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The stochastic fields method applied to a partially premixed flame with wall heat transfer

D. Fredrich, W.P. Jones and A.J. Marquis

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The stochastic fields method applied to a partially premixed flame with wall heat transfer and thermo-acoustic coupling

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Motivation

Modern gas turbine combustion is characterised by:

i. Lean equivalence ratios
ii. Partial premixing
iii. Swirl-stabilised flames

Simulations potentially need to account for:

i. Fuel injection and mixing
ii. Finite-rate chemistry effects
iii. Turbulence-chemistry interactions (LES)
iv. Wall heat transfer effects
v. Thermo-acoustic coupling
vi. …

PRECCINSTA burner at DLR test rig (*Meier et al. 2007*)

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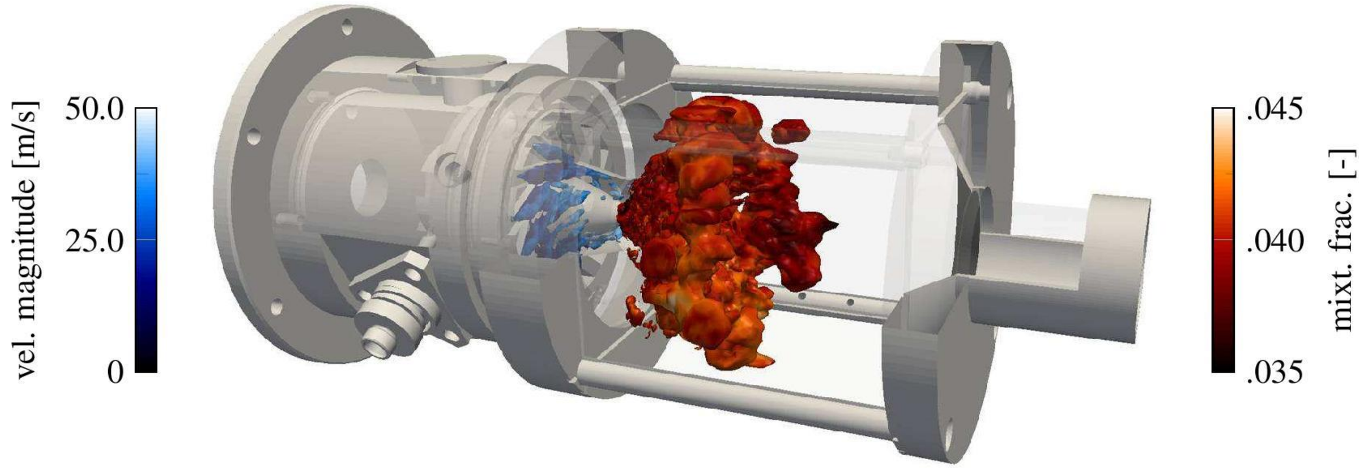
Numerical Approach



Application of **BOFFIN-LES** to PRECCINSTA case:

i. Fuel injection and mixing
ii. Finite-rate chemistry effects
iii. Turbulence-chemistry interactions (LES)
iv. Wall heat transfer effects
v. Thermo-acoustic coupling
vi. …

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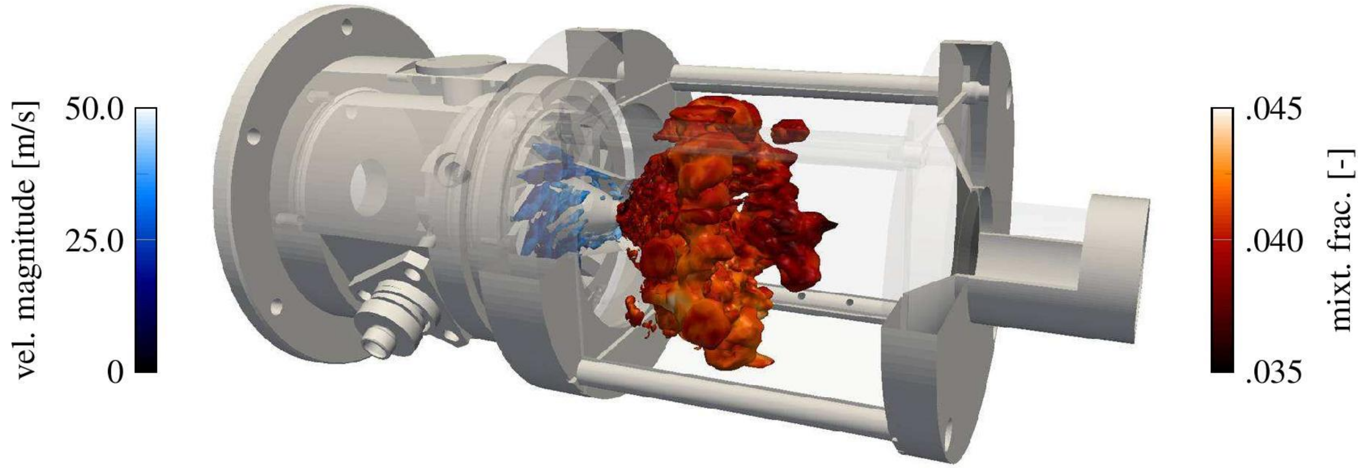
Numerical Approach



Application of **BOFFIN-LES** to PRECCINSTA case:

i. → Fine mesh resolution in mixing region
ii. Finite-rate chemistry effects
iii. Turbulence-chemistry interactions (LES)
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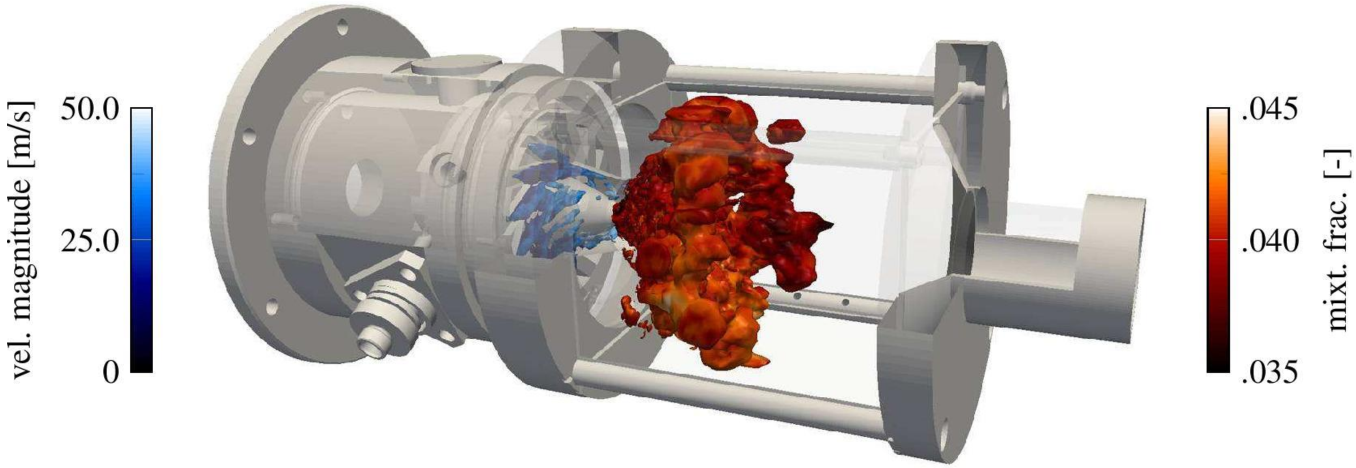
v. Thermo-acoustic coupling
vi. …

Numerical Approach



Application of **BOFFIN-LES** to PRECCINSTA case:

i. → Fine mesh resolution in mixing region
ii. → 15 step / 19 species CH_4 mechanism (*Sung et al. 2001*)
iii. Turbulence-chemistry interactions (LES)
iv. Wall heat transfer effects
v. Thermo-acoustic coupling
vi. …

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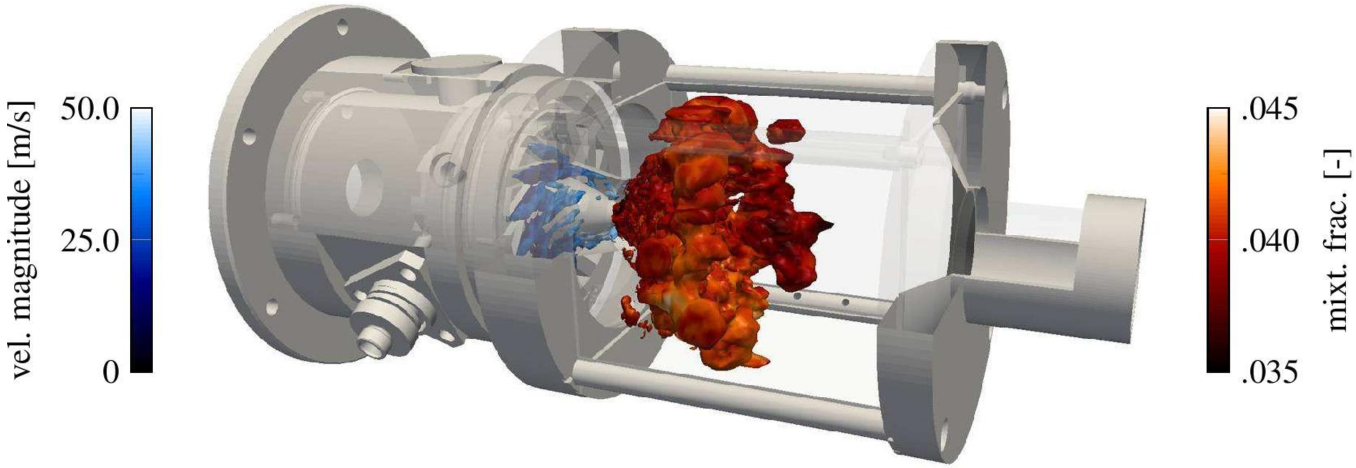
Numerical Approach



<u>Application of **BOFFIN-LES** to PRECCINSTA case:</u>

i. → Fine mesh resolution in mixing region
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iii. → Eulerian stochastic fields method (*Jones et al. 2007*)
iv. Wall heat transfer effects
v. Thermo-acoustic coupling
vi. …

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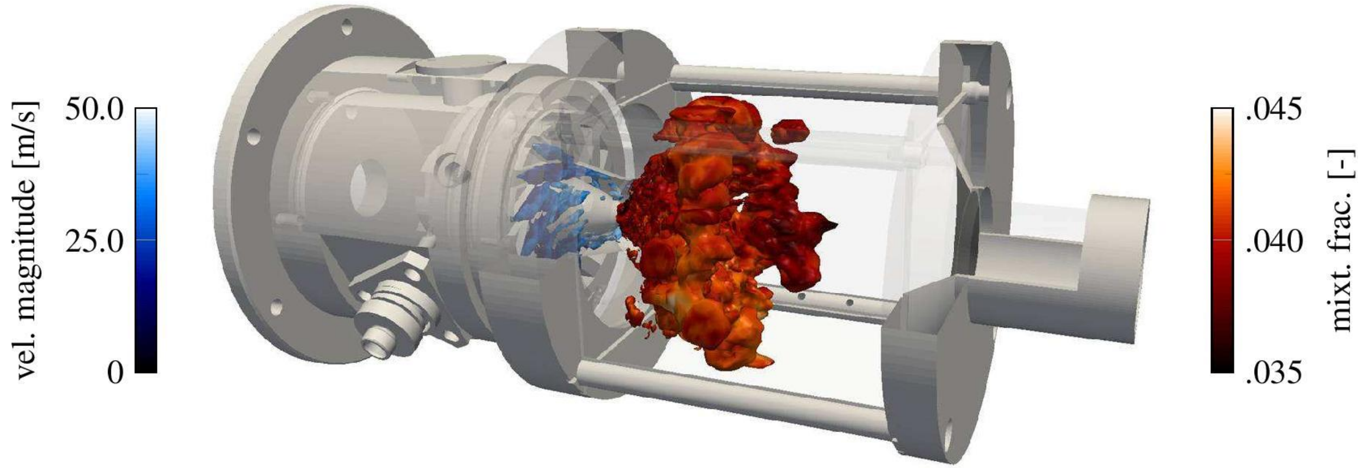
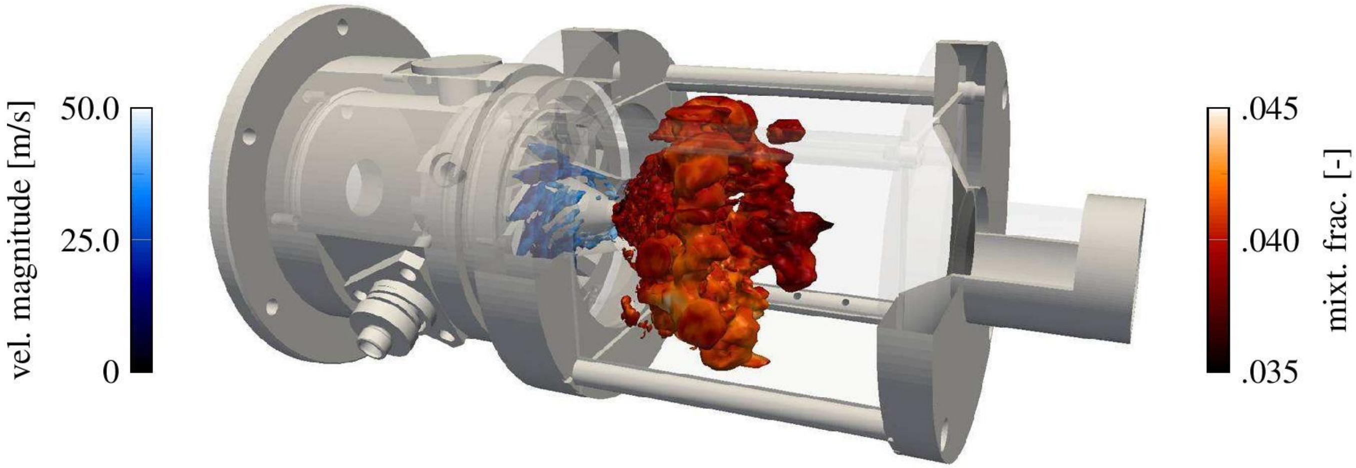
Numerical Approach



Application of **BOFFIN-LES** to PRECCINSTA case:

i. → Fine mesh resolution in mixing region
ii. → 15 step / 19 species CH_4 mechanism (*Sung et al. 2001*)
iii. → Eulerian stochastic fields method (*Jones et al. 2007*)
iv. → Isothermal wall temperatures
v. Thermo-acoustic coupling
vi. …

Numerical Approach



Application of **BOFFIN-LES** to PRECCINSTA case:

i. → Fine mesh resolution in mixing region
ii. → 15 step / 19 species CH_4 mechanism (*Sung et al. 2001*)
iii. → Eulerian stochastic fields method (*Jones et al. 2007*)
iv. → Isothermal wall temperatures
v. → Addition of compressibility effects
vi. …

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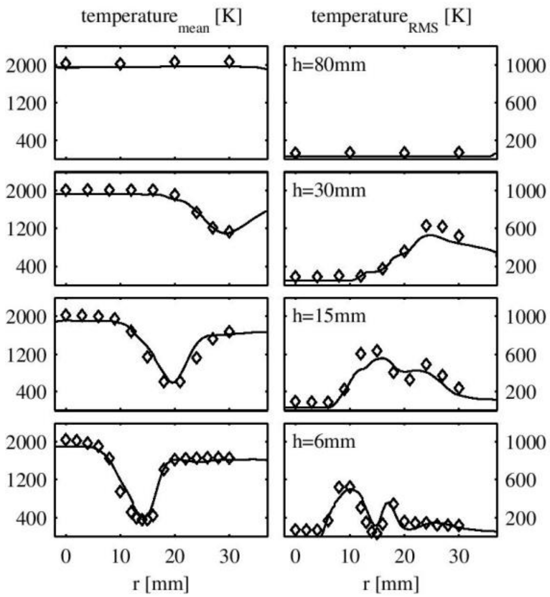
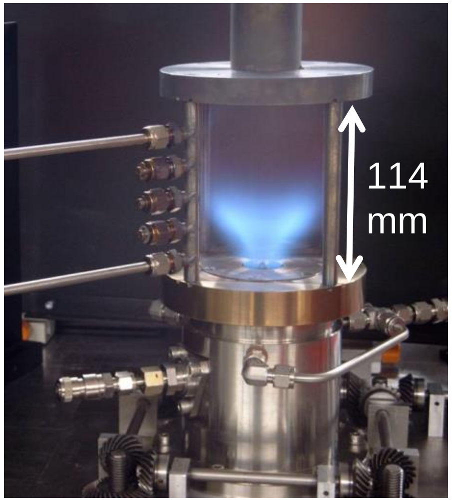
'Quiet' Flame: Test Case

PRECCINSTA burner:

- equivalence ratio = 0.83
- ambient inflow conditions
- "no" thermo-acoustics

‘Quiet’ Flame: Statistics





Symbols: Experiment
Lines: LES

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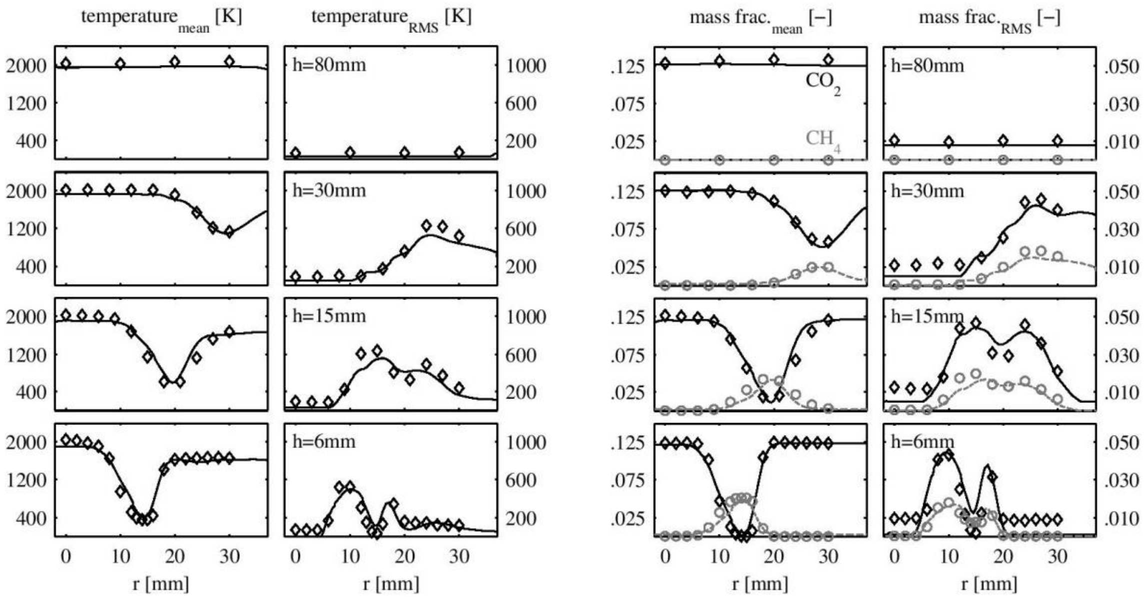
'Quiet' Flame: Statistics



Black: CO_2 mass fraction
Grey: CH_4 mass fraction

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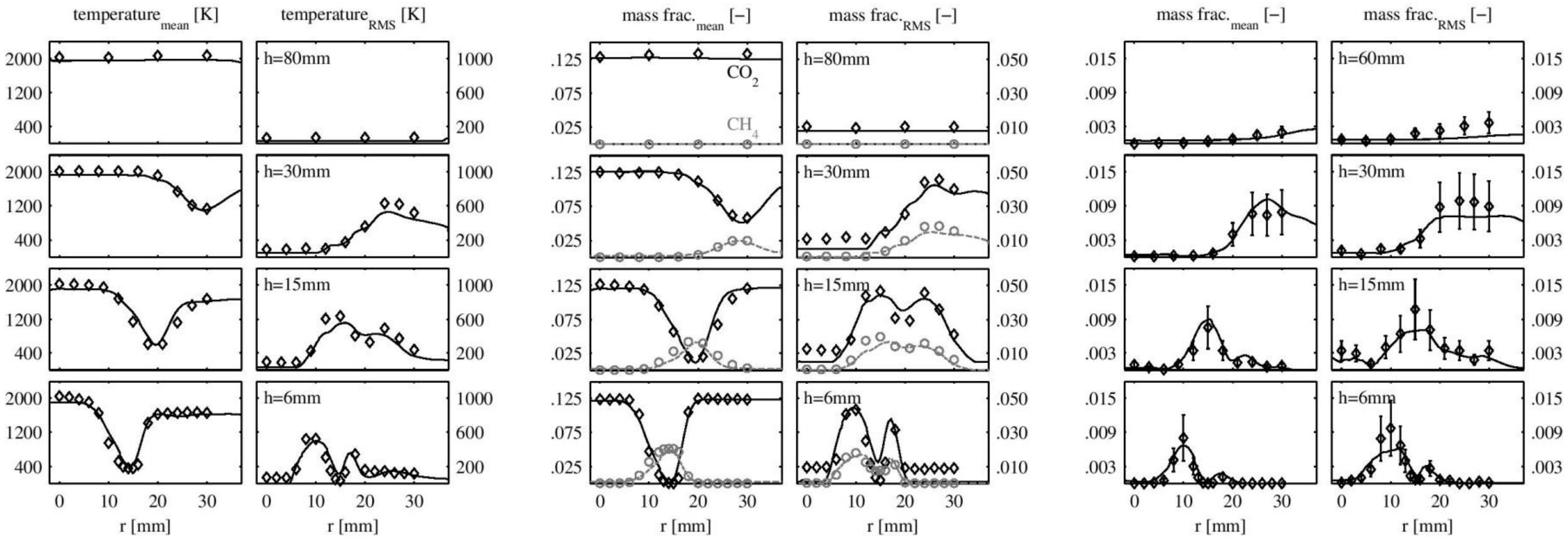
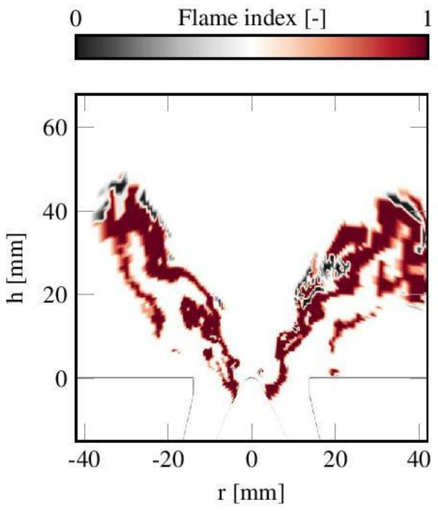
‘Quiet’ Flame: Statistics



CO measurement uncertainty of up to 50% (*Meier et al. 2007*)

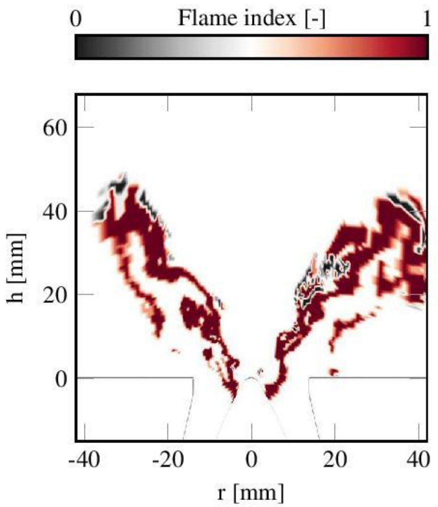
‘Quiet’ Flame: Topology

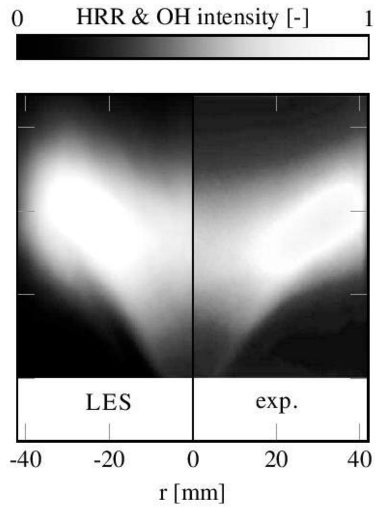
$$FI = 0.5 \cdot \left(\frac{\nabla \widetilde{Y}_{CH_4} \cdot \nabla \widetilde{Y}_{O_2}}{|\nabla \widetilde{Y}_{CH_4} \cdot \nabla \widetilde{Y}_{O_2}|} + 1 \right)$$



Small regions in the diffusion regime
→ partially premixed

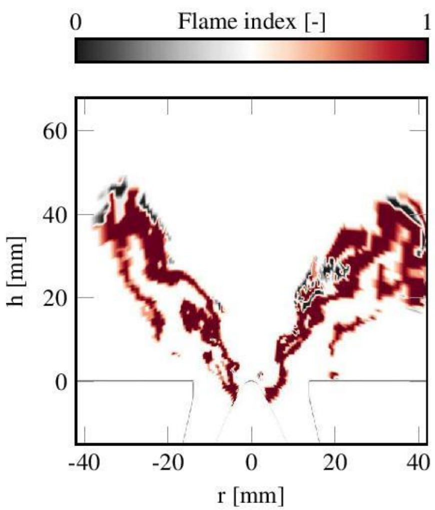
‘Quiet’ Flame: Topology

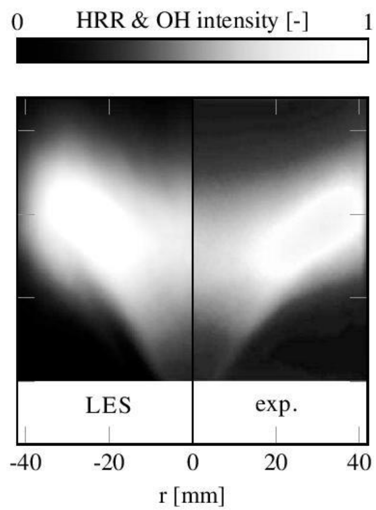


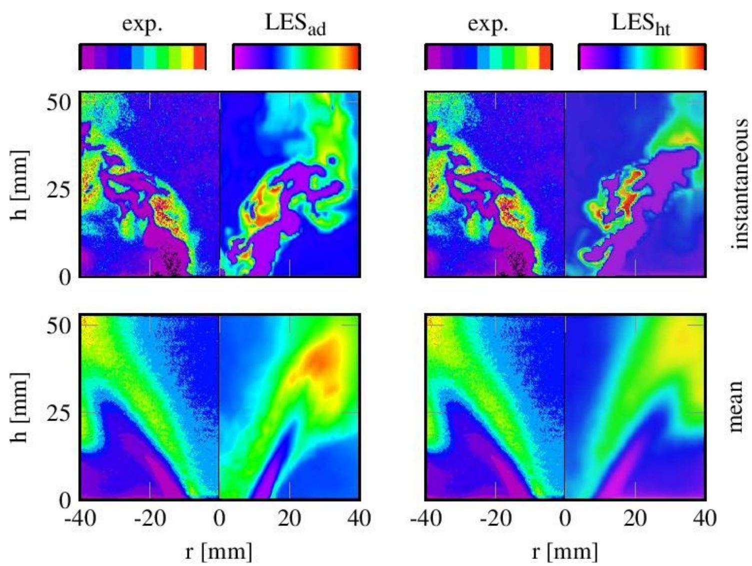


Mean heat release rate (HRR) vs. mean OH* Chemiluminescence

‘Quiet’ Flame: Topology







Improved agreement in terms of OH concentration when accounting for wall heat transfer (ht)

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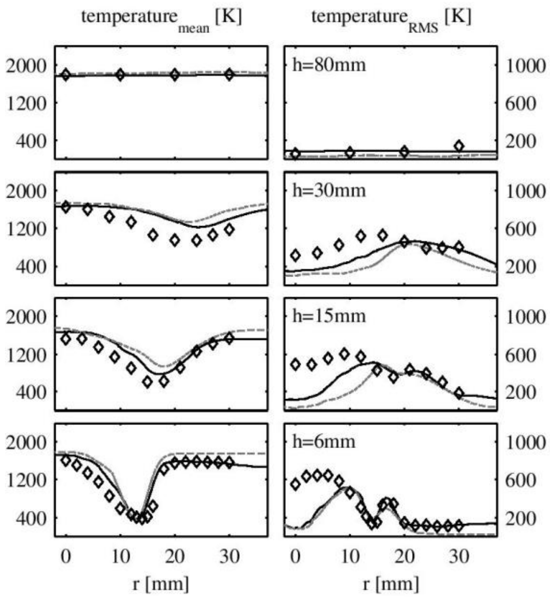
Oscillating Flame: Test Case

PRECCINSTA burner:

- equivalence ratio = 0.7
- ambient inflow conditions
- thermo-acoustic oscillations

Oscillating Flame: Statistics



Black: Wall heat transfer
Grey: Adiabatic

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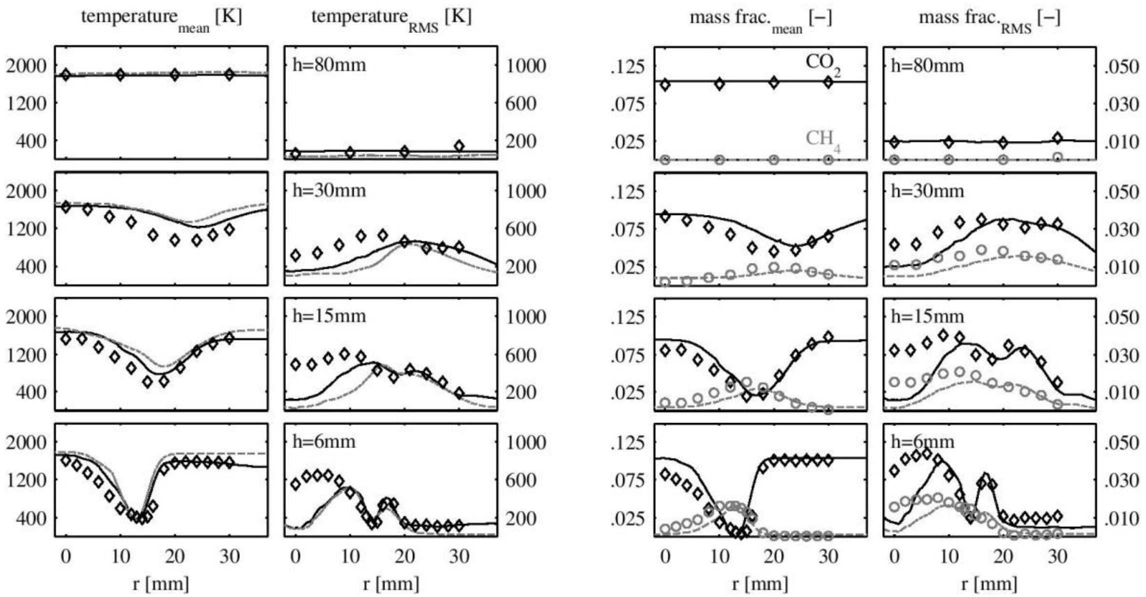
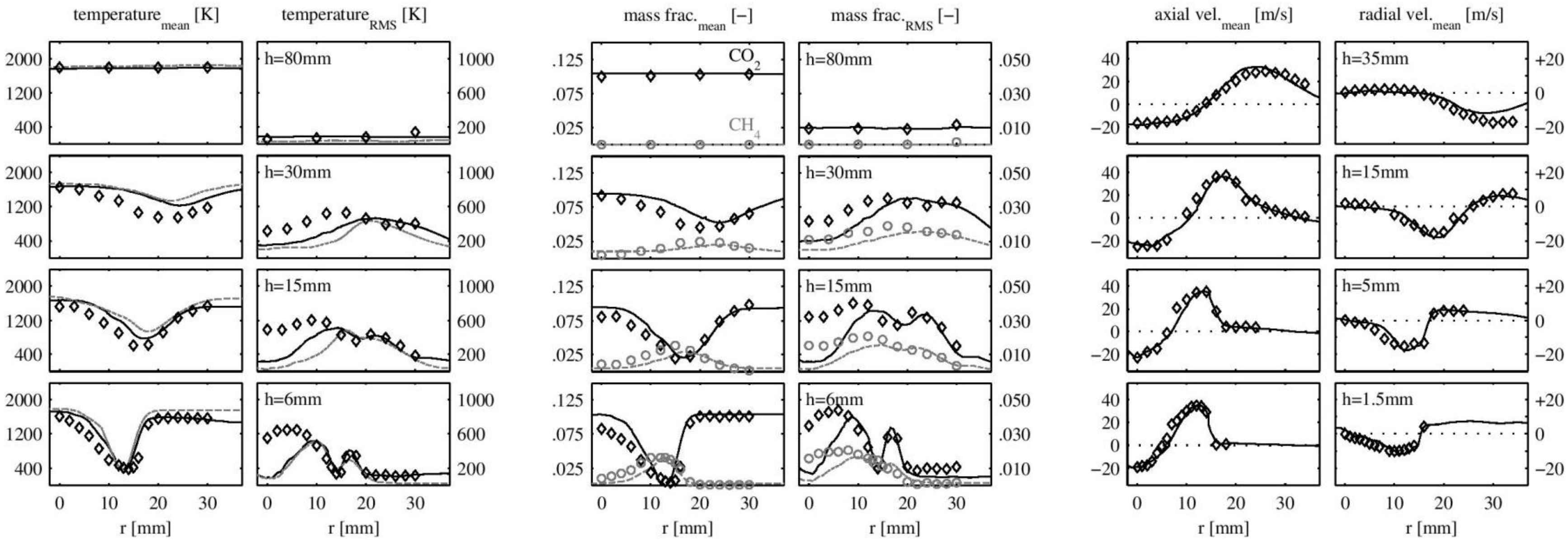
Oscillating Flame: Statistics



Scalar fluctuations near centreline underpredicted
→ thermo-acoustics?

Oscillating Flame: Statistics



Scalar fluctuations near centreline underpredicted → thermo-acoustics?

Compressible LES

Potential challenges in the development of compressible LES solvers:

i. Compressible Navier-Stokes equations
ii. Pressure-density dependency
iii. Acoustic wave reflection at boundaries

Compressible LES

Major modifications in BOFFIN-LES:

i. Compressible Navier-Stokes equations
ii. Pressure-density dependency
iii. Acoustic wave reflection at boundaries

Compressible LES

Major modifications in BOFFIN-LES:

i. → Additional pressure time-derivative in scalar transport equation
ii. Pressure-density dependency
iii. Acoustic wave reflection at boundaries

Compressible LES

Major modifications in BOFFIN-LES:

i. → Additional pressure time-derivative in scalar transport equation
ii. → Equation of state solved using calculated pressure
iii. Acoustic wave reflection at boundaries

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Compressible LES

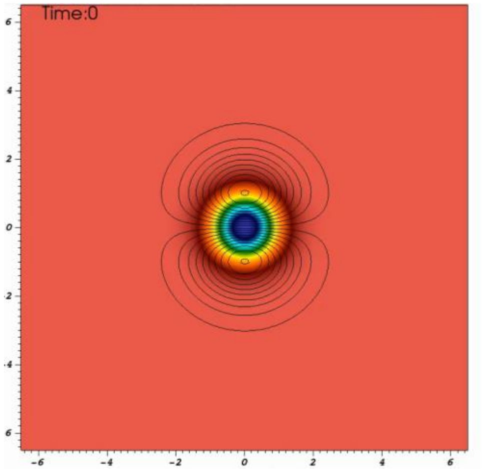
Major modifications in BOFFIN-LES:

i. → Additional pressure time-derivative in scalar transport equation

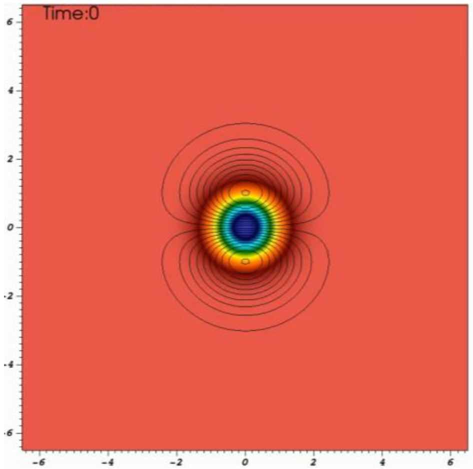
ii. → Equation of state solved using calculated pressure

iii. → Characteristic outflow boundary condition (*Lodato et al. 2008*)

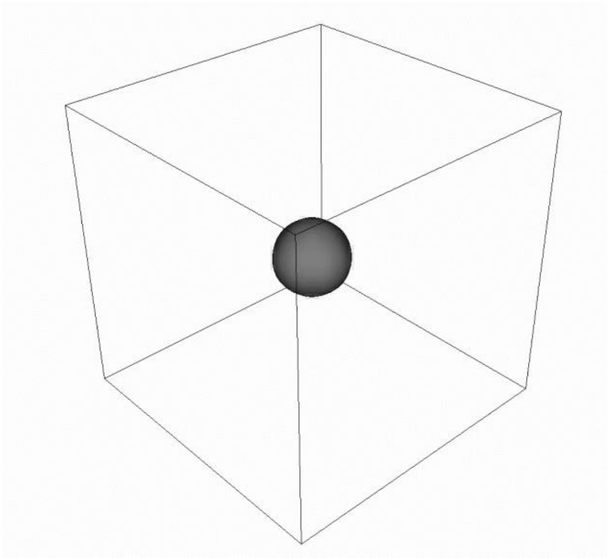
Reflective outflow



Non-reflective outflow



Non-reflective outflow



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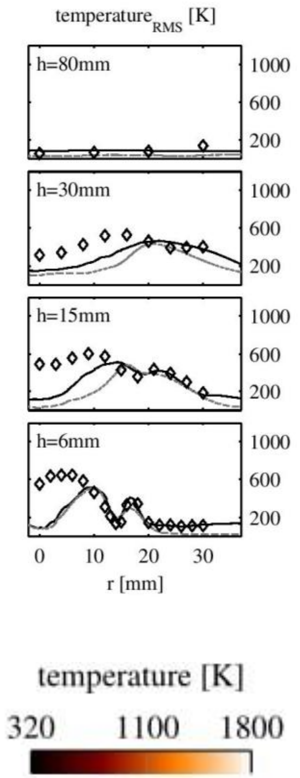
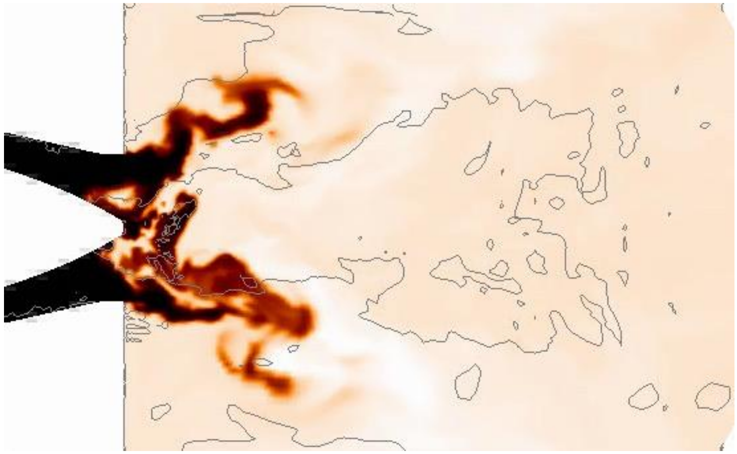
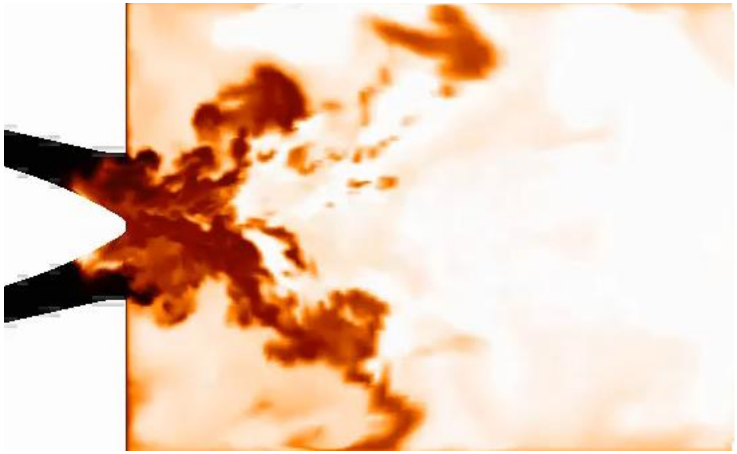
Flame Dynamics



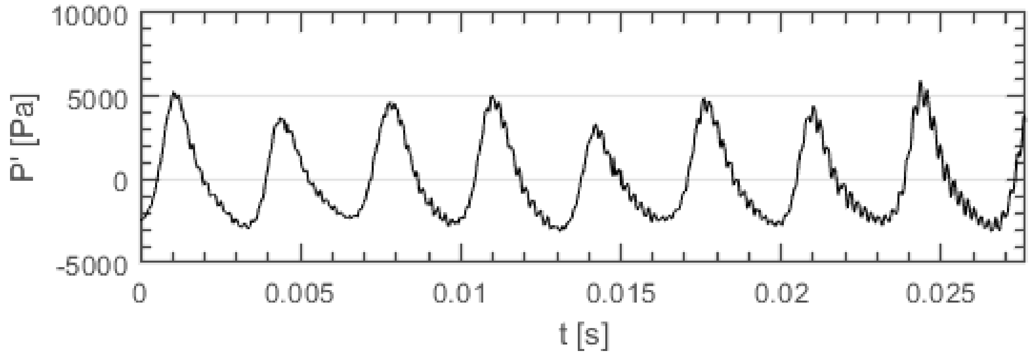


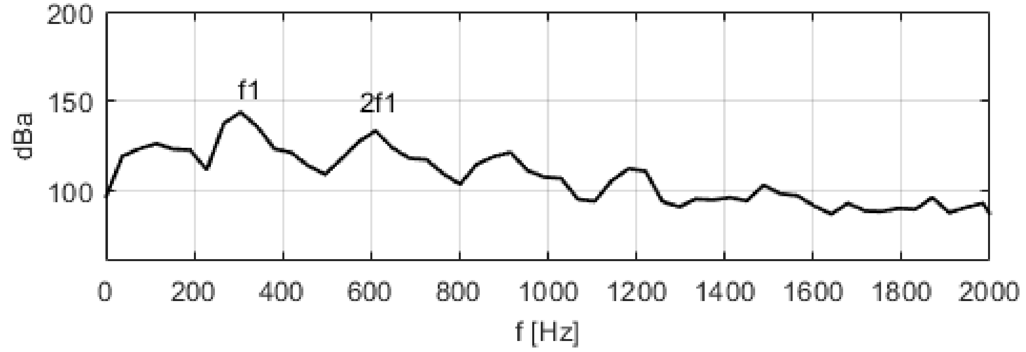
Incompressible LES

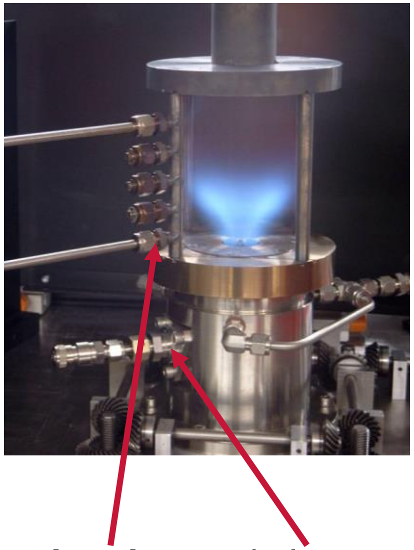


Compressible LES

LES Pressure Signal







Chamber and plenum pressure probes

Experimentally measured oscillations at 290 Hz

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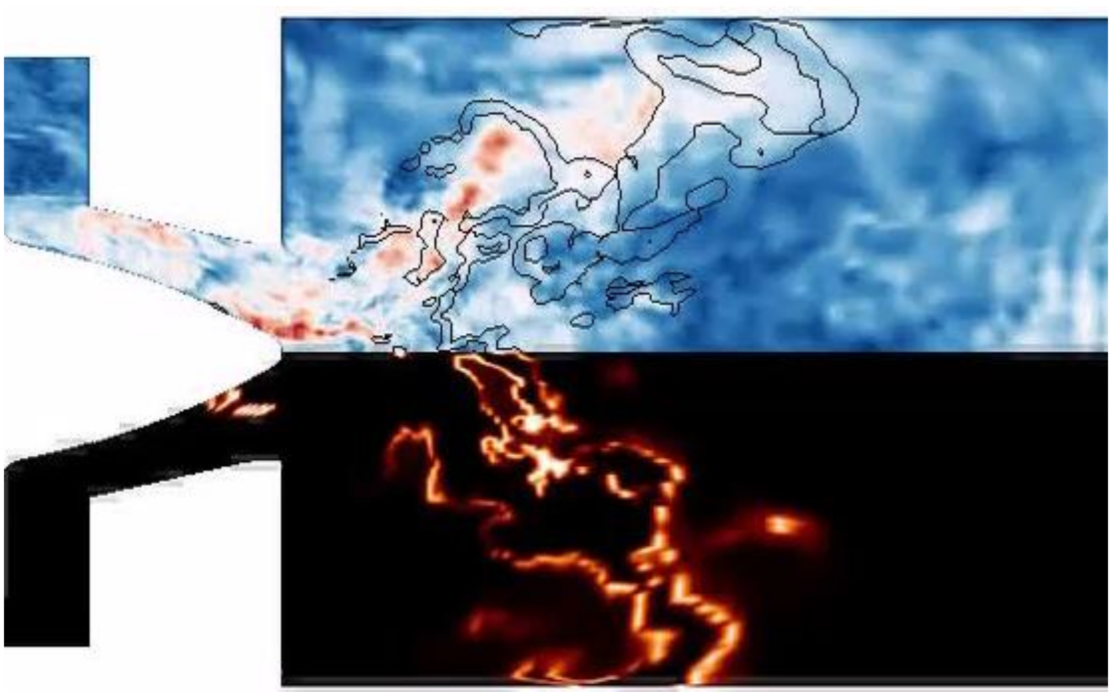
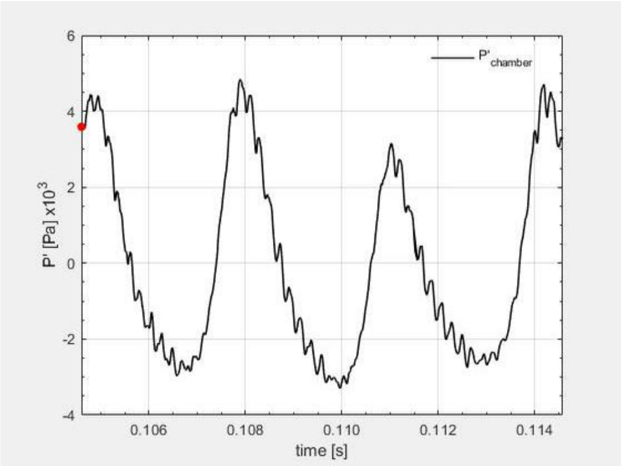
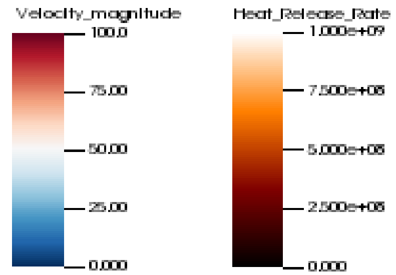
Self-Excited Oscillations







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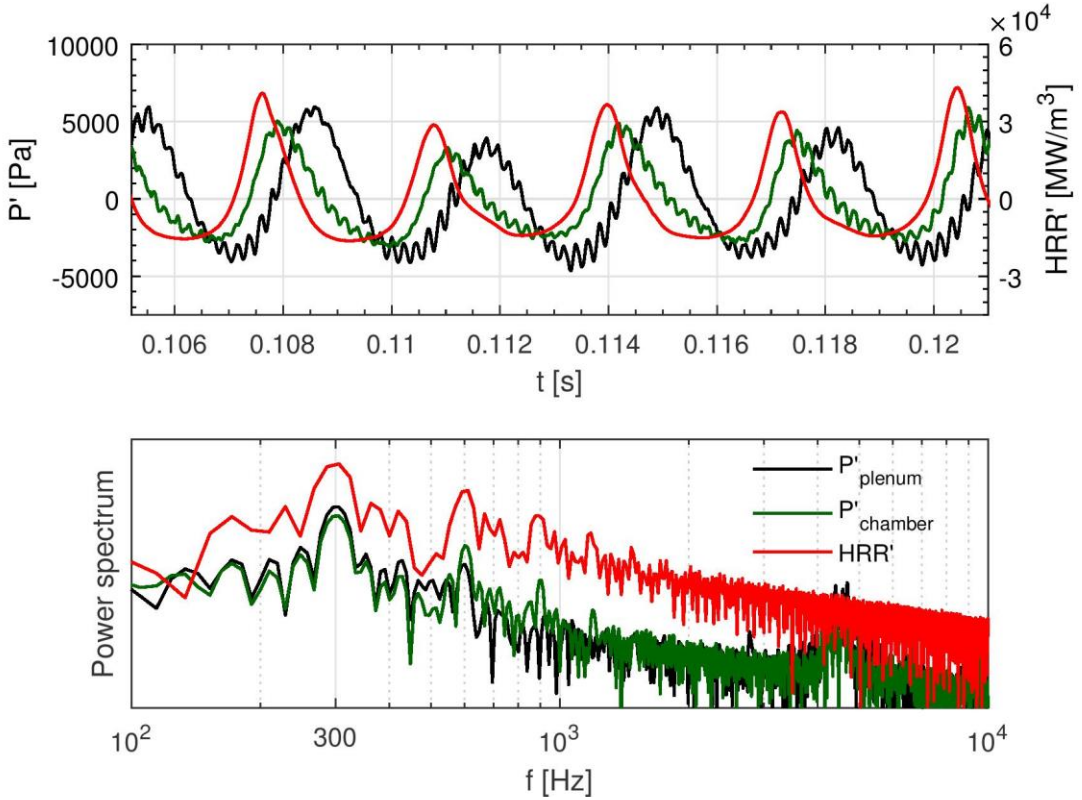
Thermo-Acoustic Coupling



- Rayleigh criterion

$$\int_V \int_T p'q'dV\,dt > 0$$

- Phase shift of ~80° between chamber and plenum pressure (similar to experiment)

  → creates pressure drop

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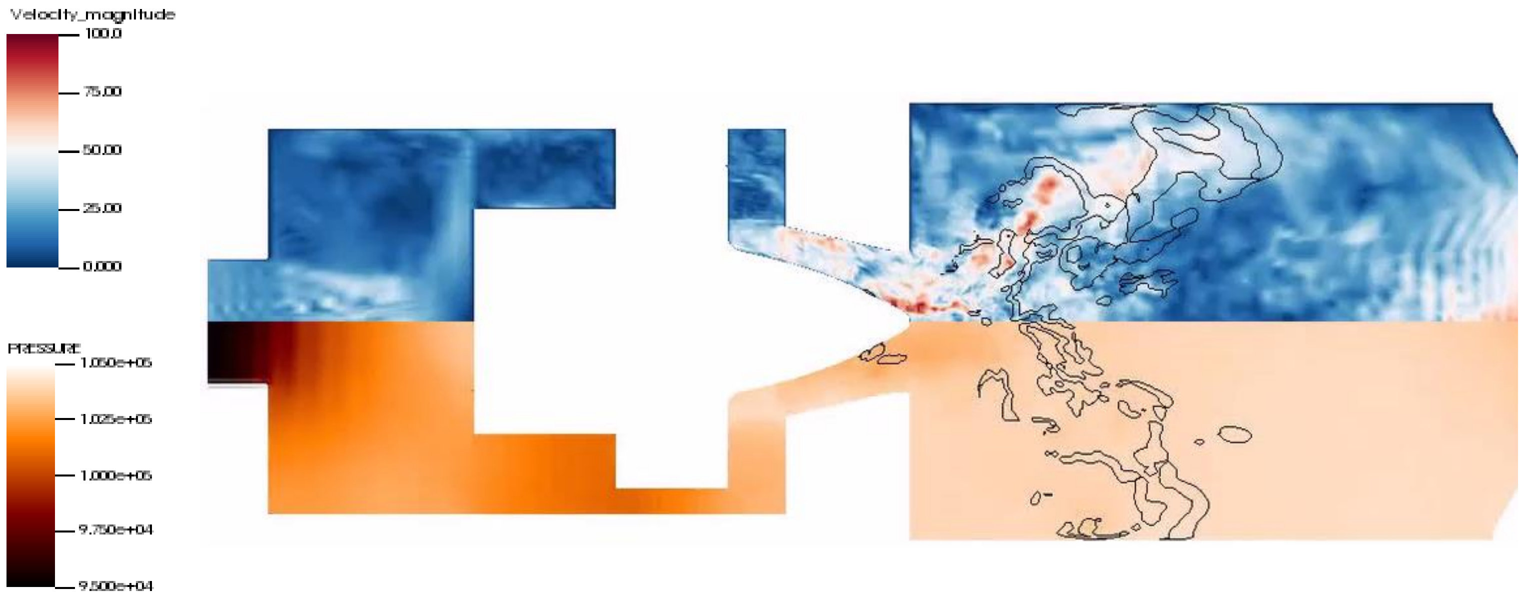
Underlying Mechanisms



Main drivers of the thermo-acoustic coupling:

i. Fluctuation of total mass flow rate entering combustion chamber
ii. Equivalence ratio fluctuation caused by fuel accumulation in swirler
iii. Flame surface modulation due to vortex breakdown / PVC?

Conclusions

I. Stochastic fields method
   - Good agreement in terms of time-averaged statistics and flame topology

II. Wall heat transfer
   - Improved temperature and species predictions especially near walls

III. Self-excited thermo-acoustic coupling
   - Frequency prediction (300 Hz) close to measured value (290 Hz)
   - Successful identification of main drivers

IV. Future work
   - More detailed phase-dependent study of the oscillating flame case

Acknowledgements

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archer

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UK CONSORTIUM ON TURBULENT REACTING FLOWS

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