Influence of turbulent inflow conditions on the Large-Eddy Simulation of a non-premixed hydrogen-air jet flame

F. Garnier [a], T. Jaravel [a], A. Boudin [a], D. Laera [b], T. Poinsot [a,c]

[a] CERFACS, 42 Avenue Gaspard Coriolis, 31057 Toulouse, France
[b] Politecnico di Bari, Via Orabona 4, Bari, 70125, Italy
[c] Institut de Mécanique des Fluides de Toulouse, Université de Toulouse, CNRS, 31400 Toulouse, France

E-mail: *garnier@cerfacs.fr*

Abstract

Hydrogen jet flames take part in numerous safety scenarios raised by the use of hydrogen throughout multiple industry sectors. For instance, in case of ignition during an accidental leak or an overpressure venting operation, a large turbulent diffusion flame may establish and anchor at the hydrogen outlet rim, potentially causing mechanical destruction. This study aims at achieving a fine physical understanding of such flames, particularly their response to turbulent inflow conditions.

The Large-Eddy Simulation (LES) methodology is applied to the turbulent non-premixed hydrogen-air flame investigated by Barlow and Carter [1,2]. The jet flame is stabilized at the outlet of a pipe of diameter D = 3.75 mm, where pure hydrogen flows at Re = 10,000 into air, yielding a flame of visible length L = 180D (Fig. 1).

In the reference computation, the turbulent hydrogen jet is modeled by injecting synthetic anisotropic nonhomogeneous turbulence on a pipe inlet. The pipe length is kept short (2.6D) to limit computational cost. Even though it results in partially developed turbulence at the pipe exit, results show that the turbulent fluctuations are sufficient to correctly capture the jet destabilization and the flame structure over its whole length. The mixing process is found to be tightly coupled to the jet destabilization mode, which is strongly sensitive to the inlet conditions [3,4,5]. In the jet flame LES, the hydrogen jet destabilizes under the combined effects of Kelvin-Helmoltz instability, driven by shear, and turbulent fluctuations, convected from the injection tube.

The LES is able to retrieve finite rate chemistry and differential diffusion effects, which are expected in such flames [6,7]. Results also show a fair agreement with the mean and RMS experimental dataset, including common safety metrics such as flame length. In particular, the rate of decay of axial velocity and mixture fraction is well-predicted, indicating that the mixing rate is correctly captured. The flame structure fairly agrees with temperature and intermediate species measurements throughout the flame. Furthermore, the numerical results suggest the occurrence of local extinction events in the flame base region, associated with locally high scalar dissipation rate.

In order to quantify the sensitivity of jet stability and flame structure to the turbulent inflow conditions, a supplementary LES is performed where the hydrogen turbulent inlet is supplied by a precursor periodic pipe simulation. At the hydrogen injector exit, the turbulent flow is fully developed with higher levels of fluctuations than in the synthetic turbulence injection case. Discrepancies between both injection methods seem to prevail in the flame base. As the mixing process in the near field influences the far field, the flames are compared downstream of the potential core breakup. The numerical results seem to indicate that the far field is sensitive to jet exit conditions to a lesser extent than the near field, as the discrepancies observed at the flame base are smeared out by the far field smoother gradients.

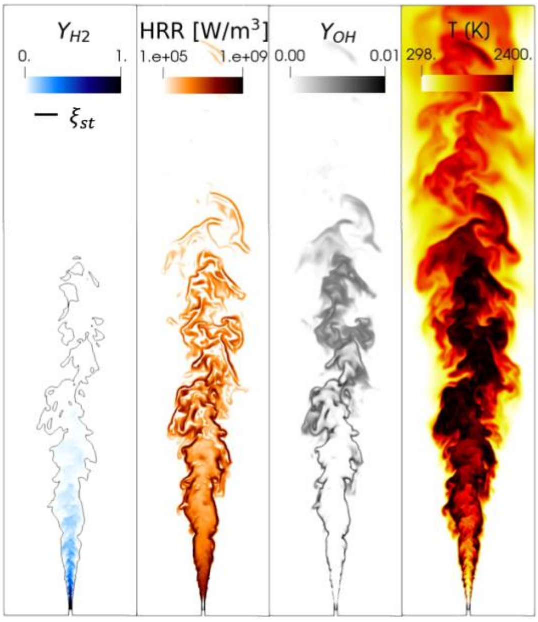

Figure 1 – Mid-plane instantaneous fields of H_2 mass fraction with stoichiometric mixture fraction contour, heat release rate, OH mass fraction and temperature.

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