Understanding methanol combustion for the design of a dedicated low-emission burner

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Abstract

This study investigates methanol combustion characteristics to support the design of a clean, fuel-flexible burner for integration into an externally-fired Brayton cycle. One-dimensional laminar flame simulations were used to evaluate combustion behavior and emissions across a range of conditions, identifying optimal operating parameters. A first-guess combustor design was then tested using 2D CFD simulations with both methanol and methane to assess performance and fuel flexibility. Results show that the burner can operate efficiently with both fuels, with methanol exhibiting slightly higher reactivity.

Introduction

In the transition toward a low-carbon energy system, green methanol is a promising fuel—especially for hard-to-electrify sectors like transport, energy-intensive industries, and power generation. Methanol (CH_3OH), a liquid with an established supply chain, can be produced in grey, blue, or green forms, depending on the sustainability of its feedstocks. Green methanol, derived from renewable hydrogen and captured CO_2 or biomass gasification, offers a carbon-neutral or even carbon-negative alternative. Compared to hydrogen, methanol is easier to handle, store, and transport, making it attractive as an energy carrier and as a fuel in high-temperature applications and gas turbines. However, to fully harness its potential, a detailed understanding of its combustion behavior is essential. This study analyzes methanol combustion characteristics to support the design of a clean, fuel-flexible burner. To ensure operational resilience under fluctuating renewable fuel availability, the burner will also accommodate methane or methanol-methane blends.

Methodology

Numerical simulations were used to analyze methanol combustion and guide burner design. One-dimensional laminar flame simulations explored a range of operating conditions to identify key parameters affecting performance and emissions. Based on these results, an initial combustor geometry adapted from a ULB laboratory design [1] was evaluated using two-dimensional RANS CFD simulations with both methanol and methane.

Case study

The methanol combustor is integrated into an externally-fired Brayton cycle (Figure 1), operating at atmospheric pressure with a thermal input of 20 kWth. Operating conditions can vary between two extremes points: A) $\Phi = 0.10$, $T_{in} = 320°C$, and B) $\Phi = 0.15$, $T_{in} = 570°C$. Due to the low equivalence ratios, stable combustion requires splitting the airflow: a primary stream for combustion and a secondary stream for post-flame dilution and cooling before the heat exchanger. A first-guess geometry of the methanol burner was derived from an existing reverse-flow combustor installed at the ULB laboratory [1].

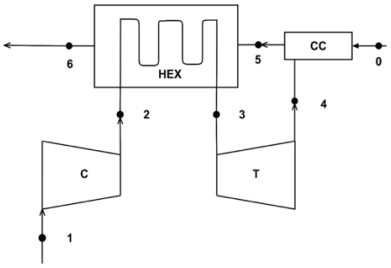

Figure 1. Sketch of the externally-fired Brayton cycle: 0) fuel inlet, 1) compressor inlet, 2) heat exchanger inlet, 3) turbine inlet, 4) combustion chamber inlet, 5) combustion chamber outlet, 6) heat exchanger outlet.

Results and discussion

1D methanol-air premixed flame simulations were carried out at various air inlet temperatures and equivalence ratios, as shown in Figure 2. As visible, T_{in} has a marginal effect on CO emissions, slightly higher effect on NO as well as on the flame stability, extending the stable flame region when T_{in} increases. On the other hand, the equivalence ratio has a much bigger impact on both CO and NO emissions which become reasonably low at $\Phi<0.5$. Anyhow, Φ values lower than 0.3 must avoided to avoid flame extinction. Therefore, $\Phi=0.4$ was considered as optimal operating point and used for subsequent 3D CFD simulations carried out on a first-guess combustor design, as shown in Figure 3.

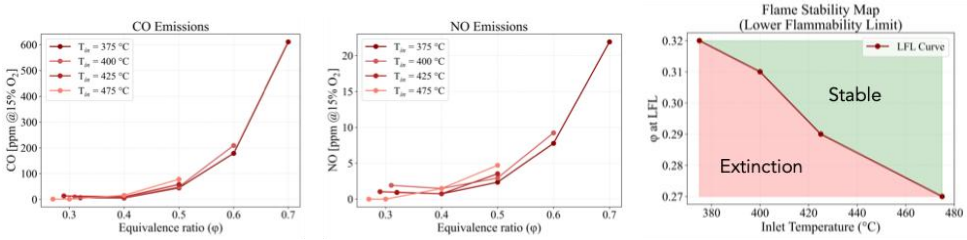

Figure 2. CO (left), NO (center), and stability map predicted with 1-D methanol-air premixed flames for different air inlet temperatures (T_{in}) and equivalence ratios (Φ).

Temperature and OH molar fraction contours are reported for both methane and methanol combustion with T_{in}=320°C and T_{in}=570°C. As visible, the combustor can

flexibly accommodate both fuels with minimal differences in the temperature field. Form the OH field, methanol combustion is slightly more intense, especially at higher T_{in} at which the system reactivity is enhanced leading to a more compact and less distributed flame.

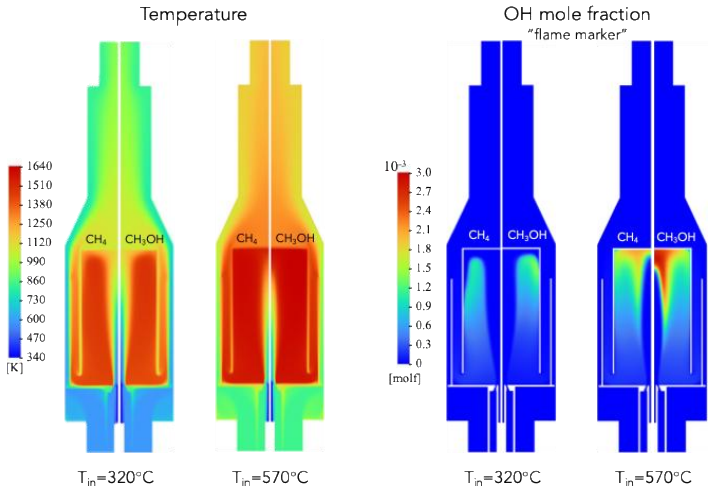

Figure 3. Temperature (left) and OH mole fraction (right) contours for methane (CH_4) and methanol (CH_3OH) at Φ=0.4, for two different air inlet temperatures, T_{in} = 320°C and T_{in} = 570°C.

Conclusions

In conclusion, 1-D flame simulations identified Φ = 0.4 as an optimal equivalence ratio for flame stability and low emissions. Subsequent, CFD simulations confirmed that the proposed burner design can accommodate both methanol and methane, ensuring operational flexibility under variable fuel availability.

Acknowledgments

The authors acknowledge the ResMe2E Project, which has received funding from the Horizon Europe programme under grant agreement No 101172988.

References

[1] Giuntini, L., Novelli, C., Kamal, M.M., Cafiero, M., Galletti, C., Coussement, A., Parente, A., "Continuously-staged NH_3 oxidation in a stagnation-point reverse-flow combustor for low NO_x emissions", Proc. Comb. Inst. 40:1–4, 105674 (2024).