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Thermoacoustic Instabilities of Hydrogen-enriched Premixed Flames in a Swirl Combustor

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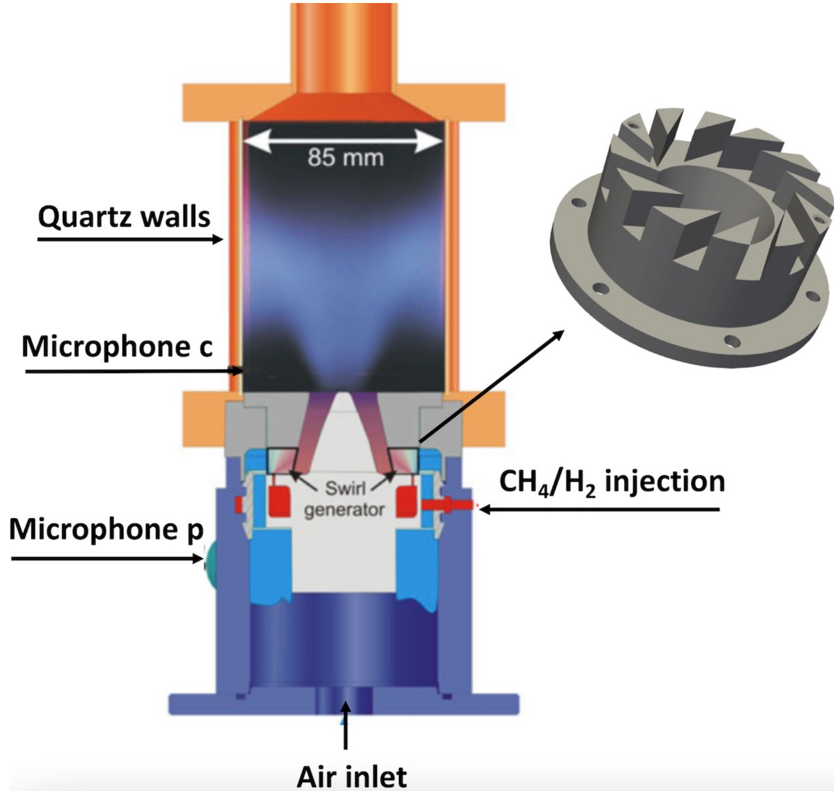
LES of Hydrogen Enriched Flames

Backgrounds

- H_2 combustion exhibits higher laminar flame speed, higher flame temperature and lower lean flammability limit.
- Lean premixed combustion often exhibits thermoacoustic and hydrodynamic instability.

Experimental work

- Hydrogen enriched flames based on PRECCINSTA burner studied experimentally at DLR (Chterev, 2019).
- Premixed, swirl stabilised flames
- Optical access to chamber: quartz glass side walls
- Pressure measured by two microphones in chamber (c) and plenum (p).



The experimental configuration of the PRECCINSTA burner with a view of the swirler structure on the right.

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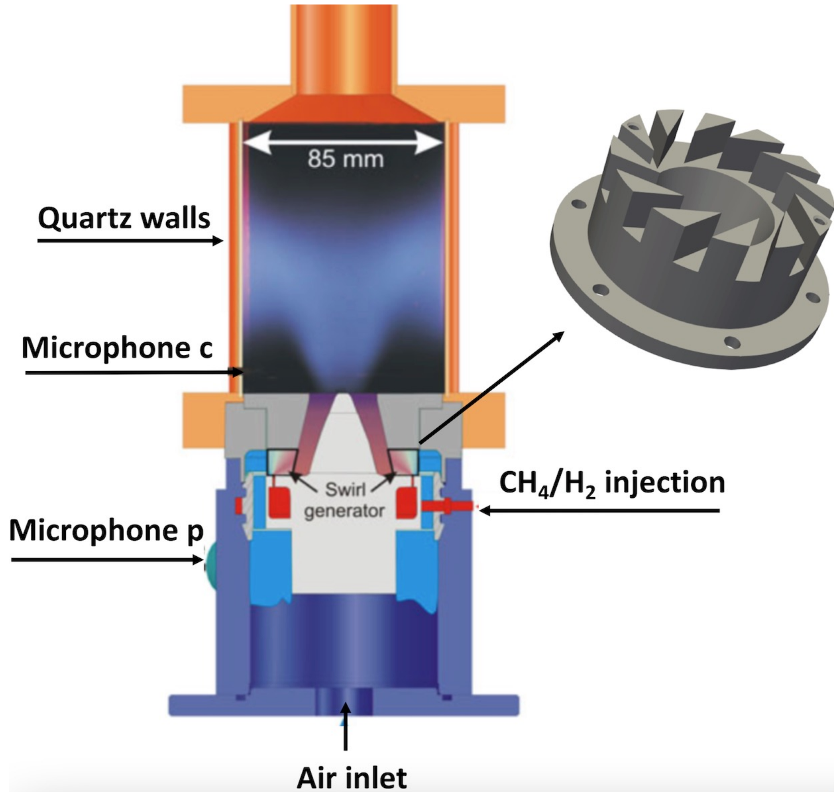

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BOFFIN-LESc

In house compressible LES code: BOFFIN-LESc (Fredrich,2020)

Models and methods

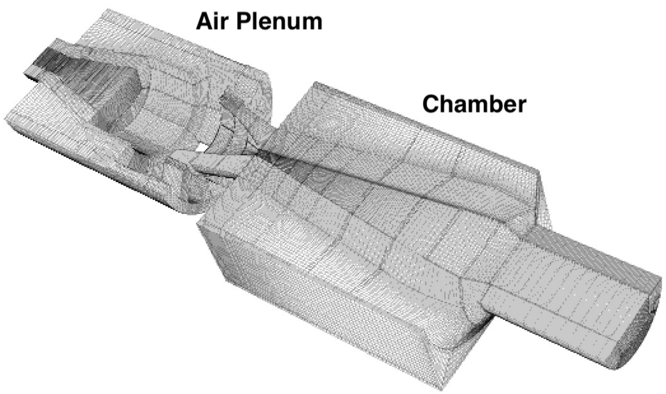
- Smagorinsky model with the dynamic procedure of Piomelli and Liu (Piomelli, 1995)
- Transported probability density function (pdf) approach— chemical source term closed
- Eulerian stochastic field method — solve pdf equation

Numerical setups

- Non-reflective outflow boundary conditions at chamber outlet (Yoo, 2005)
- Non-adiabatic combustion chamber walls
- Multiblock structured mesh ~2.7 million cells, including air plenum, swirler and combustion chamber — to resolve non-perfect mixing
- Mesh independent study done with the same geometry in previous work (Fredrich, 2020)

Chemical kinetics

- 15-step reduced mechanism based on GRI-Mech 3.0 (Lu, 2008)

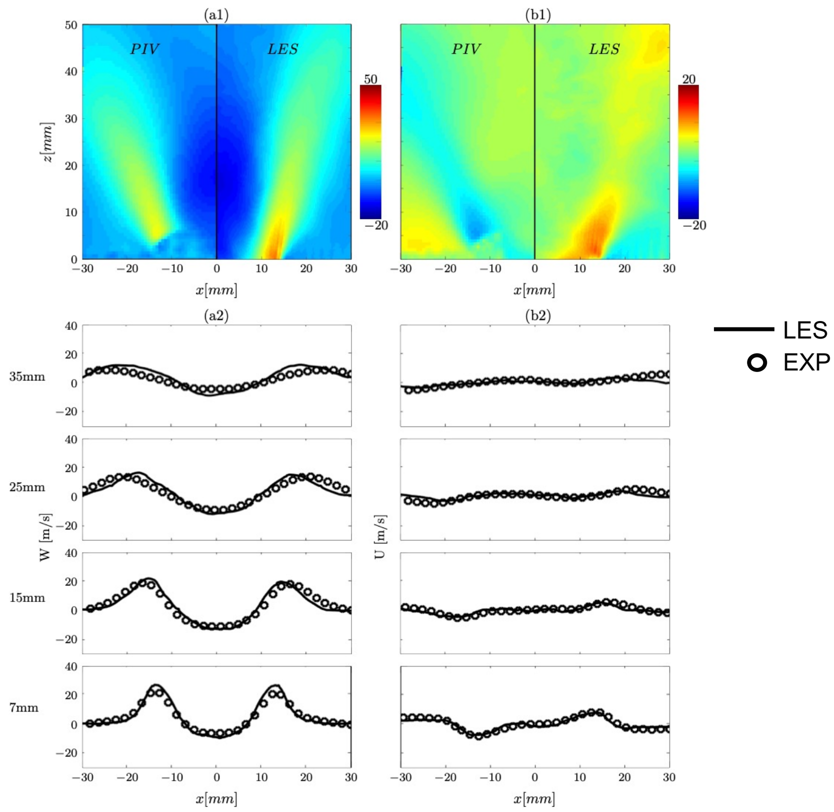


A view of the computational mesh.

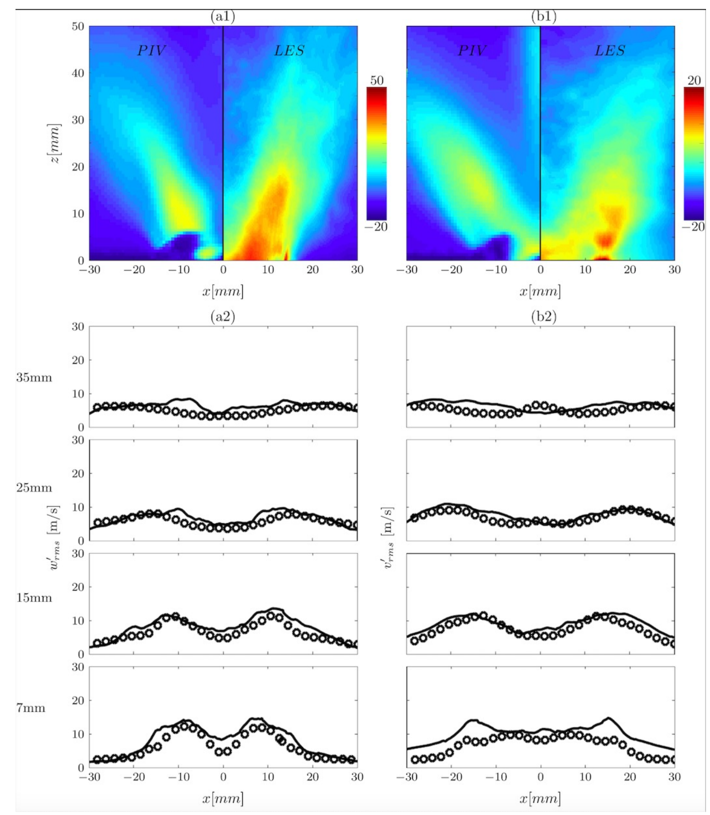
Selected operating conditions

- Operated at atmospheric pressure
- Thermal power: 23kw; equivalence ratio: 0.85
- Three hydrogen fuel fractions by volume: C1 - 0%, C2 - 20%, C3 - 40%

Iso-thermal flow field



Mean velocity fields and profiles at 4 downstream positions:
(a) axial mean velocity (b) radial mean velocity.

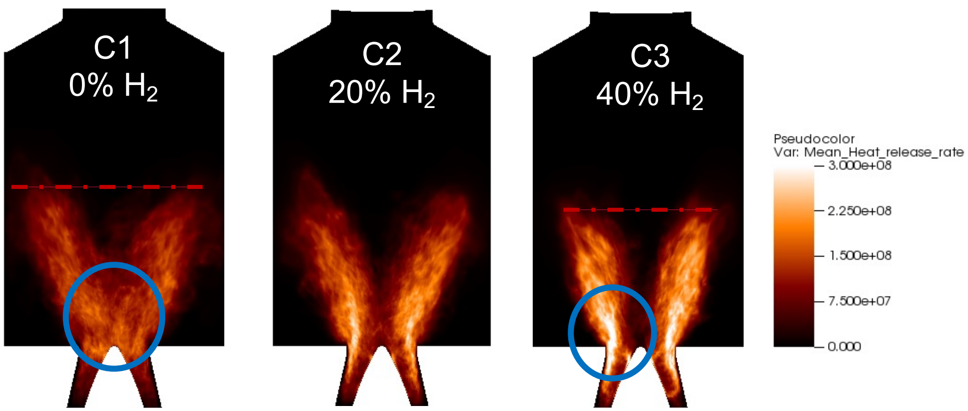


RMS velocity fields and profiles at 4 downstream positions:
(a) axial RMS velocity (b) radial RMS velocity.

- LES reproduce the flow field of the non-reacting case with good agreement with measured conditions.

Flame topology

Time averaged heat release rate (HRR)



Mean Heat release rate in 3 cases investigated (sliced)

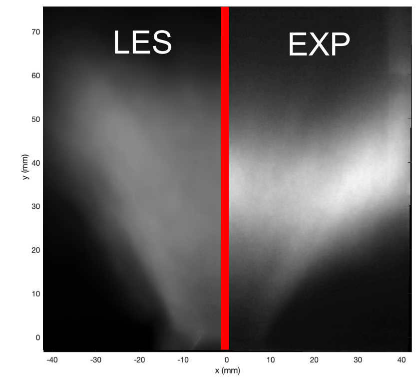
Hydrogen addition results in

- Higher heat release rate on average
- Shorter flame, closer to the combustor inlet
- More flash back, less lift off

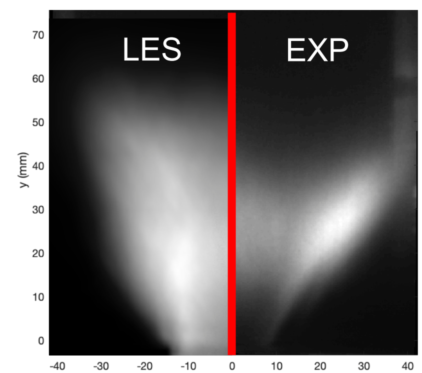
Comparison of flame shape in LES and EXP

- Both V-shape flame (inner share layer stablised)
- LES predicts longer flame and smaller flame angle

C1 0% H_2



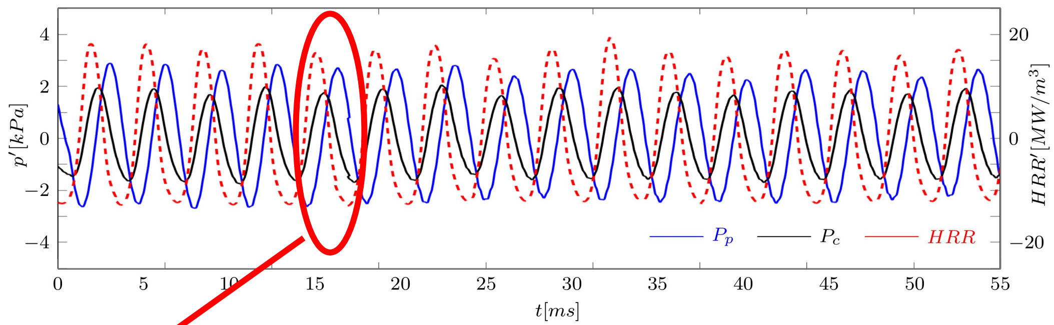
C3 40% H_2



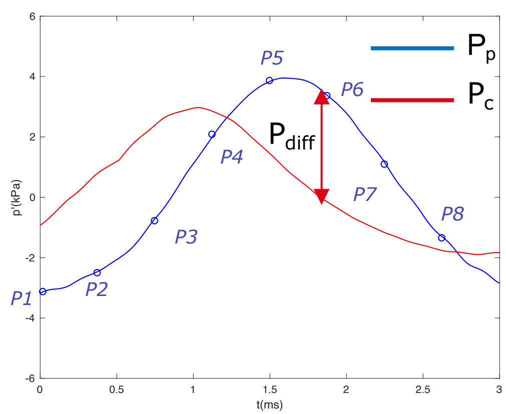
Mean heat release rate in LES (line of ght integration) and OH chemiluminescence i P)
Only for qualitative comparison for flame topolog

Acoustic fluctuations

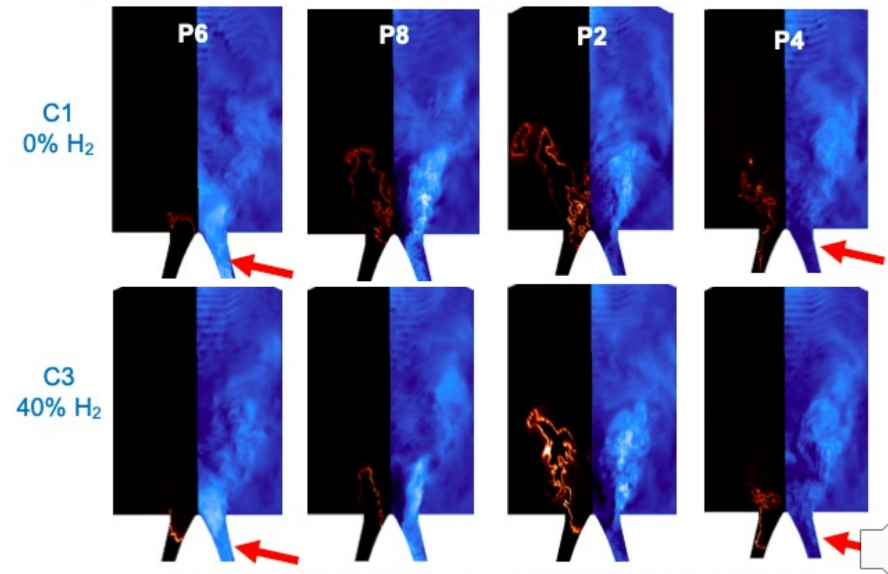
Self-sustained limit cycle oscillations



Pressure signals in air plenum (Pp) and combustion chamber (Pc) together with integrated heat release rate for C3

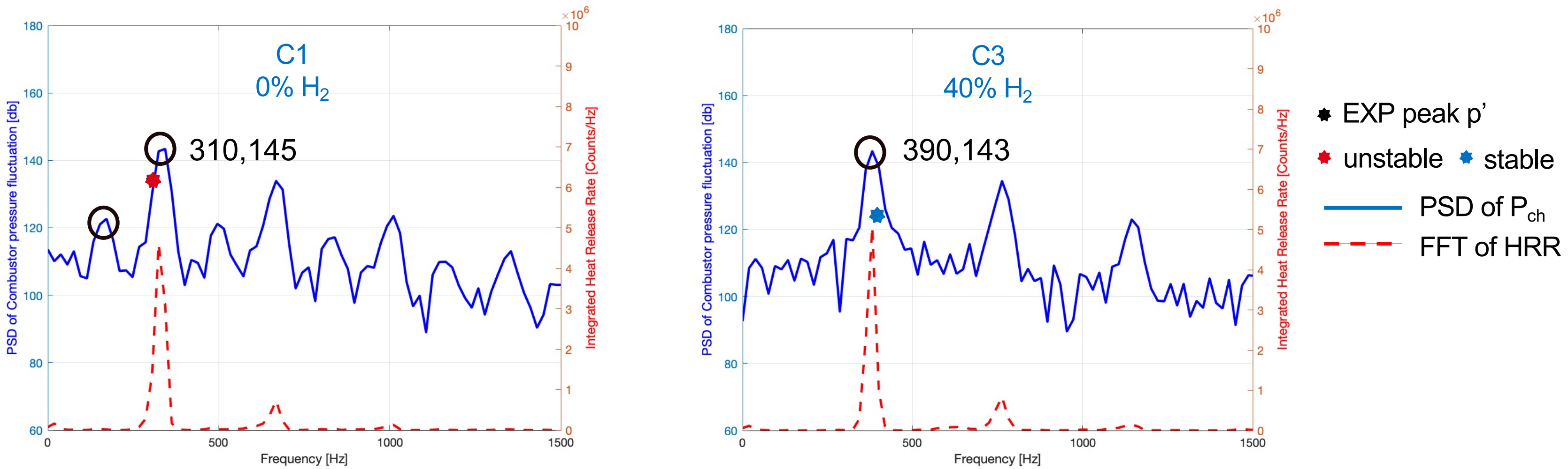


Temporal variation of P-pl and P-ch in one limit cycle.



Heat release rate (left) and axial velocity (right) in phase

PSD of P’, FFT of HRR compared to EXP



- EXP p’ with estimation of damping wall effect ~13dB (Lourier,2017)
- First peak frequencies matches – Helmholtz f, thermoacoustic oscillations
- Over predicted amplitude: both in C1 (8dB) and C3 (20dB)
- Coupled peak f of p’ and HRR in C1 and C3

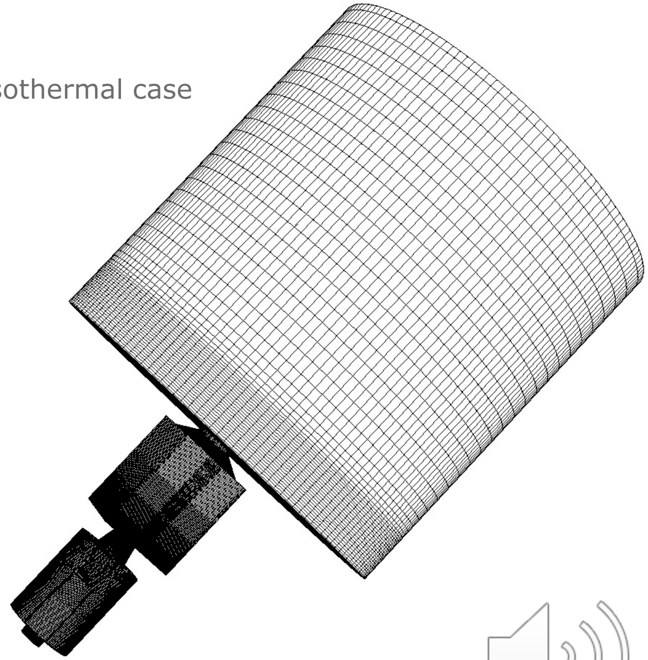
Conclusions and future work

Conclusions

- Self-excited limit cycle oscillations can be successfully reproduced in this compressible LES method
- Effect of hydrogen addition on the flame topology is basically captured
- Strong pressure oscillations are found in all the cases investigated

Why so strong fluctuations?

- Relative to the coupling of flame and pressure fluctuations: not observed in isothermal case
- Varies with operation conditions c
- The effect of damping walls on the acoustic remains unknown



Next Step Work

- Extend the computational domain
- Potential modeling of the vibrating walls
- Different operating conditions study

References

I. Chterev and I. Boxx, Flame and Flow Topology, and Combustion Instability Limits of a Lean Premixed Hydrogen Enriched Flame, 29. Deutscher Flammentag.

Fredrich, D., Jones, W.P. & Marquis, A.J. Thermo-acoustic Instabilities in the PRECCINSTA Combustor Investigated Using a Compressible LES-pdf Approach. Flow Turbulence Combust (2020).

Lu, T., and Law, C. K., 2008. "A criterion based on computational singular perturbation for the identification of quasisteady state species: A reduced mechanism for methane oxidation with NO chemistry". Combustion and Flame,154(4), Sept., pp. 761–774.

U. Piomelli, J. Liu, Large-eddy simulation of rotating channel flows using a localized dynamic model, Phys. Fluids 7 (4) (1995) 839–848.

Lourier, J. M., Stöhr, M., Noll, B., Werner, S., & Fiolitakis, A. (2017). Scale Adaptive Simulation of a thermoacoustic instability in a partially premixed lean swirl combustor, 1–15.

Acknowledgement

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