Flame Control by Low-Temperature Hydrogen Injection in a Trapped Vortex Combustor

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Introduction

- The aviation industry is shifting toward sustainable propulsion technologies, with hydrogen gaining attention as a promising fuel due to its high specific energy and zero carbon emissions.
- The TRIATHLON Project aims at developing a Trapped Vortex Combustor (TVC) in a Rich-Quench-Lean (RQL) configuration: a promising design for a hydrogen-fuelled aeronautical combustor.
- This research centres on the behaviour of rich premixed hydrogen flames at cryogenic temperatures (~150 K), which have been shown to sustain combustion even at such temperatures [1], leveraging hydrogen thermal sink properties in the rich premixed section of the RQL, investigating stability and potential for NOx suppression within the combustor cavity.
- Future research will explore the use of liquid water or steam injection, utilizing the byproducts of a Proton Exchange Membrane Fuel Cell (PEMFC).

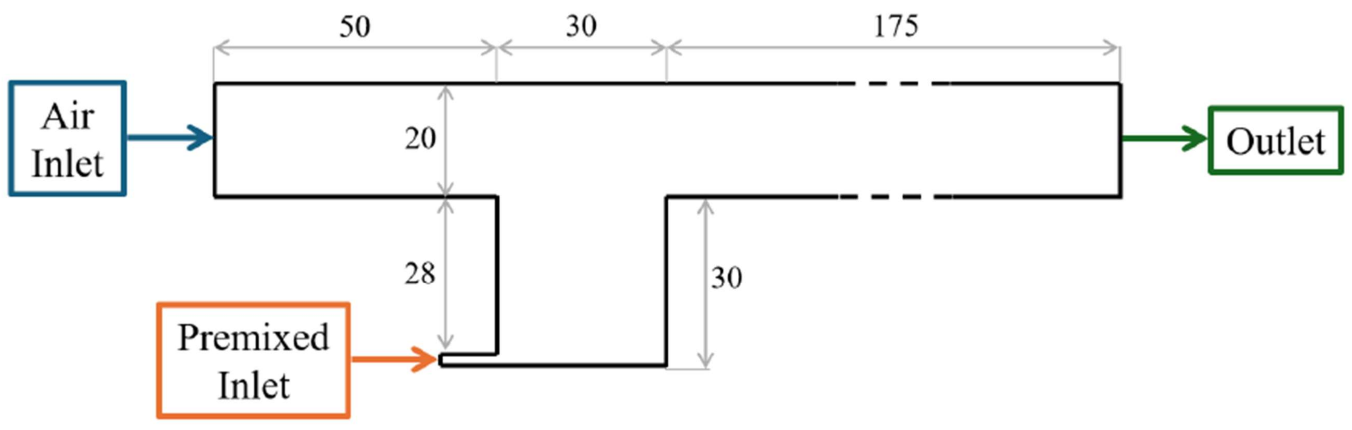

Fig. 1: Section of the test rig employed in the experiments found in [2]. Dimensions are given in mm. The out-of-the plane thickness is 50 mm.

Methodology

- The combustor geometry follows the atmospheric TVC test rig from Verma et al. [2].
- Four simulations are conducted to attain a parametric study:

V: Validation case using a hydrogen/methane blend. Furthermore, two turbulent combustion models are compared: the Dynamically Thickened Flame Model (DTF) and the Filtered Density Function – Eulerian Stochastic Field (FDF-ESF).
S1: 100% hydrogen baseline case.
S2: Impact of lower injection temperature.
S3: Effect of reducing equivalence ratio at low injection temperature.

Symbol (units)	V	S1	S2	S3
ϕ_{rich} (-)	1.5	5	5	3
$H_{2\%,\mathrm{vol}}$ (-)	0.5	1	1	1
P_{th} (kW)	13	10	10	10
T_{cavity} (K)	300	300	150	150
s_{L}^0 (m/s)	0.216	1.328	0.368	0.942
δ_{L}^0 (mm)	0.79	0.60	0.62	0.31
τ_{L}^0 (ms)	3.65	0.45	1.68	0.33
T_{ad} (K)	1989	1406	1281	1648
σ (-)	6.85	4.36	7.95	9.91
Y_{NO} (-)	6.19e-5	2.70e-8	1.30e-8	1.41e-7

Tab. 1: Simulation cases with results from 1D free flames: s_L^0 symbolizes the unstretched laminar flame speed, δ_L^0 the flame thickness, τ_L^0 the flame timescale, T_{ad} the adiabatic flame temperature and σ defines the ratio between density of reactants and products.

V - Validation:

- Three flame regions are identified:
  1. Premixed Flame in the Cavity: No wrinkling.
  2. Premixed Flame in the Main Flow: Wrinkling due to vortex shedding, increased mixing and reactivity.
  3. Diffusion Flame in the Cavity: The DTF model (centre) better captures HRR distribution compared to the FDF-ESF (right).
- The FDF-ESF model is effective in the premixed flame region and is used for further investigations, as it is deemed necessary for accurate turbulence-chemistry modelling.

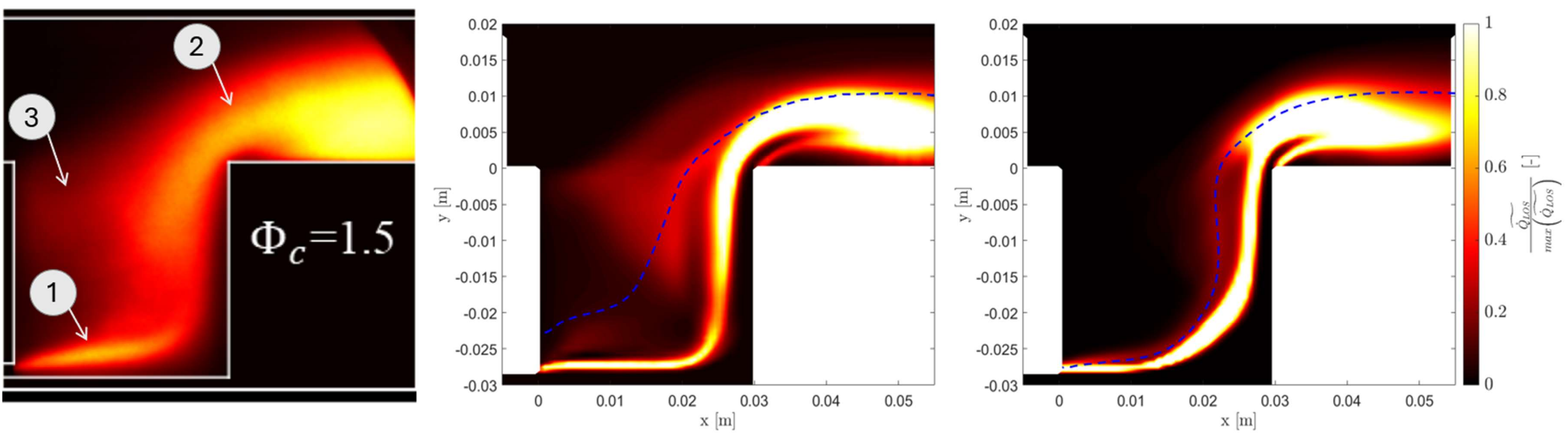

Fig. 2: Contours of (left) experimental averaged OH* chemiluminescence [2], and normalized mean LOS HRR from LES employing (centre) DTF and (right) ESF approaches. The dashed blue line indicates the LOS averaged stoichiometric mixture level.

S1 - Baseline Design with Hydrogen Injection:

- The momentum flux ratio used in the validation (J = 10) resulted in excessive oscillations, triggering a shift from deep to shallow cavity behavior [3].
- Lowering the momentum flux from J = 10 to J = 1 stabilized vortex shedding in the shear layer, minimizing the interaction between the main flow and the cavity flow.
- The spurious diffusion flame, located at the boundary between the cavity and main flow, is not the focus of this study and will not be further investigated; however, this stabilization was necessary to analyze the cavity flame independently from the main flow.

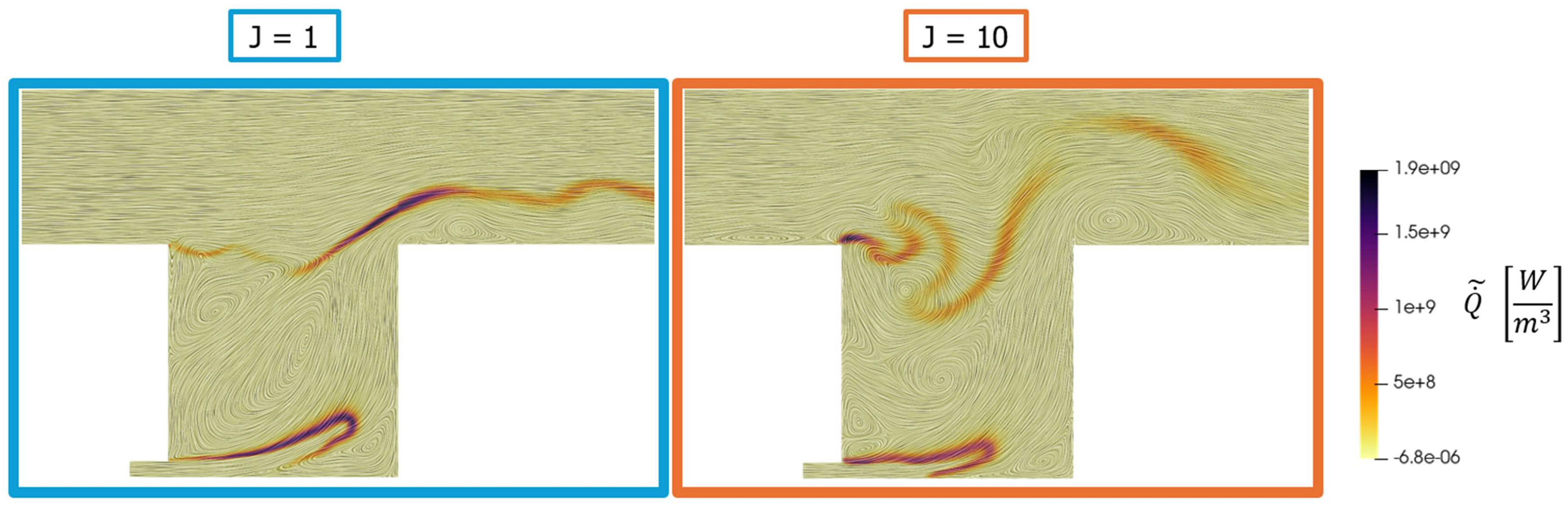

Fig. 3: Instantaneous Heat Release Rate contours on streamlines of velocity at a representative timestep. Left: J = 1. Right: J = 10.

S2 - Effect of Low-Temperature Injection (150 K):

- Decreasing the hydrogen/air mixture temperature to 150 K increased flame wrinkling and heat release fluctuations in the premixed flame at the cavity's bottom.
- This instability is associated with large-scale wrinkling due to baroclinic vorticity and Darrieus-Landau instability.
- The wrinkling dynamics follow a cyclical process, with bubbles forming and detaching from the flame front.

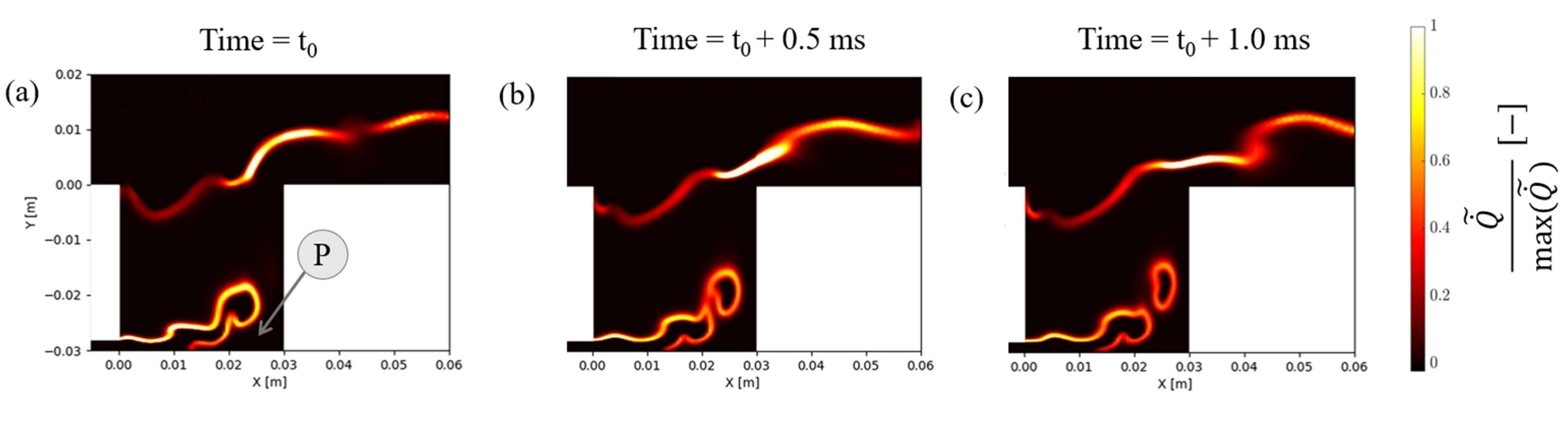

Fig. 4: Midplane contours of heat release rate from LES-ESF model for case S2 for different instant of times starting from time t_0. The label P indicates a probe used in the comparative analysis between S1, S2 and S3

S3 - Effect of Decreasing Equivalence Ratio:

- Reducing the equivalence ratio from 5 to 3 at the same low temperature (150 K) led to enhanced flame front stability: Darrieus-Landau instability and baroclinic vorticity production were stabilized due to increased flame speed and reduced flame thickness.
- Temperature fluctuations were smaller in the lower equivalence ratio case compared to the higher one (S1, ϕ = 5), at the cost of a higher average temperature.

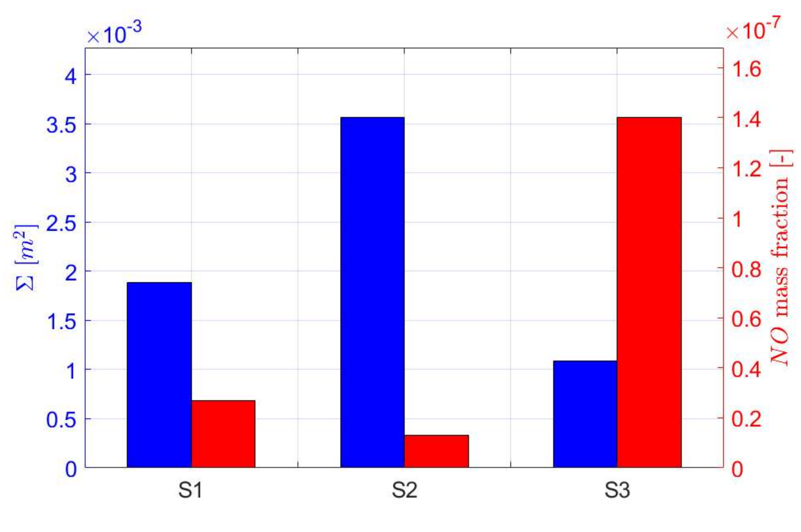

Fig. 5: (Left axis, blue bar) Time Averaged Flame Surface Σ computed at an isosurface of T = 0.7 T_{ad} for simulations S1, S2 and S3. (Right axis, red bar) NO mass fractions computed at the products of a 1D freely propagating flame simulation for cases S1, S2 and S3.

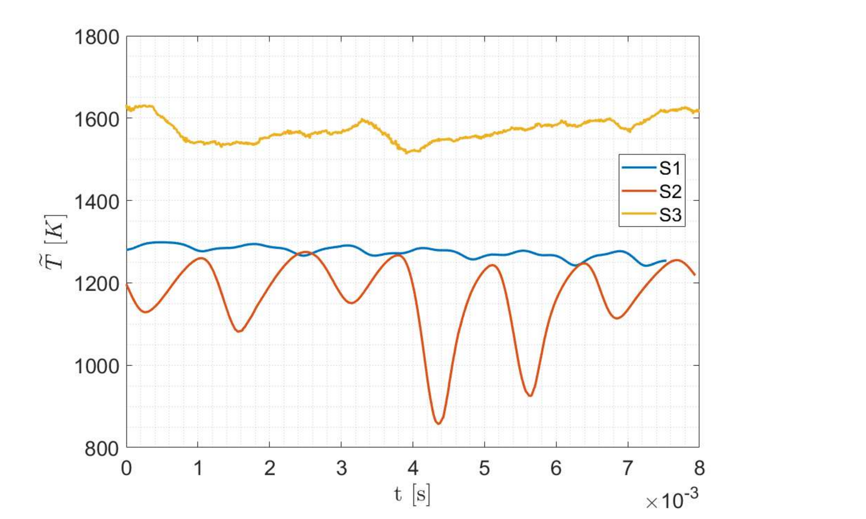

Fig. 6: Instantaneous Temperature signal from a probe placed in (x = 0.025 m, y = −0.028 m), marked by label P in Figure 4. Signals are captured for cases S1, S2 and S3.

Conclusions

- Results indicated that lowering the injection temperature from 300 K to 150 K at a very rich equivalence ratio led to strong flame oscillations, characterized by enhanced flame wrinkling. These instabilities were primarily driven by the interplay of Darrieus-Landau instabilities and baroclinic vorticity generation.
- When the equivalence ratio was decreased from 5 to 3 at the same low temperature injection of 150 K, flame oscillations were suppressed, bringing the flame dynamics back to stability. However, this stabilization resulted in an increase in the adiabatic flame temperature, although temperatures remained below 1700 K. The increase in NO was counterbalanced by a strong reduction in flame surface area, which was halved compared to the baseline case at 300 K, indicating that despite the temperature increase, NO formation remained relatively controlled.

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