International Conference on Numerical Combustion
Rome, Italy, October 14-17, 2025
www.icnc2025.com

Effects of backstep geometry on multiple hydrogen jet flames in cross-flow

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Pure hydrogen combustion in gas turbines is extremely challenging due to its unique transport and thermochemical properties, such as high diffusivity and deflagration speed. The "Micromix" combustion technology [1] addresses these challenges by injecting hydrogen through an array of miniaturized jets located very close to the combustion chamber to prevent flashback, while minimizing NO_x formation thanks to intense turbulent mixing. In this study, direct numerical simulations (DNS) are performed for two non-autoignitive pure hydrogen jets injected perpendicularly into an air crossflow. The focus is on the influence of backstep on the overall flame stabilization and propagation behavior. Two configurations are considered, which differ in the geometry of the upper and lower boundaries: one is a straight channel, and the other features a backstep positioned downstream of the jet exit.

The two cases share the same thermochemistry condition and jet/air injection parameters. The nominal pressure, P_0, is 4 atm. The jets temperature (T_j) and velocity (U_j) are $300\ \mathrm{K}$ and $231\ \mathrm{m/s}$, leading to a jet Mach number (Ma_j) of 0.17. The jets have a diameter, D_jet, of $0.45\ \mathrm{mm}$, which yields a Reynolds number ($Re_j = U_\mathrm{j} D_\mathrm{j}/\nu_\mathrm{j}$) of 4000. The air crossflow has a nominal mean bulk velocity (U_cf) of $37.5\ \mathrm{m/s}$ and a temperature of $750\ \mathrm{K}$. The jet-to-crossflow momentum flux ratio, $J = \rho_\mathrm{j} U_\mathrm{j}^2/\rho_\mathrm{cf} U_\mathrm{cf}^2$, is 6.6, where ρ denotes the density, and the global equivalence ratio is 0.6. To characterize the NO_x production, the mixture fraction weighted residence time is transported. For both cases, isothermal wall conditions with $T_\mathrm{wall} = T_\mathrm{cf} = 750\ \mathrm{K}$ are considered. The simulations are performed with PeleLMeX and the backstep geometry is modeled by the embedded boundary method.

The results reveal distinct flame stabilization behaviors between the two configurations. In the straight channel case, the flame exhibits two main branches, one anchoring closely to the leeward side of the jet, and another stabilizing at the windward side. Near the lower wall, an edge flame-like structure forms along the periphery of the jet, where the convective velocity is relatively low due to the combined effect of the boundary layer and recirculation. The resulting hot products are entrained into the low-velocity recirculation zone on the leeward side, where premixed flames reside. In contrast, the introduction of a backstep shifts the flame stabilization further downstream into the shear layer induced by the backstep. At these stabilization sites, a triple interaction occurs between the hydrogen fuel, air crossflow, and burned products trapped within the backstep-induced recirculation zone. Moreover, the presence of the backstep leads to a higher jet expansion rate and thus potentially a higher level of premixedness. The effects of flame stabilization on the production of NO_x is quantified by reaction pathway analyses and residence time. These findings highlight the strong influence of burner geometry, even simplified, on hydrogen Micromix flame stabilization, which may further translate into different pathways of NO_x production.

References

[1] Funke HHW *et al.*, Numerical and experimental evaluation of a dual-fuel dry-low-NO_x micromix combustor for industrial gas turbine applications, J. Thermal Sci. and Eng. Appl. 2018;11:011015-1