout occurred. For each steam fraction, this procedure was conducted three times, to show repeatability of the experiments and to exclude possible deviations due to sudden instabilities in one of the flows.

Finally, the chemical kinetic simulations were performed, using `OpenSMOKE++` [3]. The idea was to show the importance of the kinetics in the final CO emissions in a qualitative way. The combustion chamber was simulated as a Perfectly Stirred Reactor (PSR) with a constant residence time. The residence time was kept constant at 2 s, which was calculated from the volumetric flow rate and the volume of the chamber. In these calculations, temperature was also kept constant and no energy calculations were performed. The temperature was calculated by taking the average of the inlet temperature and the expected flame temperature, taking into account the combustion efficiency. Finally, the GRI-Mech 3.0 for modelling of natural gas combustion has been used [4].

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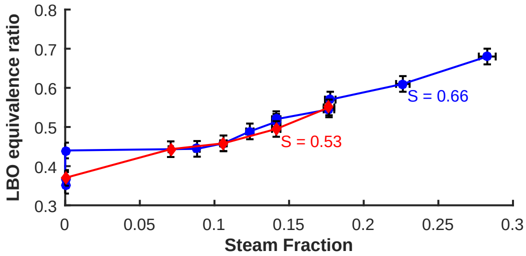

Figure 2: The LBO equivalence ratio increases linearly with increasing steam fraction in the combustion air.

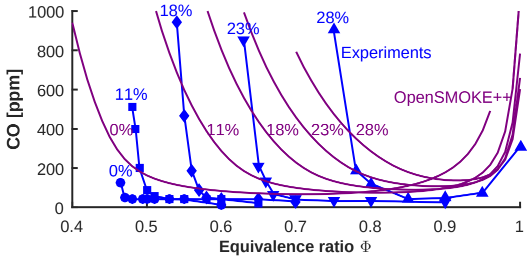

Figure 3: CO levels increase with decreasing equivalence ratio. At high steam fraction, CO levels are still low which indicate that the combustion efficiency remains high. Chemical kinetics simulations performed in `OpenSMOKE++` show these increasing CO emission levels when approaching the LBO limit. CO emissions do not match perfectly, since the PSR is a rough approximation of the burner.

Results

Increasing the steam fraction will increase the LBO equivalence ratio for methane combustion (Figure 2). The increasing LBO equivalence ratio from Figure 2 is a result of the increasing steam fraction. The presence of the steam in the combustion air will absorb heat of the combustion. This results in a lower flame temperature, enabling LBO at higher equivalence ratio, which explains the increasing LBO equivalence ratio.

CO levels in the exhaust gases start to rise at higher equivalence ratios with increasing steam fraction (Figure 3). This is a result of the higher LBO equivalence ratio. At full combustion with a flame concentrated around the inner recirculation zone, CO levels are of the same order of magnitude as the pure methane combustion for all steam fractions (Figure 3). This indicates that the combustion is complete, which will result in a high combustion efficiency. However, the equivalence ratio at which the flame is still concentrated around the inner recirculation zone shifts towards higher equivalence ratios. Therefore, full combustion occurs at higher equivalence ratio which indicates that more fuel needs to be added to the combustion chamber under steam injection conditions to achieve high combustion efficiency.

Finally, the simulations using `OpenSMOKE++` indicate that it is possible to reproduce the specific profile of the CO emissions in a qualitative way (Figure 3). CO emissions are low when complete combustion occurs. When lowering the equivalence ratio by reducing the fuel flow rate, CO emissions start to rise due to a decreasing combustion temperature in combination with a limited reaction time.

Conclusion

Steam dilution experiments have been conducted on an atmospheric, variable-swirl premixed combustor to study the effect of humidified combustion air on the CO emissions and LBO limit for methane combustion. The major conclusions from these experiments were:

- The LBO equivalence ratio increases linearly with increasing steam fraction.
- The CO levels start to rise at higher equivalence ratios when injecting more steam.
- CO levels at complete, stable humid combustion are constant and equal to those of dry combustion.
- Steam has a stabilizing effect on methane combustion when lowering the equivalence ratio.

Summarizing for mGT applications, it is possible to maintain a stable and complete combustion under steam injection conditions. However equivalence ratio needs to be increased in order to stay away from LBO limit and to keep CO emissions low.

Acknowledgments

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