Flashback onset mechanisms after hydrogen ignition: a comprehensive LES study

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Abstract

High-fidelity Large Eddy Simulations are used to investigate the flashback dynamics after the ignition process of an atmospheric, perfectly premixed, lean hydrogen mixture. A bluff body is adopted to stabilize the flame, and a perforated plate is placed at the outlet to mimic the flow blockage characteristic of a turbine cascade. Although the global criterion presented in [1] is satisfied, the onset of flashback is preceded by a boundary layer flashback mechanism along two preferential directions dictated by the expansion of the flame during the ignition process.

Introduction

Mitigating flashback in advanced burner configurations employing alternative fuels such as hydrogen constitutes a fundamental challenge. Indeed, the peculiar combustion characteristics of hydrogen in terms of high reactivity, strong overpressure generated during ignition and reduced quenching distance can significantly enhance the propensity for flashback [1], [2], [3].

Therefore, the study aims to investigate the mechanisms governing flashback onset after the ignition of a lean, perfectly premixed hydrogen flame.

Test case and numerical setup

High-fidelity LES simulations are performed using the pressure-based solver ANSYS Fluent 22R1. Initially, a cold simulation with a hydrogen-air mixture is flushed for around 170 ms and then the spark is released. The full rig [1] with an external hemisphere at the chamber outlet are included in the computational domain (**Figure 1**). In addition, the operating conditions with the main boundary conditions are reported schematically. A fully unstructured grid is adopted based on polyhedral elements, as shown in **Figure 1** along with the local sizing. Furthermore, a specific refinement close to the external injector wall is performed to resolve the flame within the computational grid. The effect of the unresolved eddies is modeled with the dynamic Smagorinsky-Lilly subgrid-scale model and the skeletal mechanism obtained by Boivin (9S12R) [4] is used to describe the system reactivity. The mixture-average approach is chosen to account for the diffusive problem with the inclusion of the Soret effect. The turbulence chemistry interaction is handled with the Thickened Flame Model (TFM) [5] and the sub-scale wrinkling effects are

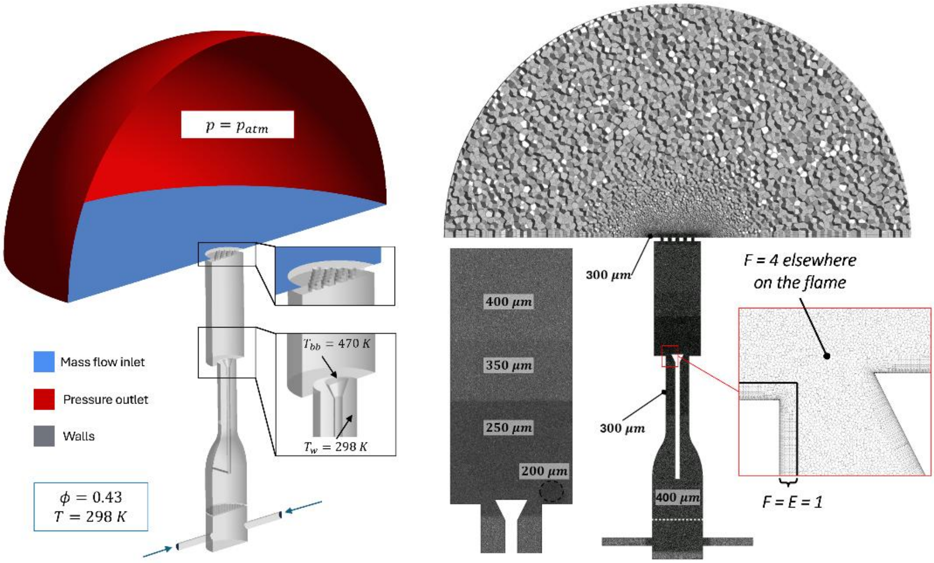

Figure 1: Numerical domain with the prescribed boundary conditions(left) and computational grid with the local sizing employed (right).

modeled with the Colin efficiency function. A thickening factor F equal to 4 is dynamically applied on the flame front except for the regions close to the wall where the grid is sufficient to resolve the flame. Finally, the ignition of the mixture is performed with the Energy Deposition [6] model and a constant time step of 5E-6 s is used to maintain the convective Courant number Co < 5 in regions of interest.

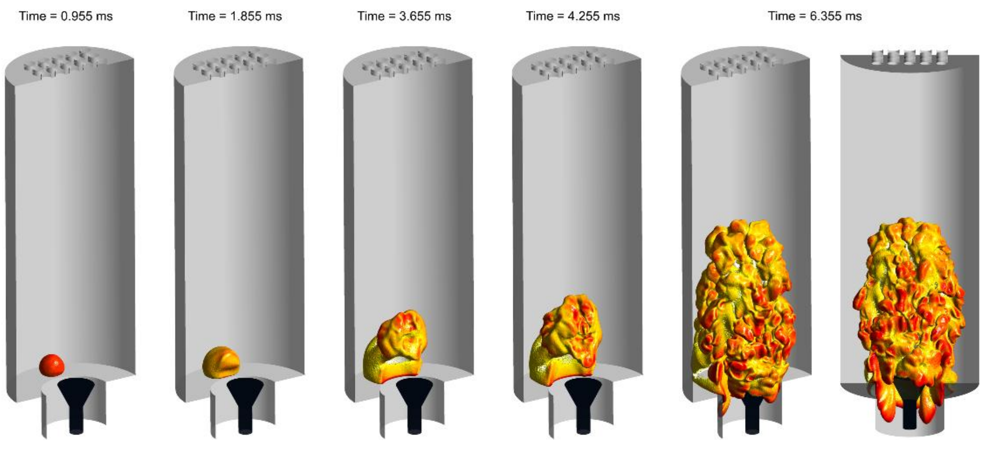

Figure 2: Ignition sequence visualization through an isosurface of PV colored by the local temperature.

Results

A three-dimensional representation of the ignition process is provided in **Figure 2** through an isosurface of the PV, colored according to the local temperature. The low turbulence levels maintain initially an almost spherical kernel, without exhibiting significant increases in local reactivity. Subsequently, due to the interaction with the shear layer and the penetration of the annular jet, a flame front wrinkling is observed. This behavior is attributed to the interaction with turbulence scales and the onset of thermodiffusive instabilities, which promote preferential flame propagation in specific directions due to a localized enhancement in fuel consumption. This effect is evident at t = 3.655 ms with the formation of two flame leading edges that are symmetrically located near the burner exit rim. The results at t = 4.255 indicate that the flashback originates from these two regions, consistent with the boundary-layer flashback theory. Subsequently, the flame propagates inside the injector, preserving the characteristic structure defined by two flame tongues located upstream of the

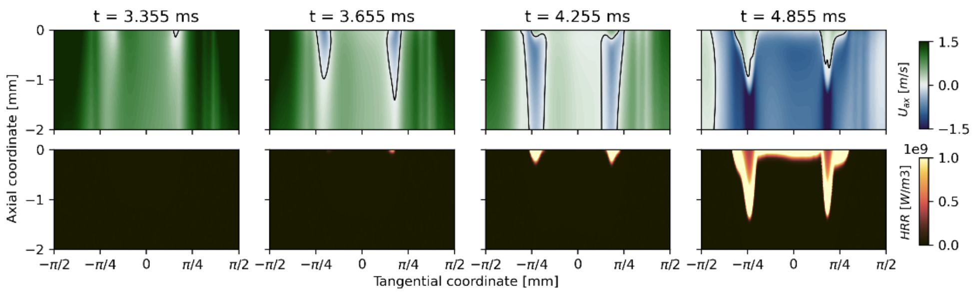

Figure 3: Axial velocity and HRR on an unrolled iso-radial plane close to the external injector wall.

burner exit. This configuration is maintained throughout the transient, as highlighted at t=6.355 ms.

The time evolution of axial velocity and HRR is examined in **Figure 3** on a radial isosurface located 100 µm from the external wall of the injector and unrolled onto a plane as a function of the tangential coordinate (0° corresponds to the plane intersecting the spark location). As a result of the aerodynamic blockage induced by the flame penetration of the annular jet, a velocity reduction is observed, mainly in the two flame leading edges positions (±40°). Subsequently, these regions promote localized boundary layer separation, leading to the formation of two small recirculation zones near the burner exit edge (t=3.655 ms) where the flashback starts. The structures of a confined boundary layer flashback are finally retrieved at t=4.855 ms.

Conclusion

High-fidelity LES simulation of the hydrogen ignition process reveals that the flame propagation in preferential directions promotes the formation of localized separation regions within the injector where flashback occurs.

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