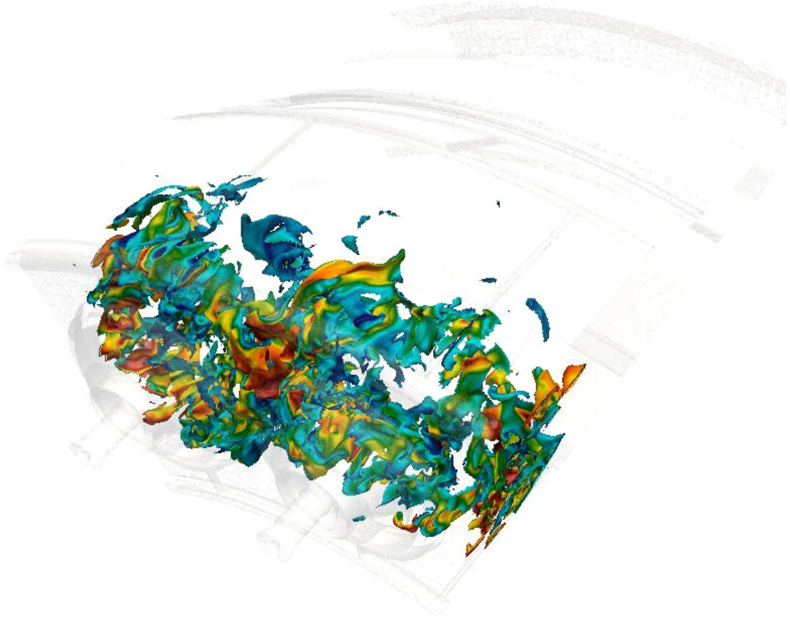
Modelling of high-pressure lean-burn combustors for aero-engines



Ivan Langella

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TU Delft

Summary

- Overview prospect in aviation
- Lean-burn technology
- Combustion modelling
- Validation at high pressure
- Combustion dynamics at high pressure (kerosene)
- Hydrogen fuelled combustors

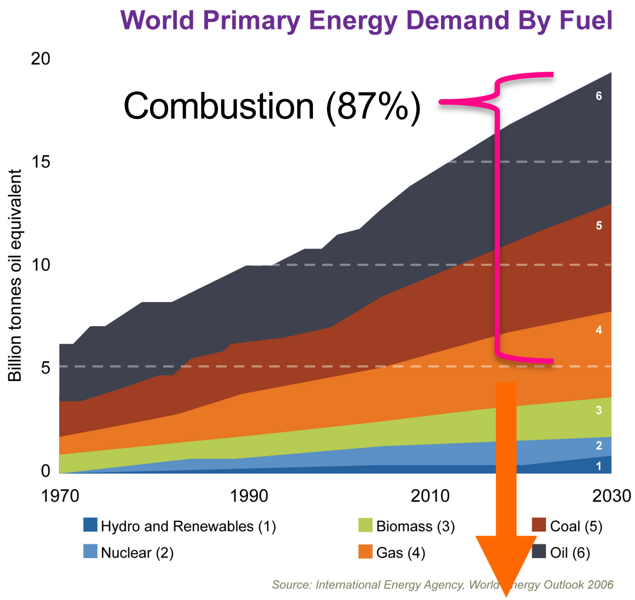
Introduction & Overview

Why research in combustion?

Need to reduce pollution and CO_2 emissions to fight the climate change

- Energy demand increases 2% p.a. (37% by 2040)
- 900 billion dollar per year needed by 2030
- 186 trillion cubic meters of gas and 1.7 billion barrels (+ North America growth in supplies) of oil reserves will last for more than 50 years.

Combustion will be the main source of energy for many decades



Increasing split of renewables and alternative fuels

Need to adapt

- Use of alternative fuels
- Integration in multi-cycle generation

Introduction & Overview

Combustion for aero-engines

- Aviation is ~2-3% human contamination and 12% CO_2 emission from transport, but with lack of alternative sources and boom in air traffic could account for up to a quarter of the total global emissions by 2050 [EU parliament].
- Number of passengers to double in 2037 [IATA] mainly due middle class in the Asia-Pacific and African regions.
- 21,450 air transport units in 2018 and 37,390 more over the next 20 years, with yearly 4.4% growth in air traffic [Global Market Forecast 2018–2037];

Higher BR turbofans, turbine entry temperatures and AFR have allowed reduction in fuel burn and emissions at cruise but figures are modest in **off-design.** CO is primarily generated at near-idle conditions (80% of total CO production); while NOx at high power settings. Controlling at off-design is of paramount importance and requires multi-component interaction

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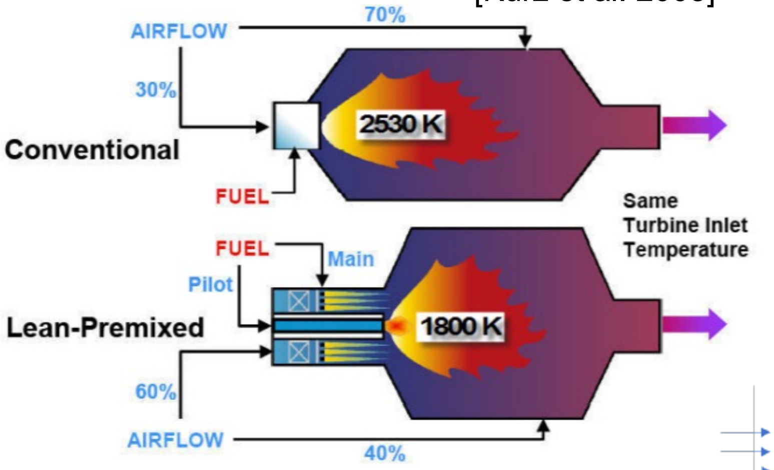
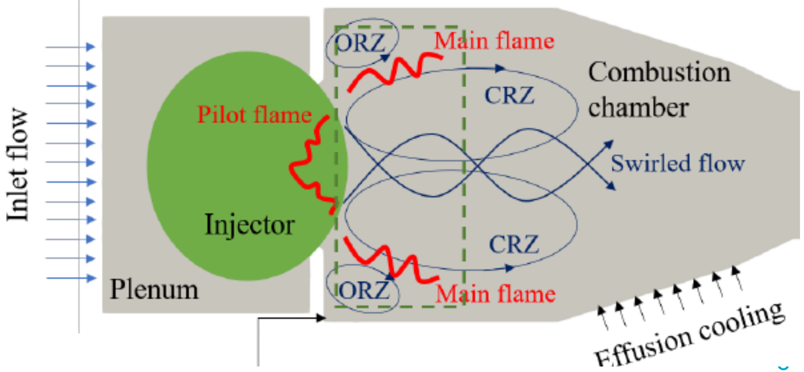
Lean Premixed Technology

Lean direct injection

[Kurz et al. 2003]





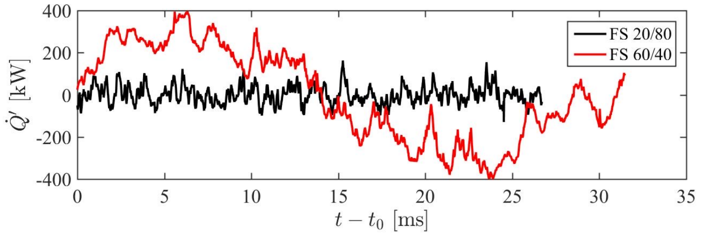
Lean Premixed Technology

Why **lean premixed** combustion → High efficiency and low emissions

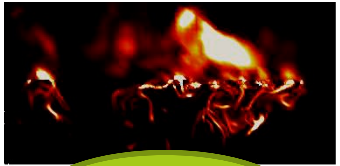
- Premixed combustion can control the temperature
- Emissions and efficiency intrinsically related

Flame + lean + turbulence

Heat release, turbulence and acoustics are coupled

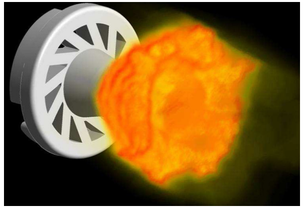


Instabilities



Injector

Flashback



Possible result: Inefficiencies, higher emissions, local extinctions and/or blowoff, acoustic resonance, vibrations, component stress (e.g. turbine blades)

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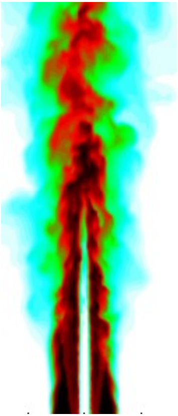
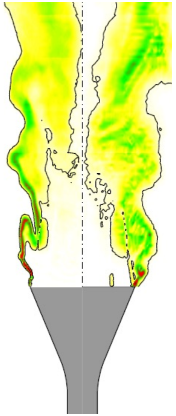
Laboratory-scale flames

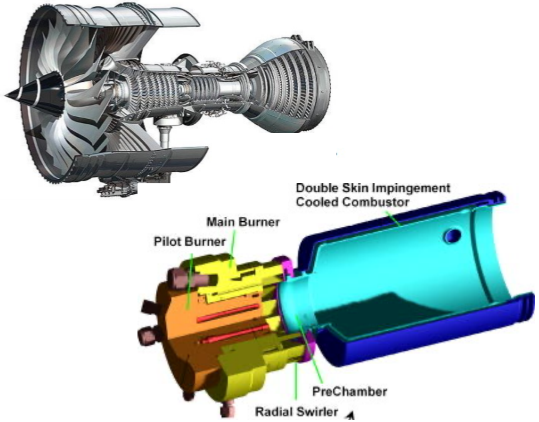
Piloted & non-piloted flames, bluff bodies





Industrial devices

Power plants, aero engines, furnaces…



Modelling

[Massey, Langella & Swaminathan, JFM 2019]
[Chen et al., CnF 2020, Soli et al. FTaC 2021]

***A-priori* analyses**

[Langella et al. PRF 2018]
[Nilsson, et al., FTaC 2019]
[Nillson, Langella et al., CTM 2019]

Flashback

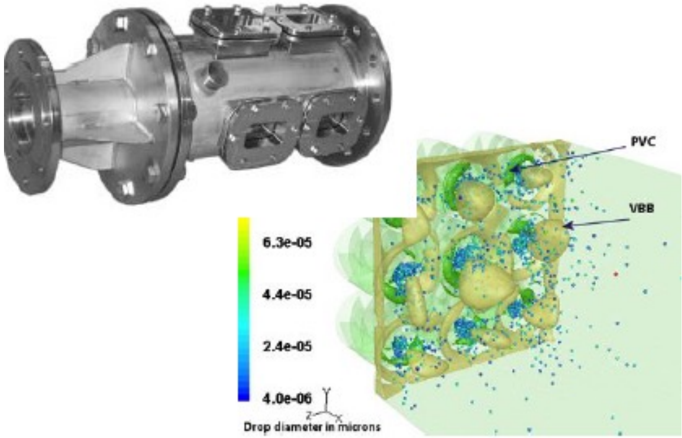
[Langella et al., J. Eng. Gas Turbine Power 2020; Soli and Langella, J. Gas Turb. Power 2022]

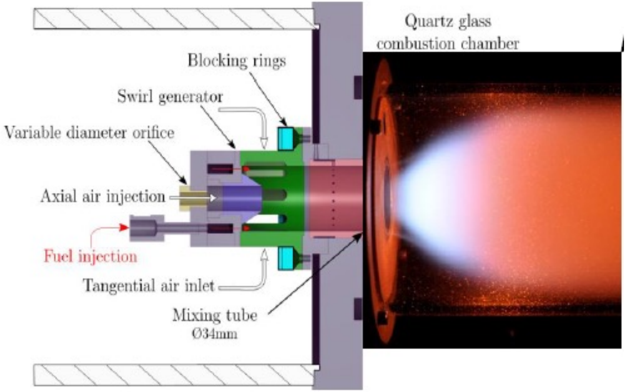
Thermoacoustics

[Chen, Langella et al., CnF 2019]
[Semlitsch, Langella, et al., JPP 2019]

Lean Premixed Technology

Hydrogen combustion research





Thoralf Reichel & Oliver Paschereit –Chair of Fluid Dynamics– TU Berlin

Clean Combustion Laboratory

2 PhD students (numerical)
1 PhD student (experimental)

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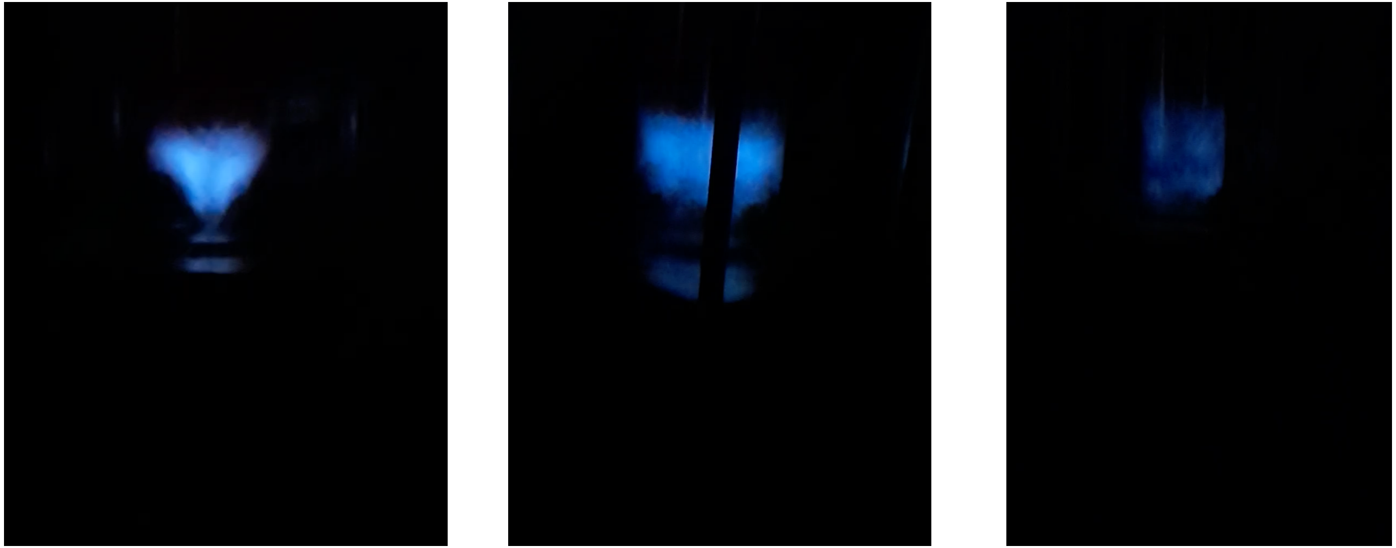
leaner

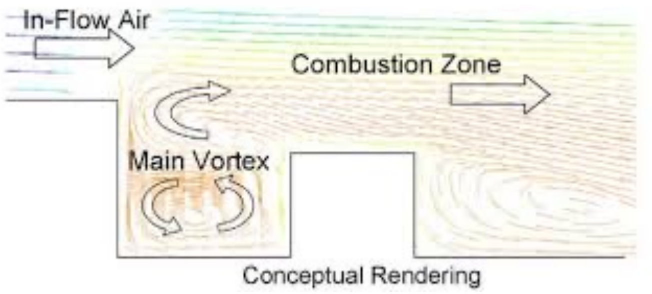


[Experiments from R. Sampat & S. Link, FPP combustion lab]

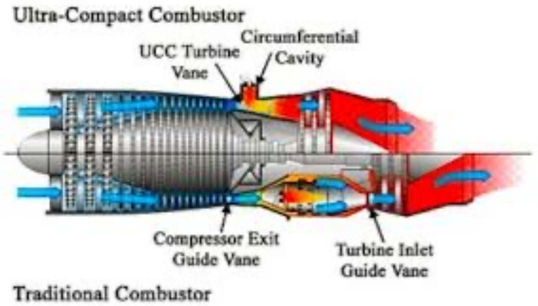
Lean Premixed Technology

Hydrogen combustion research

Ultra-compact devices & Trapped Vortex

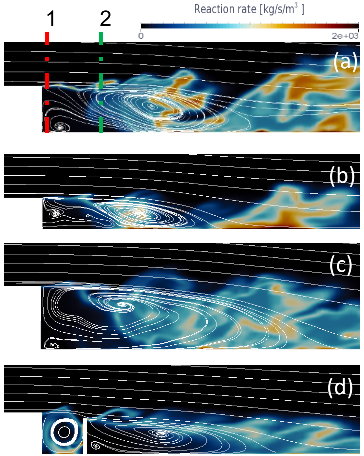


[Zhao *et al.*, Prog. Energy Combust. Sci 66, 2018]



1 postdoc @ TU Delft
1 PhD @ LU

Preliminary research



[Dr B. Kruljevic]

Challenges

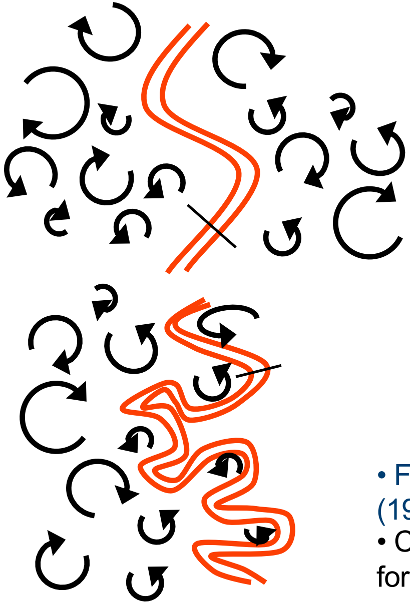
- Acceleration and compressibility effects if the TV is near the NGV
- Autoignition physics
- Heat transfer at the wall
- Effects in alternative fuels like differential diffusion
- Stronger flame anchoring
- Together with LP technology for low NOx

Combustion Modelling

Flamelets and LES modelling

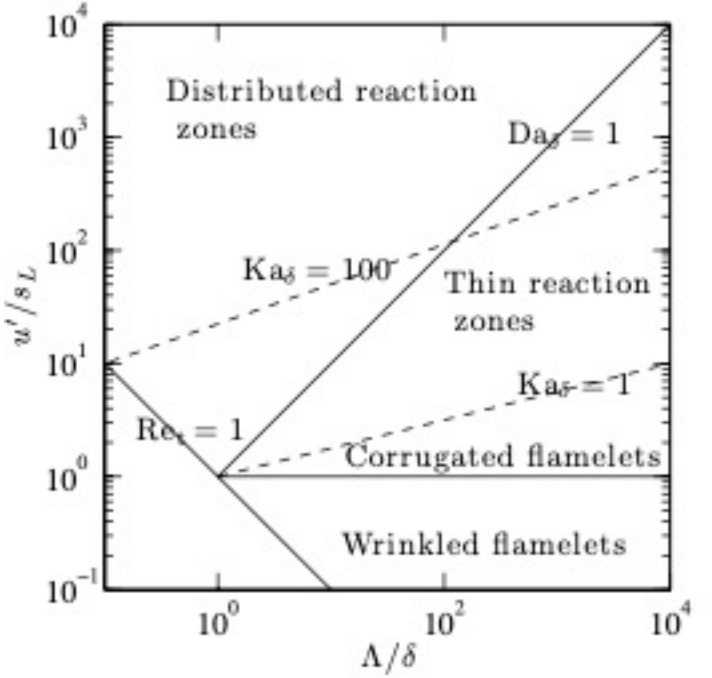
Description

FLAMELET assumption: turbulence does not alter flame inner structure and can be separated from thermochemistry



- Attractive for industry – computationally less expensive
- Interesting to explore and further assess its advantages and limitations on scientific and practical aspects

• First used by Bradley et al. CnF 71 (1988) – RANS
• Cook&Riley, Phys. Fluids 6 (1994) for LES



Flamelets and LES modelling

Description

$$\frac{\partial \overline{\rho}\widetilde{c}}{\partial t} + \frac{\partial \overline{\rho}\widetilde{u_i}\widetilde{c}}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\overline{\rho D \frac{\partial c}{\partial x_i}}\right) - \frac{\partial}{\partial x_i}\left(\overline{\rho}\widetilde{u_i c} - \overline{\rho}\widetilde{u_i}\widetilde{c}\right) + \overline{\dot{\omega}}$$

Unstrained flamelet

$$\overline{\dot{\omega}} = \overline{\rho}\int_0^1\int_0^1 \frac{\dot{\omega}}{\rho}\boxed{P(c,\xi;\widetilde{c},\widetilde{c''^2},\widetilde{\xi},\widetilde{\xi''^2})}\,\mathrm{d}c\,\mathrm{d}\xi$$

Product of two Beta-PDFs (ad-hoc numerical integration needed)

$$\overline{\rho}\frac{D\widetilde{c''^2}}{Dt} = \frac{\partial}{\partial x_j}\left[\left(\frac{\widetilde{\mu}}{Sc_l} + \frac{\mu_t}{\sigma_{c^2}}\right)\frac{\partial \widetilde{c''^2}}{\partial x_j}\right] - \underbrace{2\overline{\rho}\widetilde{\varepsilon}_c}_{\text{SDR}} + \underbrace{2(\overline{\dot{\omega}c} - \overline{\dot{\omega}}\widetilde{c})}_{\text{Reactive term}} - \underbrace{\cancel{\frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_c}\frac{\partial \widetilde{c}^2}{\partial x_j}\right)}}_{\approx 0} + \underbrace{2\frac{\widetilde{\mu}}{\sigma_c}\frac{\partial \widetilde{c}}{\partial x_j}\frac{\partial \widetilde{c}}{\partial x_j}}_{\text{Turbulent production}}$$

Flamelets and LES modelling

Description

$$\bar{\rho}\frac{D\widetilde{c''^2}}{Dt} = \frac{\partial}{\partial x_j}\left[\left(\frac{\widetilde{\mu}}{Sc_l}+\frac{\mu_t}{\sigma_{c^2}}\right)\frac{\partial\widetilde{c''^2}}{\partial x_j}\right] - 2\bar{\rho}\widetilde{\varepsilon}_c + 2(\overline{\dot{\omega}c}-\overline{\dot{\omega}}\widetilde{c}) - \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_c}\frac{\partial\widetilde{c}^2}{\partial x_j}\right) + 2\frac{\widetilde{\mu}}{\sigma_c}\frac{\partial\widetilde{c}}{\partial x_j}\frac{\partial\widetilde{c}}{\partial x_j}$$

Linear relaxation

$$\widetilde{\varepsilon}_c = a\frac{\nu_{\mathrm{sgs}}}{\Delta^2}\widetilde{c''^2} \sim \tau_t^{-1}$$

Revised SDR

$$\widetilde{\varepsilon}_c = \left(1-e^{-\theta_5\Delta^+}\right)\left[2K_c\frac{s_L}{\delta_{th}} + (C_3-\tau C_4\mathrm{Da}_\Delta)\frac{2u'_\Delta}{3\Delta}\right]\frac{\widetilde{c''^2}}{\beta_c}$$

$$\sim \tau_t^{-1} + \tau_c^{-1} + \tau_{ct}^{-1}$$

[Dunstan *et al.* 2013,
Langella & Swaminathan 2015,
Langella *et al.* 2015, 2016]

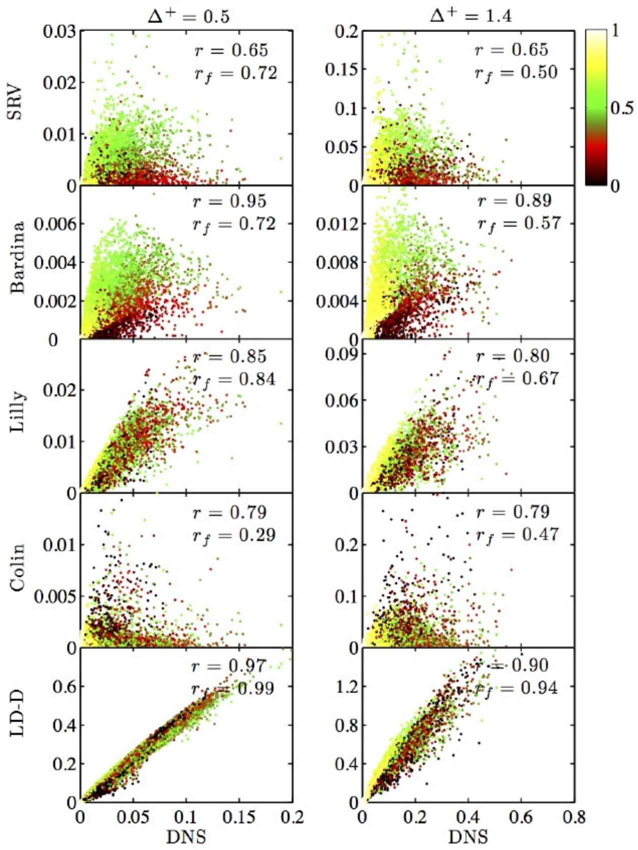
Flamelets and LES modelling

Description

Localised Dissipation (LD) model

$$u'_\Delta \approx K \frac{\sqrt{2\alpha_2}\Delta}{2} \left| 2\nabla\tilde{\mathbf{u}} : \nabla\tilde{\mathbf{u}} - \frac{\alpha_2 \Delta^2}{2} \left|\nabla^2 \tilde{\mathbf{u}}\right|^2 \right|^{1/2}$$

[Langella et al., Phys. Review Fluids 3, 2018]



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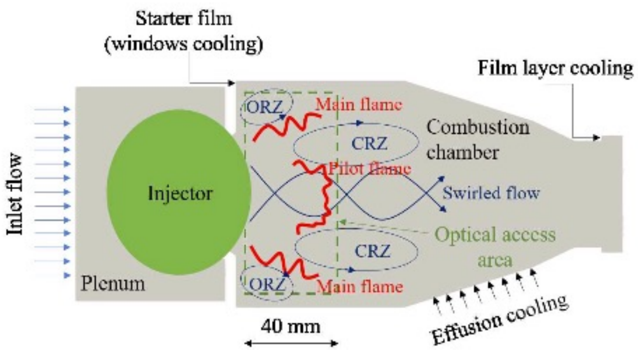
Validation at high pressure

Validation at high pressure

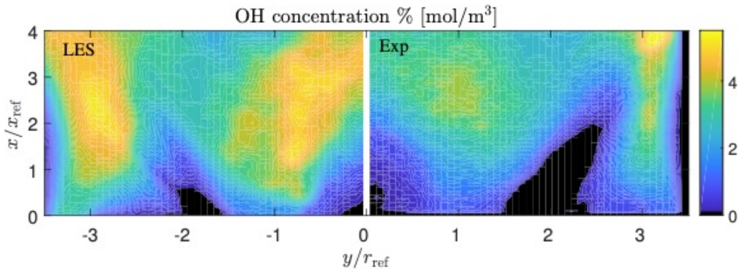
BOSS rig combustor

- Lack of experimental data makes the validation challenging and not possible at the higher pressures
- Validation is thus performed at the closest conditions
- Numerical verification is crucial to quantify the model uncertainty
- Even when measurements are available, uncertainty needs to be taken into account

~15 bar



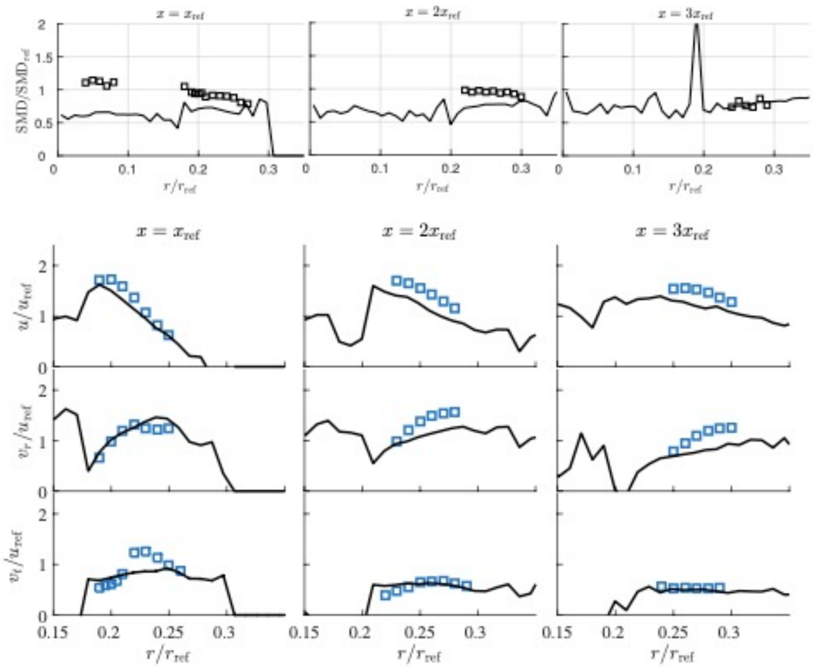
Measure	Error
OH-PLIF	20%
PDA	3-5%

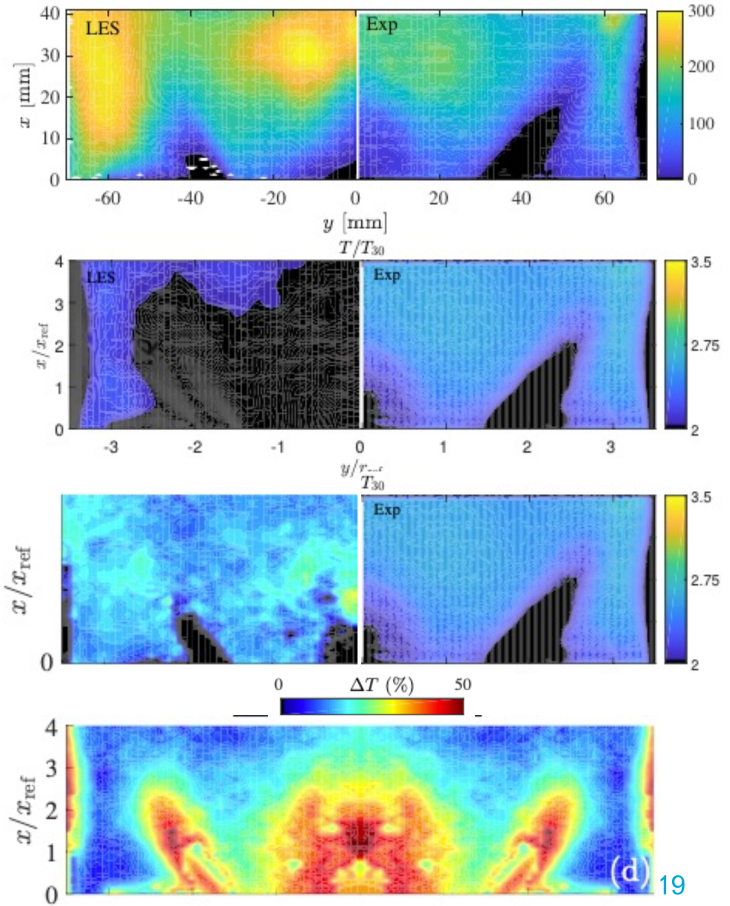


[Langella *et al.* J. Eng. Gas Turb. Power 2020]

Validation at high pressure

BOSS rig combustor



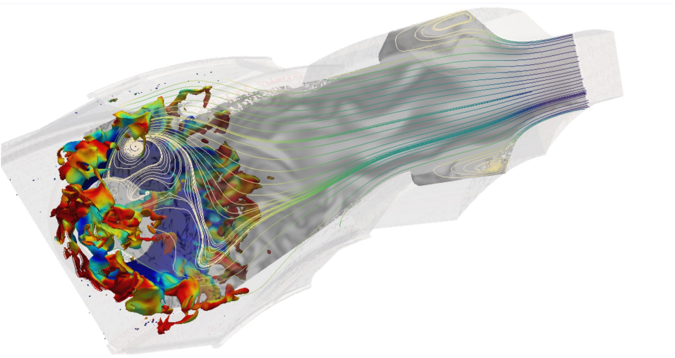


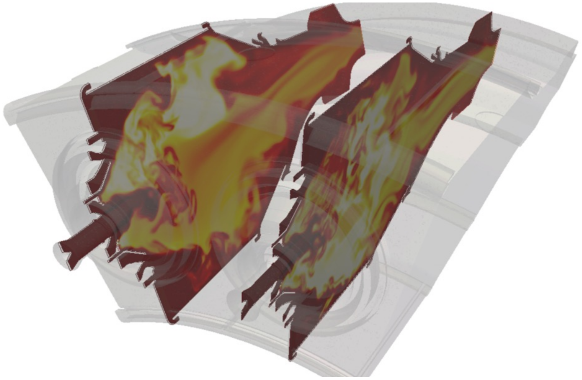
[Langella *et al.* J. Eng. Gas Turb. Power 2020]

Combustion dynamics at high pressure

Kerosene

LES of high pressure lean-burn system





- Grid 9M, 13M & 26M hexa-dominant cells
- Central diff. scheme + blending factor 0.80
- Constant Smagorinsky model

Spray

- Random injection
- Primary breakup correlation for the SMD
- Secondary breakup

Boundary conditions

- p = p*, T = T*, FS = FS1 (Approach)
- p = 2p* bar, T = 1.1T*, FS = FS2 (Cutback)
- Inlet profiles from RANS
- 40 ms physical time, 1 month on 512 cores using time step of 0.5 μs
- Dagaut mechanism for kerosene

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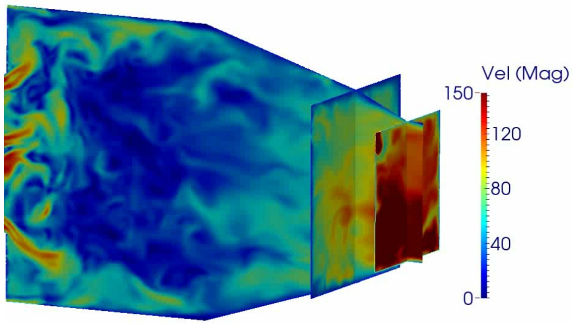
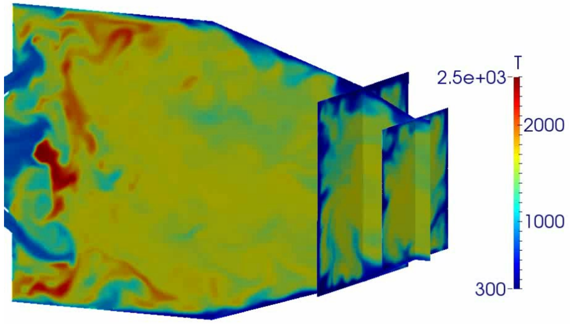
LES of high pressure lean-burn system

Turbulence-flame-spray coupling

The pilot jet opens and closes periodically



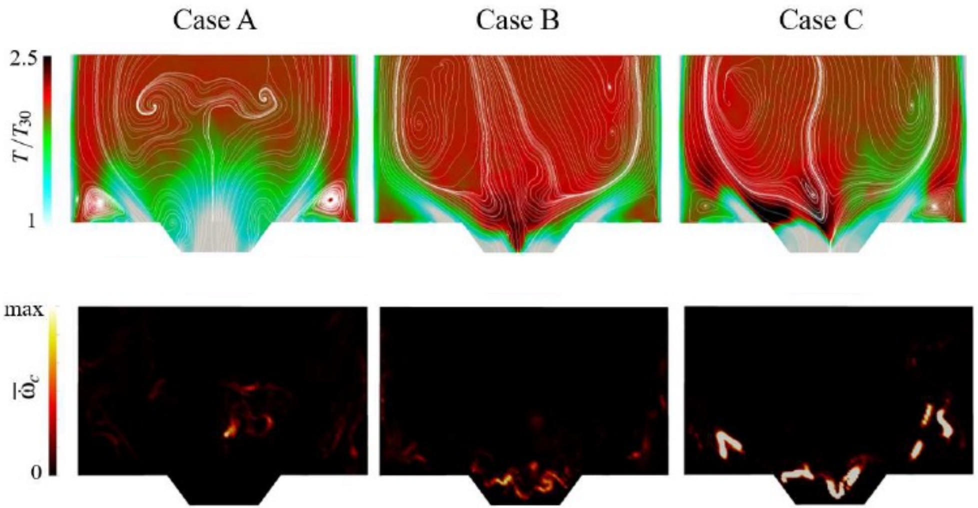


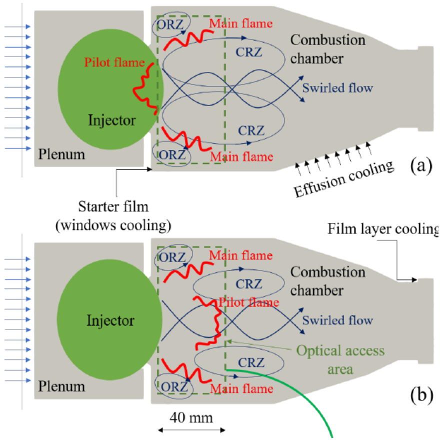
[Langella *et al.* J. Eng. Gas Turb. Power 2020]

LES of high pressure lean-burn system

Turbulence-flame-spray coupling

M-shaped flame V-shaped flame





Sensitivity to:
Turbulence & subgrid models (Case B) Combustion parameters (Case C)

[Langella *et al.* J. Eng. Gas Turb. Power 2020]

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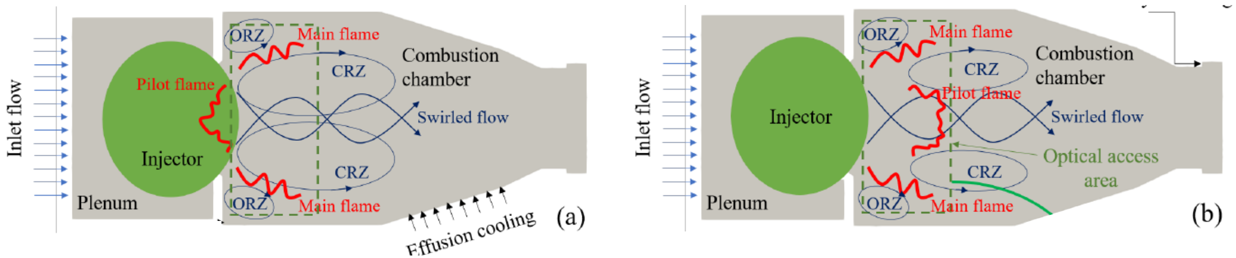
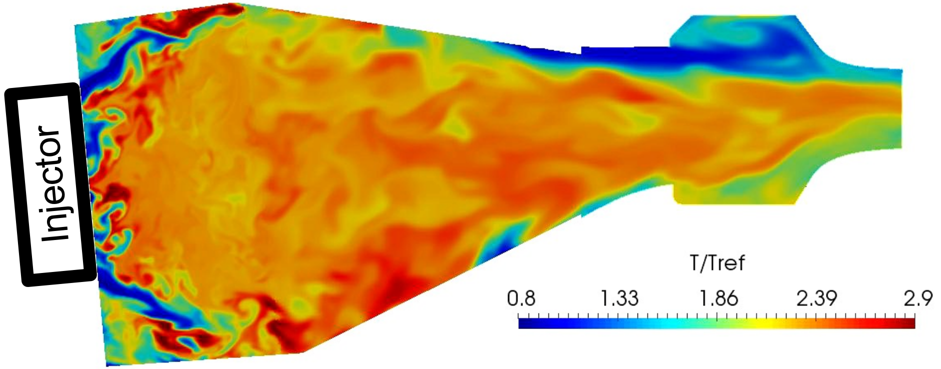
LES of high pressure lean-burn system

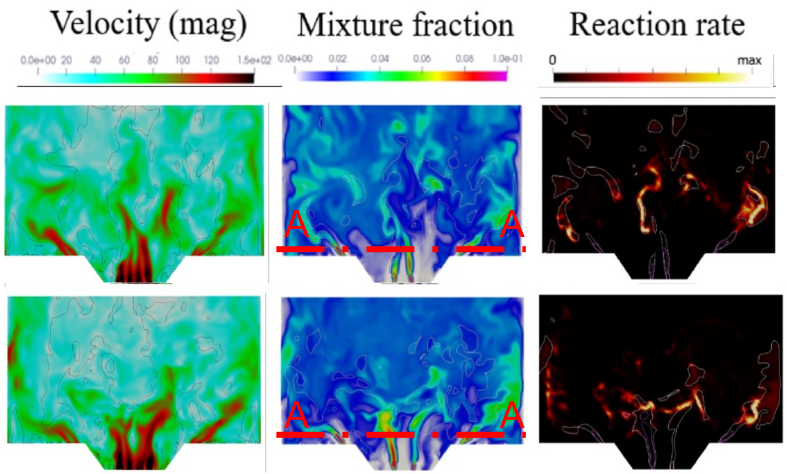
Turbulence-flame-spray coupling



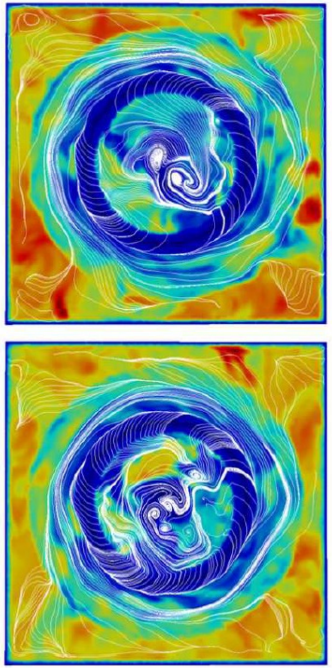


LES of high pressure lean-burn system

Turbulence-flame-spray coupling



SEC A-A

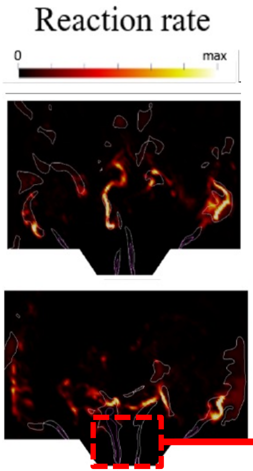


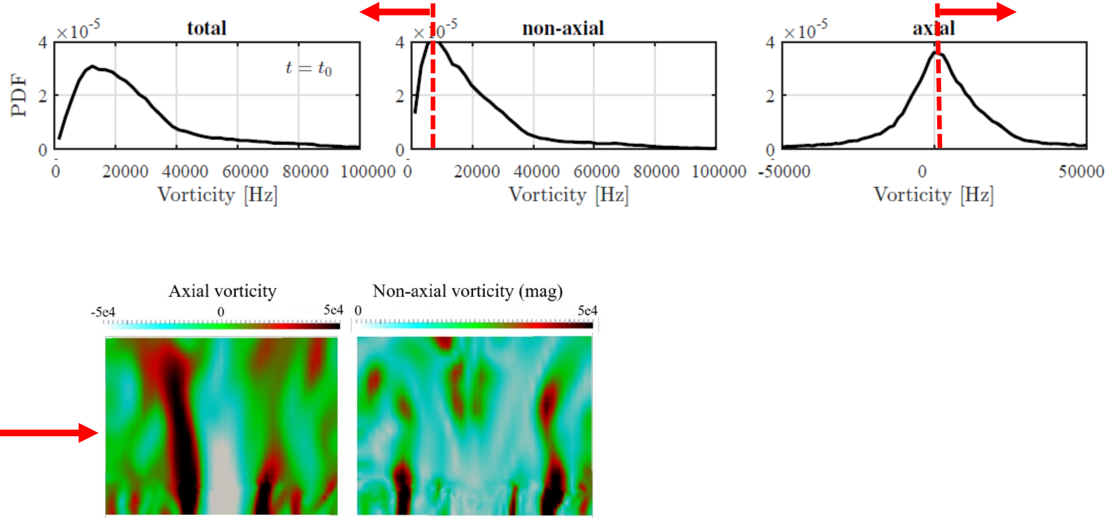
1. Pilot jet opens of 45 deg at a frequency of 400 Hz
2. The vorticity is minimum at his point causing richer patches to form
3. The flame is driven by relatively rich patches forming upstream and increases in strength only once closer to the injector
4. When this happens the pilot jet is already closing and thus the flame moves back downstream

[I. Langella *et al.*, J. Eng. Gas Turb. Power *2020*]

LES of high pressure lean-burn system

Turbulence-flame-spray coupling



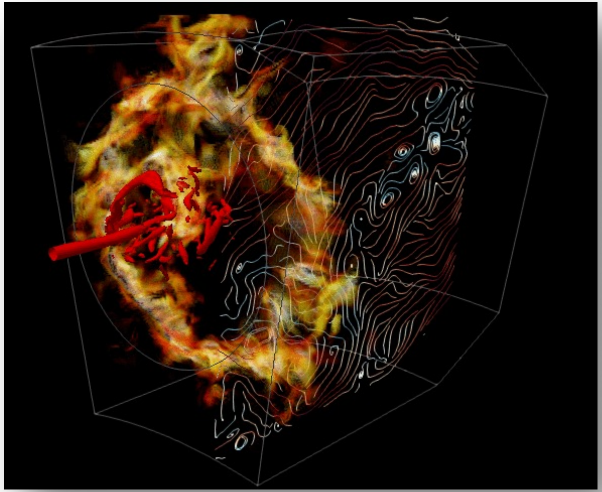


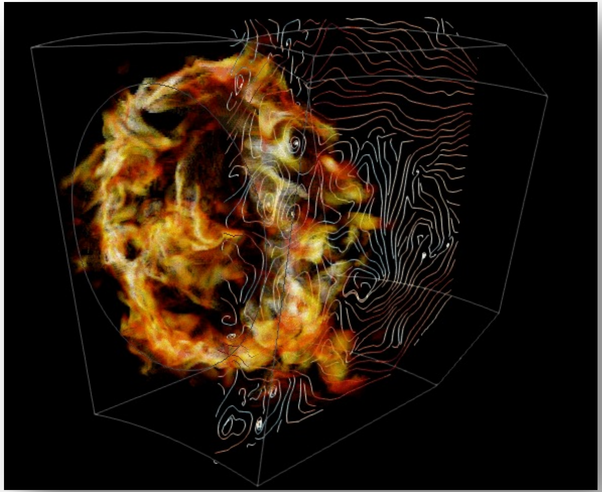
- Axial vorticity dominates the inner region, non-axial vorticity dominates the outer region
- Non-axial to axial vorticity redistribution during the formation of the inner vortex

[I. Langella *et al.*, J. Eng. Gas Turb. Power *2020*]

LES of high pressure lean-burn system

Turbulence-flame-spray coupling





- Aerodynamics, acoustics and combustion tightly coupled by PVC / flame interactions
- Even without thermoacoustic oscillations, the coupling with the spray (variation of mixture fraction) can lead to extreme events such as CIVB

[Soli and Langella., J. Eng. Gas Turb. Power *2022*]

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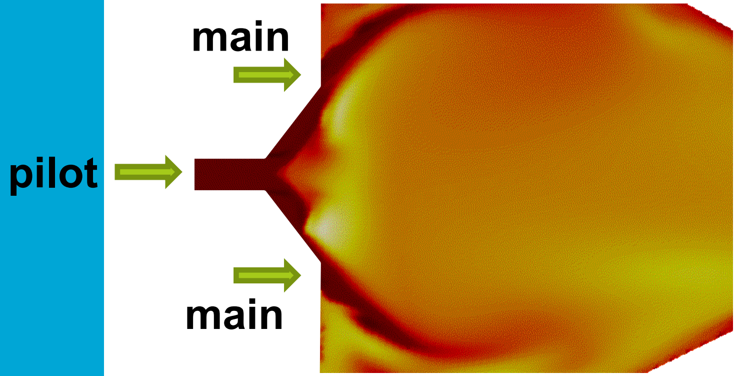
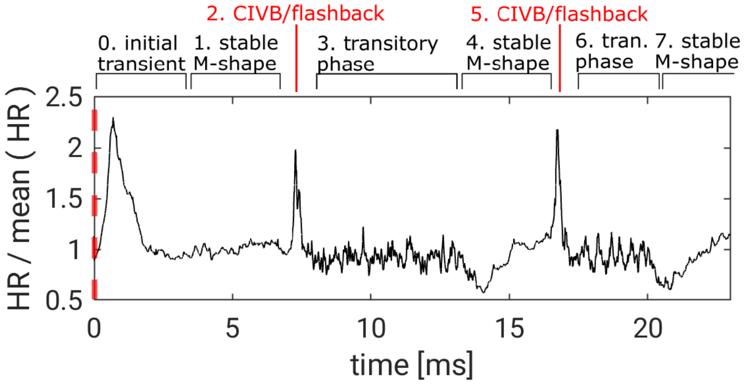
LES of high pressure lean-burn system

Turbulence-flame-spray coupling

Temporal dynamics

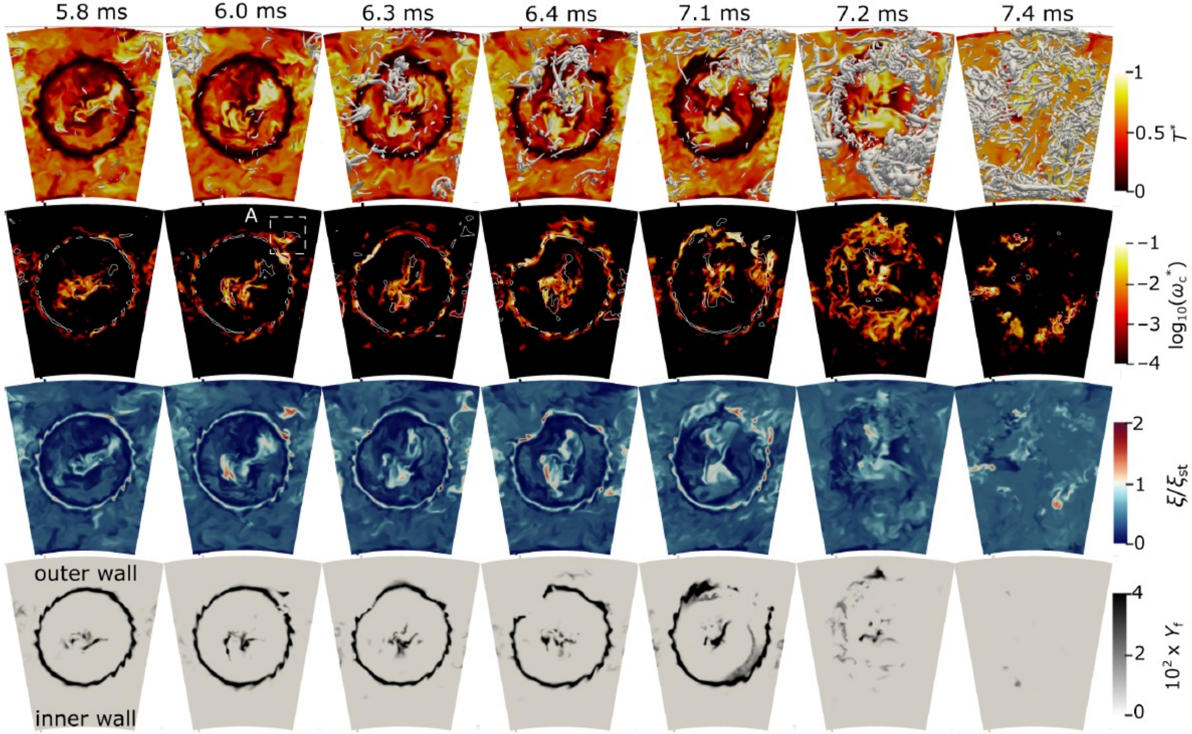


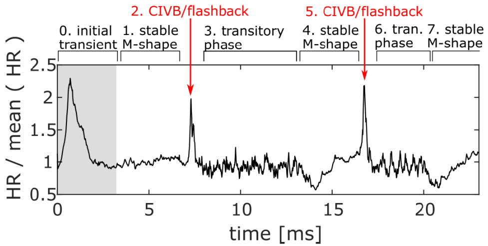


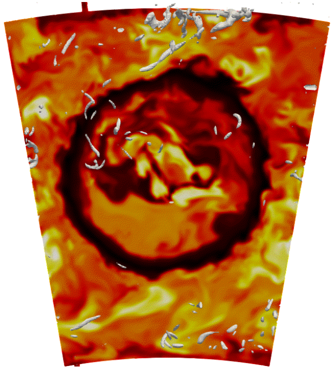
[Soli and Langella., J. Eng. Gas Turb. Power *2022*]

LES of high pressure lean-burn system

Turbulence-flame-spray coupling







[Soli and Langella., J. Eng. Gas Turb. Power *2022*]

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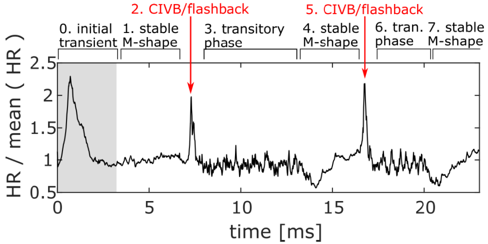
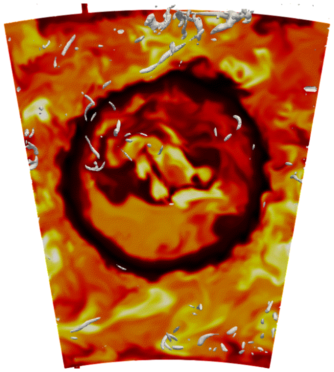
LES of high pressure lean-burn system

Turbulence-flame-spray coupling



- Convection of vitiated air onto main flame increases equivalence ratio and heat release
- Main flame is strained
- A flame hole is eventually formed (partial blow-off)
- Baroclinic and stretching terms also increasing and keep feeding the vortex growth mechanism
- Vortices interact with the pilot flame, destroying the PVC (CIVB)

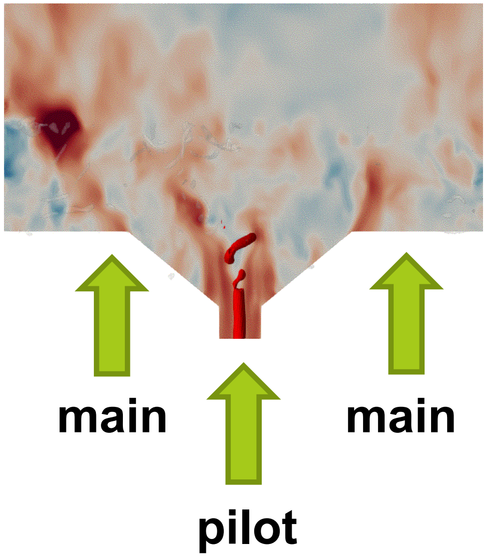
$$\frac{D\boldsymbol{\omega}}{Dt} = \underbrace{(\boldsymbol{\omega}\cdot\nabla)\,\mathbf{u}}_{\text{stretching by shear}} - \underbrace{\boldsymbol{\omega}\,(\nabla\cdot\mathbf{u})}_{\text{thermal dilatation}} + \underbrace{\frac{\nabla\rho\times\nabla p}{\rho^2}}_{\text{baroclinic instability}} + \underbrace{\nabla\times\left(\frac{\nabla\cdot\mathbf{T}}{\rho}\right)}_{\text{viscous diffusion of } \boldsymbol{\omega}}$$

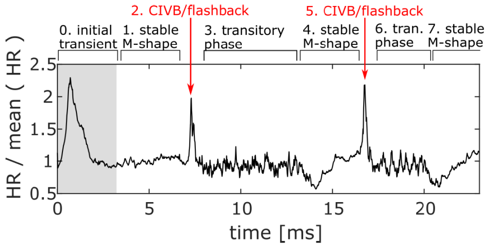


[Soli and Langella., J. Eng. Gas Turb. Power *2022*]

LES of high pressure lean-burn system

Turbulence-flame-spray coupling





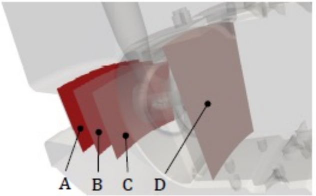
- The CIVB is then observed to progress as observed experimentally by Sattelmayer and co.

[Soli and Langella., J. Eng. Gas Turb. Power *2022*]

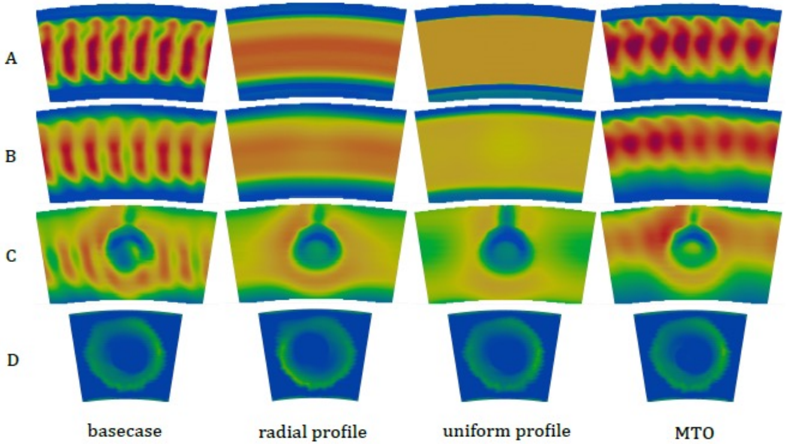
Lean Premixed Technology

Components interaction & off-design conditions

Combustor – compressor

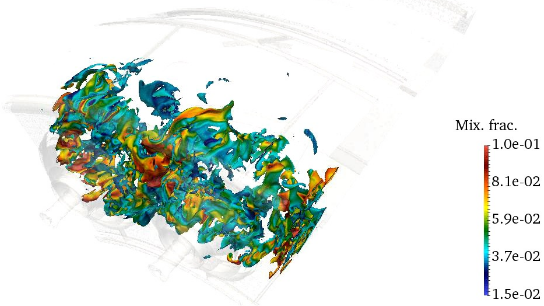


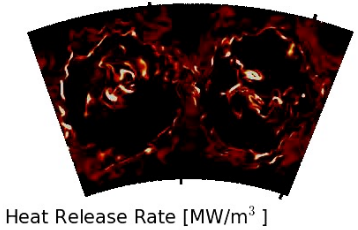
Fluctuations of velocity & temp at combustor inlet



[A. Soli et al., J. Gas Turb. Propul. Power, 2022]

Multi-sector



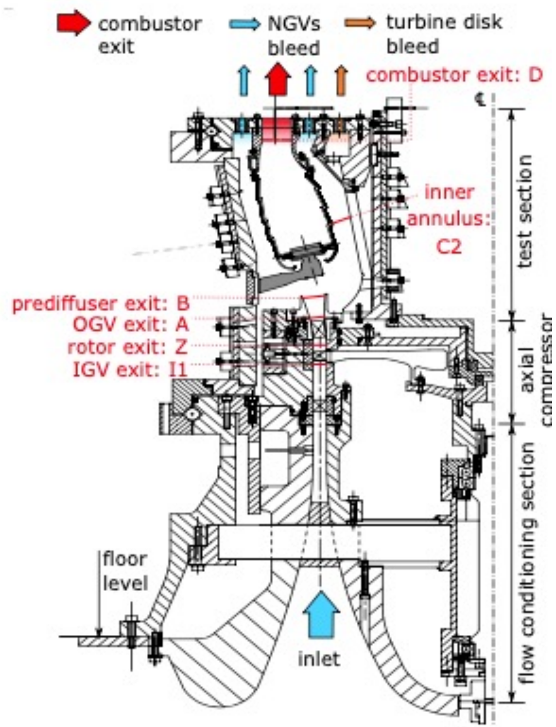


[Semlitsch, Langella, *et al.*, JPP 2019]

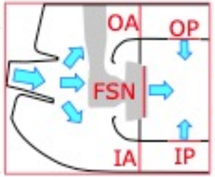
- Optimisation of emissions and efficiency
- Thermoacoustic analyses

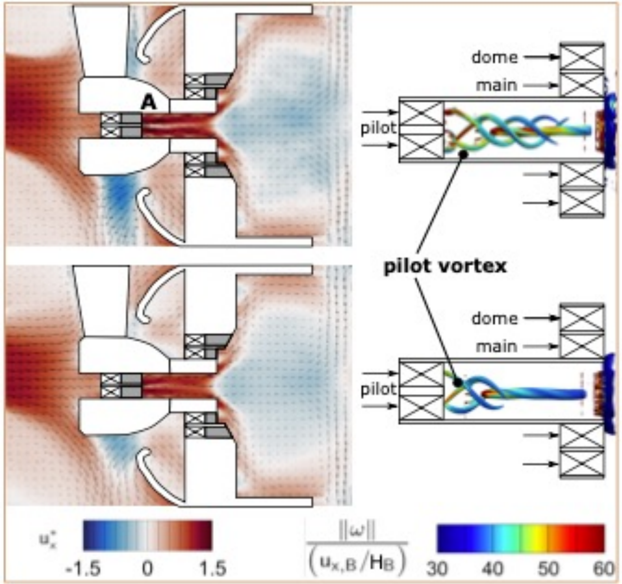
Lean Premixed Technology

Components interaction & off-design conditions



	Difference
Injector (FSN)	−0.4 %
Inner annulus (IA)	−0.3 %
Outer annulus (OA)	+0.7 %
Inner primary ports (IP)	−0.2 %
Outer primary ports (OP)	−0.5 %





[A. Soli et al., J. Gas Turb. Propul. Power, 2022]

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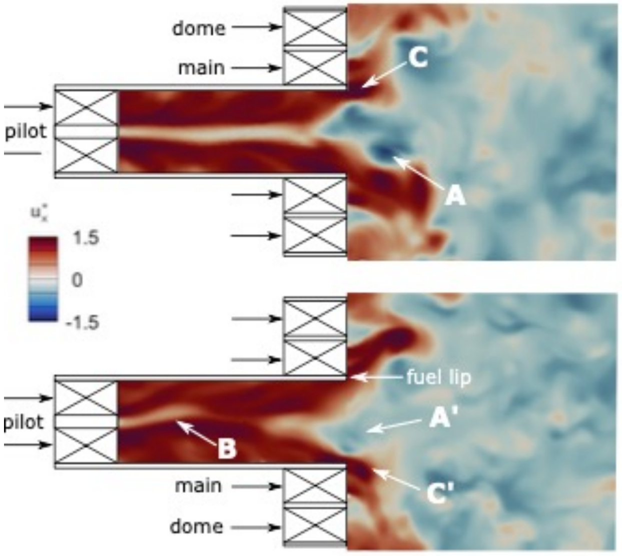
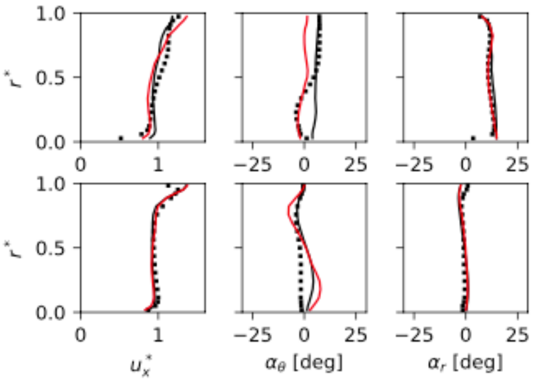
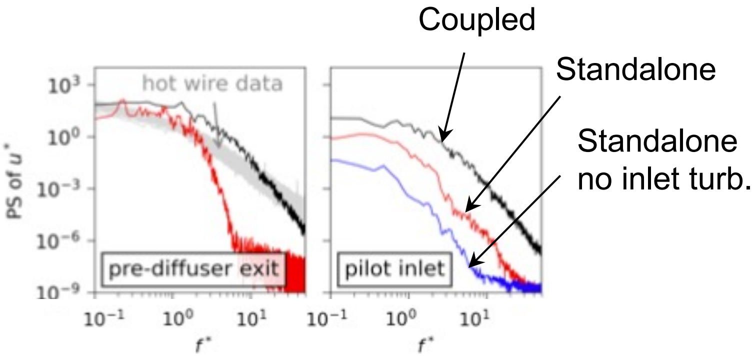
Components interaction & off-design conditions



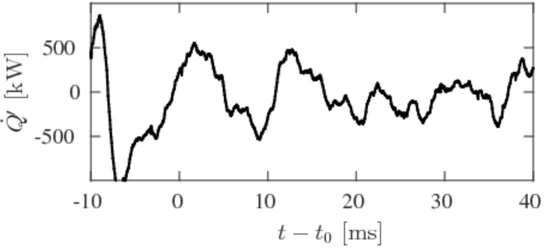


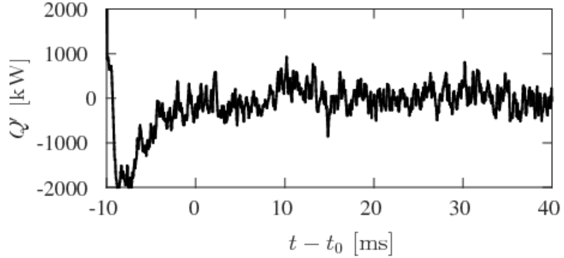


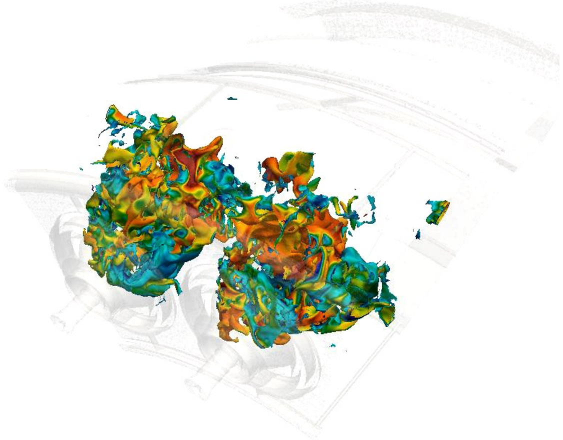
[A. Soli et al., J. Gas Turb. Propul. Power, 2022]

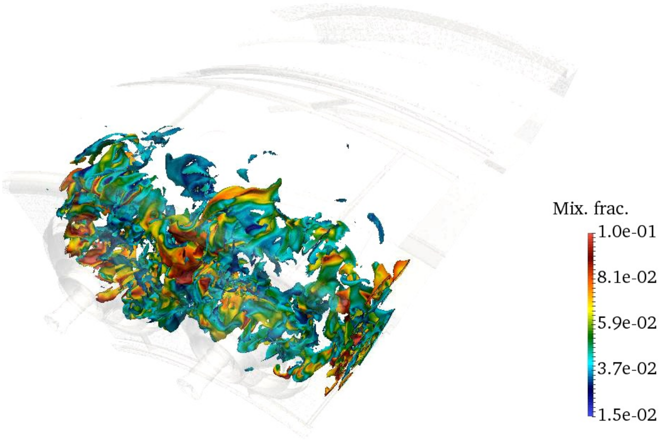
Lean Premixed Technology

Sector-sector interaction



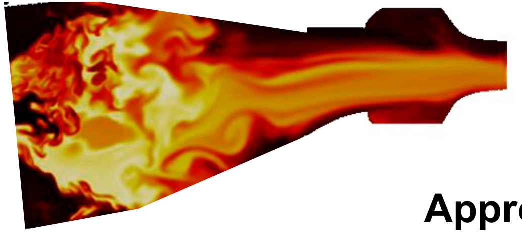




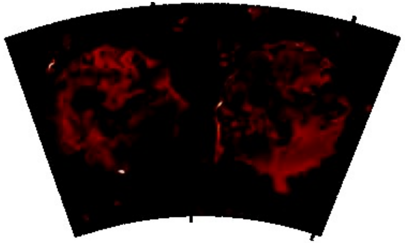


Sector-sector analysis

Sector-sector interaction

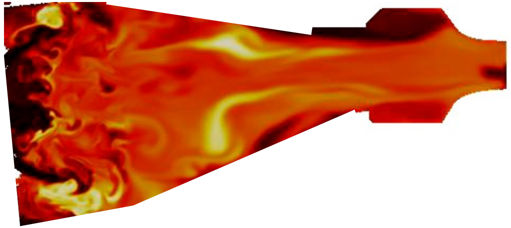


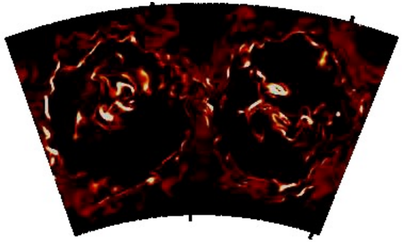
Approach



T

Heat Release Rate [MW/m^3]





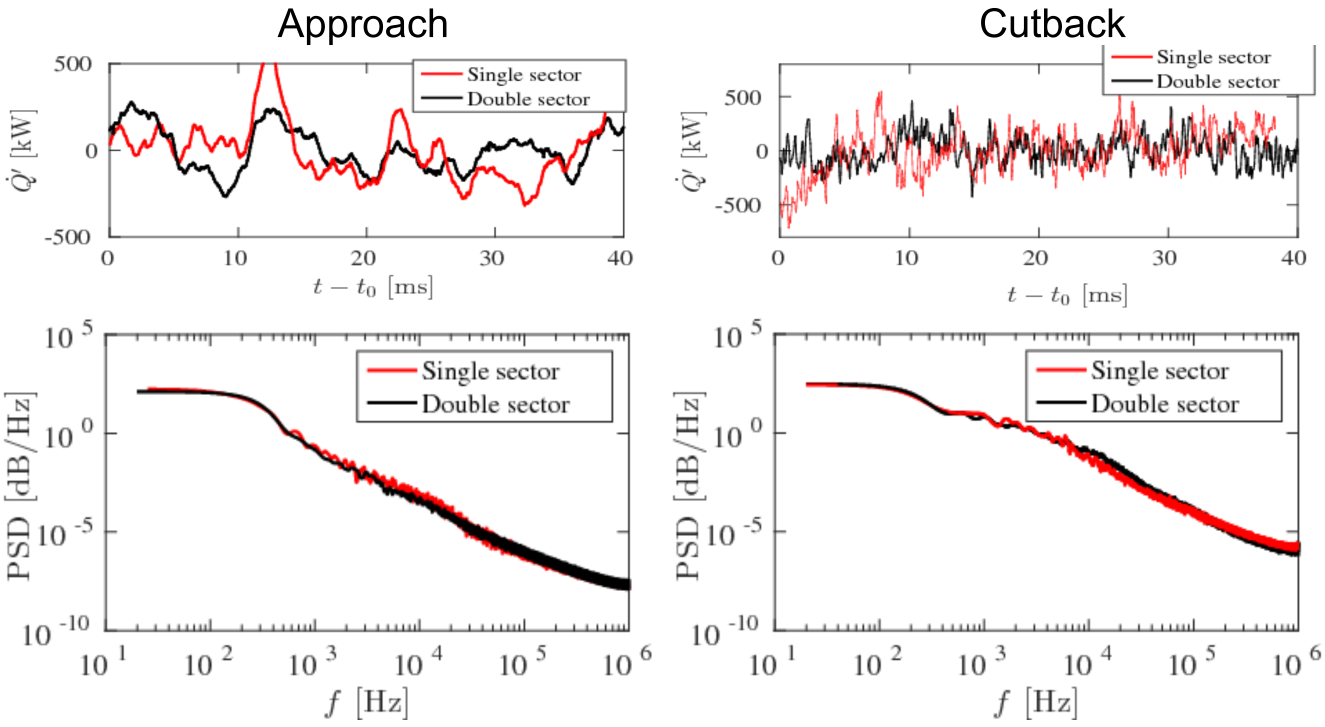
T

Heat Release Rate [MW/m^3]

Cutback

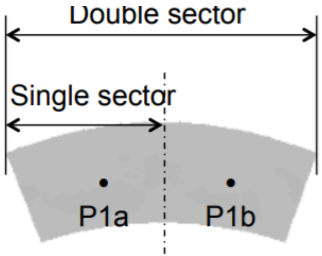
Thermoacoustic analysis

RR ALECSys combustor – Single and Double sector

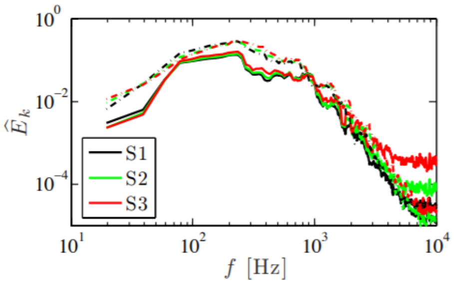


Thermoacoustic analysis

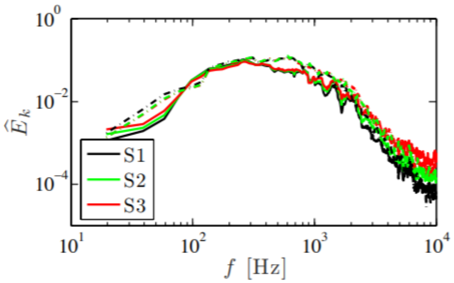
RR ALECSys combustor – Single and Double sector

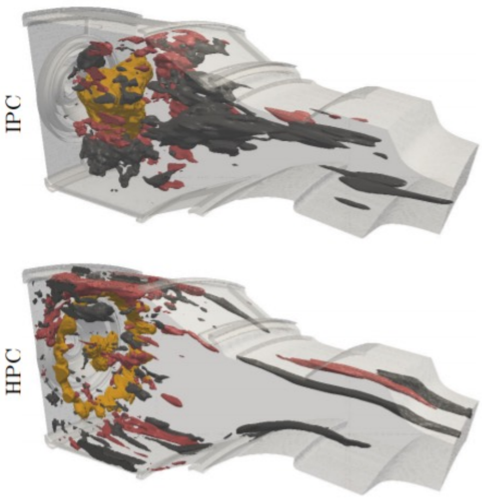


Approach



Cutback





- Axial vorticity is out-of-phase at the exit planes
- Entropy waves are generated mostly at wall (Cutback) and interface between lean main and pilot (Approach)
- Entropy and vorticity waves exhibit broadband and non-linear character → need 3D modelling

[Semilitsch *et al., J. Propu. Power 2019*]

TU Delft

UNIVERSITY OF CAMBRIDGE

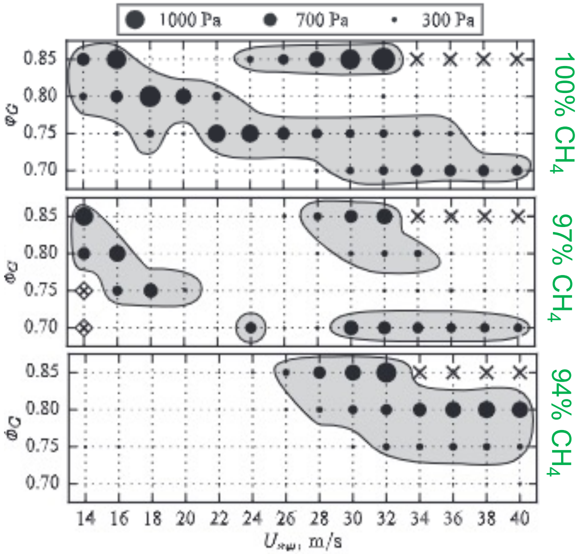
Combustion dynamics at high pressure

Hydrogen

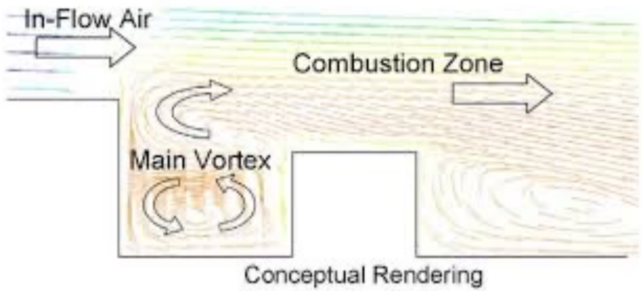
TU Delft

Combustion dynamics at high pressure

- Hydrogen introduces further challenges for modelling due to high speed, differential diffusion and small ignition delay time
- These in turn increase the risk of flashback
- The use of hydrogen might however have a beneficial effect for thermoacoustic instabilities
- **Lack of data especially at high pressure**



[Oztarlik *et al.*, CnF 214, 2020]



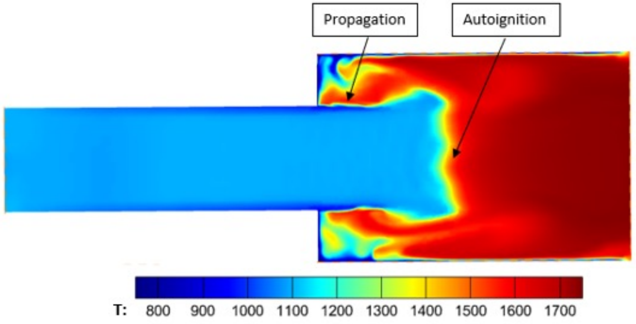
[Zhao *et al.*, Prog. Energy Combust. Sci 66, 2018]

TU Delft

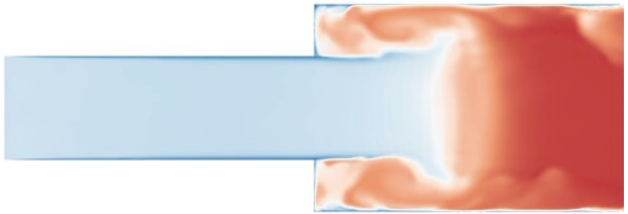
Combustion dynamics at high pressure

Reheat combustor

- Autoignition can play a major role especially at high pressure
- Pressure waves bounce in the domain following (auto)ignition and cause oscillation at low pressure. Ramping up eq. ratio stabilizes the flame.
- At high pressure this effect is stronger and not dampen out.



1 atm



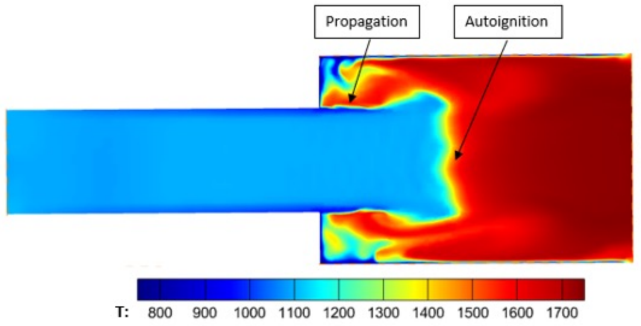
20 atm

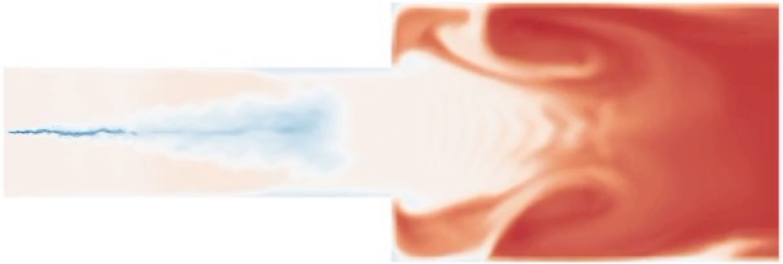
[A. Cabello Lopez, Dr B. Kruljevic]

Combustion dynamics at high pressure

Reheat combustor

- Potential use of **water injection**
- An auto-ignition assisted propagation regime can arise: need for improved models





[A. Cabello Lopez, Dr B. Kruljevic]

Summary

- In LES, the flamelet approach can still be robust in some conditions if attention is paid for SGS variance and SDR modelling
- Validation at high pressure unavoidably brings uncertainty. High-fidelity CFD is, however, very much needed due to lack of experimental data
- The coupling between flame and turbulent mixing can lead to instabilities also without thermoacoustic coupling, e.g. the CIVB
- Multi-component interaction and off-design conditions can lead to significant deviations in predictions of transient dynamics
- At high pressure the spray and evaporation properties can lead to strong changes in the combustion dynamics (kerosene)
- Pressure fluctuations may play a stronger role in the hydrogen case due to autoignition processes

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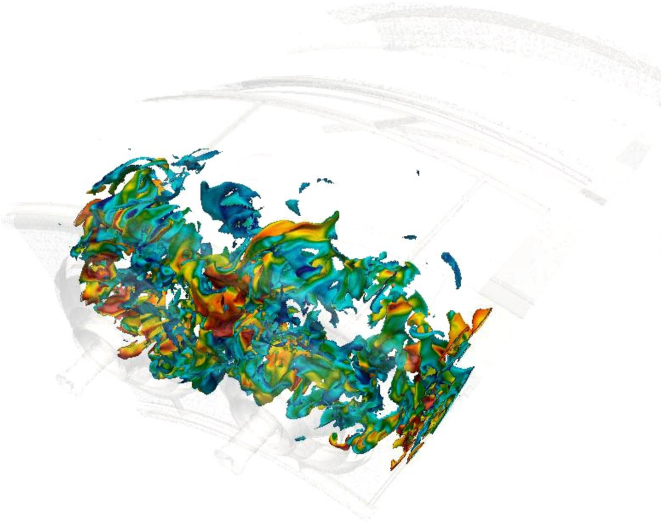
Thank you for your attention



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