FLAME QUENCHING MECHANISMS AND NOISE GENERATION IN PREMIXED METHANE AND HYDROGEN FLAMES

N. Misceo*, F. G. Schiavone*, S. M. Camporeale*, M. Torresi*, D. Laera*
n.misceo1@phd.poliba.it
*DMMM, Polytechnic University of Bari, Via Orabona 4, Bari, 70125, Italy

Abstract
This work investigates the physical mechanisms underlying flame quenching and pressure wave generation in Flame-Wall and Flame-Flame Interactions. One-dimensional (1D) simulations are carried out using a canonical Head-On Quenching (HOQ) configuration. A parametric study is performed to explore the effects of fuel (H_2 and CH_4), equivalence ratio, wall thermal condition (adiabatic and isothermal), wall surface chemistry (inert and Infinitely Fast Heterogeneous Catalysis (IFHC) [1] model), and chemical modeling (global and analytically reduced chemistries (ARC) [2]). Different physical mechanisms are found to drive flame quenching and consequently noise generation, i.e., reactant loss, wall heat loss, and loss of flame thermal power due to Lewis number effects, depending on fuel, unburnt mixture composition and wall thermal properties.

Introduction

Thermoacoustic instabilities (TAI) are a well-known issue in combustion systems, which can lead to severe mechanical failures. They arise from the interaction between pressure waves generated by the flame and the acoustics of the surrounding confinement [3]. Given hydrogen distinct physicochemical properties, including enhanced reactivity, preferential diffusion and inherent thermodiffusive instabilities [4], a more in-depth investigation into the sound generation mechanisms in H_2 flames is required. In the literature, flame-generated noise has been linked to unsteady heat release rate (HRR) processes, involving creation or destruction of flame fronts: three primary mechanisms have been identified: Flame-Wall Interaction (FWI), Flame-Flame Interaction (FFI), and Flame-Vortex Interaction (FVI) [5]. In this work, noise generation due to the first two flame annihilation mechanisms is investigated for H_2 flames.

Numerical Methodology and Configuration

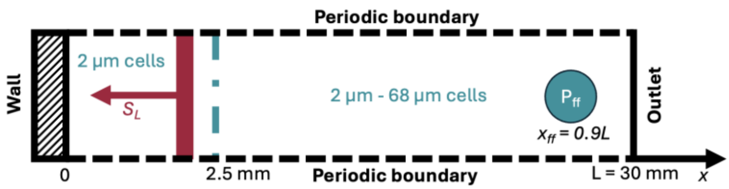

Figure 1. Schematic representation of the computational domain.

To investigate noise generation resulting from flame annihilation, an extensive set of HOQ numerical simulations of 1D flames are performed in the massively-parallel compressible Navier-Stokes solver AVBP (https://cerfacs.fr/avbp7x). Figure 1 shows the computational domain and its main features. The grid size is set to 2 µm in the near-wall region of length 2.5 mm, and then smoothly stretched towards the outlet, considered as non-reflecting and modeled with the NSCBC formalism. Pressure signals are extracted from a far-field probe (P_{ff}) located at 0.9L from the wall. The 1D flame is initialized using Cantera with unburnt mixture at a pressure of 1 atm and a temperature of 300 K. Table 1 summarizes all simulated configurations. The chemical mechanisms employed include the global 2S_CH4_BFER and the ARC CH4_15_256_9_AP [2] for CH_4 flames, and the ARC H2_9_42_0_SD and the global 1S_REV_H2AIR_FGS [6] mechanisms for H_2 flames. The 'HEAT_LOSS' wall boundary condition is set with a thermal resistance value (R_w = 1.0e-4 m^{2}K/W), effectively making the wall isothermal, as confirmed by additional verification. Wall chemistry is applied in a single case using the IFHC model [1].

Table 1. One-dimensional flame simulations summary and features.

Fuel	Wall-B.C.	T_w [K]	Mech.	ϕ
CH_4	ADIAB	-	2S_CH4_BFER	0.6-1.0-1.5
CH_4	HEAT_LOSS	300	2S_CH4_BFER	0.6-1.0-1.5
CH_4	HEAT_LOSS	600	2S_CH4_BFER	1.0
CH_4	ADIAB	-	CH4_15_256_9_AP	1.0
CH_4	HEAT_LOSS	300	CH4_15_256_9_AP	1.0
H_2	ADIAB	-	H2_9_42_0_SD	0.45-0.54-0.6-1.0-1.55.0
H_2	HEAT_LOSS	300	H2_9_42_0_SD	0.45-0.54-0.6-1.0-1.55.0
H_2	HEAT_LOSS	600	H2_9_42_0_SD	0.45
H_2	HEAT_LOSS	300	H2_9_42_0_SD	1.0 - IFHC wall-chemistry
H_2	ADIAB	-	1S_REV_H2AIR_FGS	0.45
H_2	HEAT_LOSS	300	1S_REV_H2AIR_FGS	0.45

Results and discussion

Figure 2 presents the time evolution of the domain-averaged heat release rate variation (solid line) and the acoustic pressure (dashed line) recorded at the far-field probe for CH_4 (left) and H_2 (right) flames featuring the same laminar flame speed (S_L). For each fuel, simulations with adiabatic (blue curves) and heat-loss (yellow curves) wall boundary conditions are shown.

In methane flames, HRR variation differs markedly between adiabatic and heat-loss cases, both in waveform and fluctuation intensity – sharper in the former, smoother in the latter – due to distinct quenching mechanisms: reactant depletion in the adiabatic case and thermal dissipation in the heat-loss case, occurring before wall contact [7]. The adiabatic case shows a positive HRR peak, indicating superheating of the unburnt mixture and increased reactivity before extinction, whereas in the heat-loss case, thermal exchange governs a slower HRR decay, with a time derivative at least one order of magnitude lower.

Differently, in lean hydrogen flame (with $Le < 1$), HRR evolution for adiabatic and heat-loss cases are nearly superimposable, indicating a similar dominant extinction mechanism governed by thermo-diffusive effects regardless of the wall thermal conditions: the unequal diffusion rates of temperature and the deficient reactant (fuel) cause fuel to keep diffusing toward the flame front as it nears the wall. This leads to combined depletion by reaction and diffusion, resulting in gradual extinction before wall contact. This third mechanism dominates the others, rendering quenching of lean H_2 flames independent of wall heat losses.

For same laminar flame speed (S_L), CH_4 flames exhibit higher thermal power and generate stronger SPL upon quenching. The peak sound pressure level (SPL) generated by flame quenching is compared with the predictive model in Eq.1, proposed by Talei et al. [7].

$$|p'| = \rho_u c_b \left(1 - \frac{T_u}{T_b}\right) S_L. \tag{1}$$

The Talei model accurately predicts the peak SPL in CH_4 cases with adiabatic walls (thus also for FFI), but it performs less accurately for H_2 flames and in heat-loss configurations.

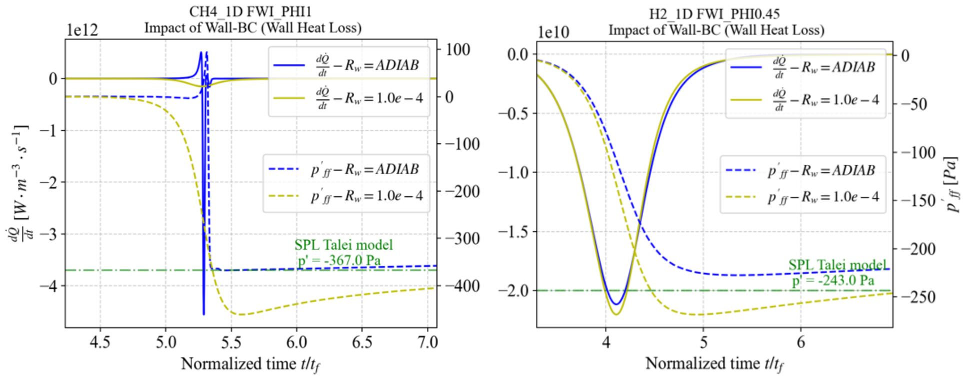

Figure 2. HRR variation (solid lines) and pressure wave generated (dashed lines) for CH_4 (left) and H_2 (right) flames employing ARC chemistry, with same laminar flame speed (S_L). Adiabatic (blue curves) and heat-loss (yellow curves) wall boundary conditions are presented for each fuel.

Further studies are planned to better understand the quenching dynamics of lean H_2 flames. Future work also intends to improve models for predicting SPL generated in both FFI and FWI, accounting for wall boundary conditions. Later, hydrogen flame simulations will be extended to two-dimensional domains to isolate the impact of thermo-diffusive instabilities on the noise spectrum generated before (FFI) and during (FFI+FWI) flame-wall quenching.

Acknowledgment
The authors would like to acknowledge CERFACS for the grant of the AVBP code and HPC resources from CRESCO/ENEAGRID. This work has been supported under the National Recovery and Resilience Plan (NRRP), funded by the European Union - NextGenerationEU, Project title “Network 4 Energy Sustainable Transition – NEST”, Project code PE0000021, CUP: D93C22000900001

References
[1] De Nardi, L., Douasbin, Q., Vermorel, O., Poinsot, T., “Infinitely fast heterogeneous catalysis model for premixed hydrogen flame-wall interaction”. *Combustion and Flame*, 261, 113328, (2024).
[2] Pestre, A., PhD Thesis (2023).
[3] Schuller, T., Poinsot, T., & Candel, S., “Dynamics and control of premixed combustion systems based on flame transfer and describing functions”. *Journal of Fluid Mechanics*, 894, P1, (2020).
[4] Tingas, E., *Hydrogen for Future Thermal Engines*, Springer Nature; 2023, First Ed.
[5] Candel, S., Durox, D., Schuller, T., “Flame interactions as a source of noise and combustion instabilities”. *In 10th AIAA/CEAS aeroacoustics conference*, p. 2928, (2004).
[6] Schiavone, F. G., Detomaso, N., Torresi, M., Laera, D., “An Arrhenius-based one-step reaction mechanism for hydrogen-air flames simulations in an extended range of operating conditions”. *International Journal of Hydrogen Energy*, 57, 1229-1243, (2024).
[7] Talei, M., Brear, M. J., Hawkes, E. R., “Sound generation by laminar premixed flame annihilation”. *Journal of Fluid Mechanics*, 679, 194-218, (2011).