CFD for aero-engine combustor design

An introduction

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What is it?

CFD

stands for

Computational Fluid Dynamics

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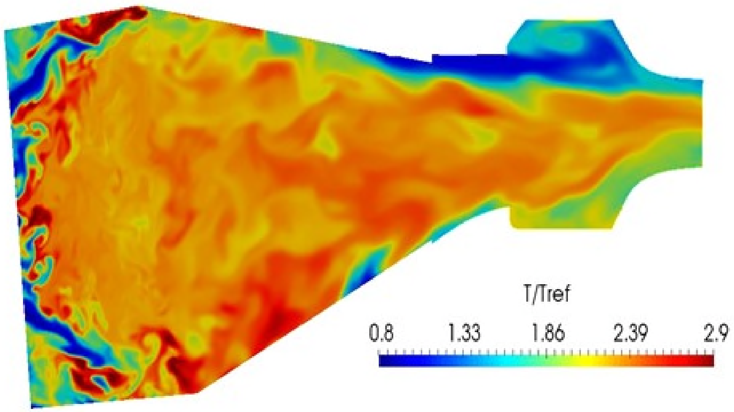
stands for

Computational Fluid Dynamics

or

Colourful Fluid Dynamics



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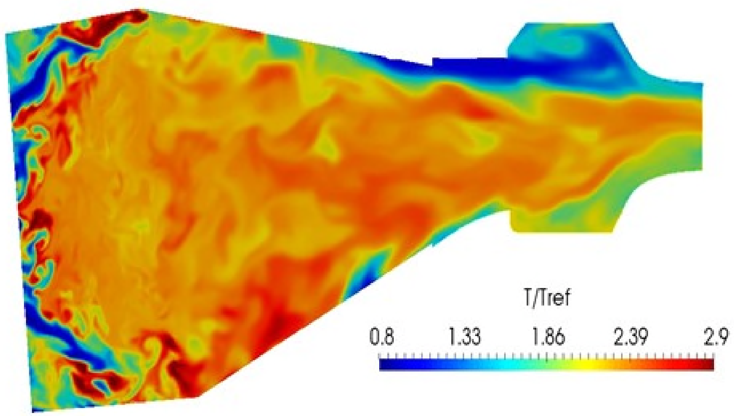


or

Completely Fabricated Data?

Content

- The challenges of combustor CFD
- Aero-engine combustor requirements
- Combustion technology development
- External aerodynamics
- Temperature traverse
- Injector design
- Emissions trends (NOx, CO, UHC, soot)
- Metal temperature
- The role of spray modelling
- The role of combustion modelling
- Relight
- Thermo-acoustics
- Volcanic ash
- Summary
- Trends in combustion CFD

The challenges of combustor CFD

- No analytical solution has been found yet to the equations governing fluid dynamics (Navier-Stokes) for an arbitrary flow– one of the great unresolved problems of maths
- Numerical methods can be used to solve them (Computational as opposed to Theoretical and Experimental) using a discretisation approach (e.g. on a mesh)
- Combustion CFD is less mature than say Turbomachinery CFD:
  - Free shear
  - Unsteadiness
  - Multi-phase (e.g. gas, liquid and solid)
  - Reaction (e.g. emissions redictions)
  - Radiation
  - Complex geometries
- Need for validation data to anchor simulations

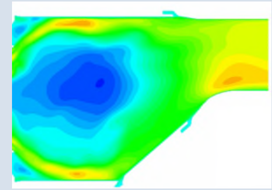
Aero-engine combustor requirements

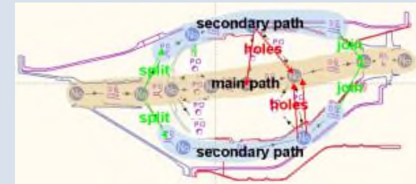
- High combustion efficiency (fuel completely burned to obtain maximum heat release)
- Reliable ignition, both on the ground and at altitude
- Wide stability limits (flame should stay alight over wide ranges of pressure, velocity, afr)
- Quiet thermo-acoustics (negligible coupling between acoustics and unsteady heat release)
- Low pressure loss (main cycle parameter)
- Gas temperature outlet profile maximizing turbine life and performance (both 1D and 2D profiles)
- Low emission of NOx, CO, UHC, smoke
- Minimum cost, maximum maintainability
- Size and shape compatible with engine envelope
- Light
- Durability
- Multi-fuel capability (especially for industrial combustors)

Combustor Technology Development

TRL

Low order modelling & CFD





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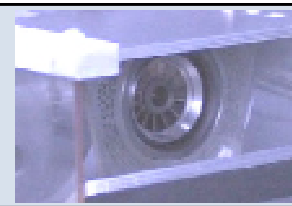
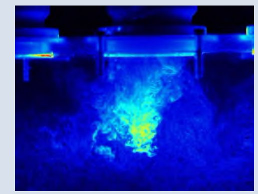
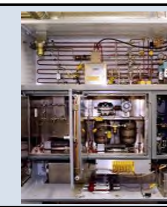
LP combustion, spray diagnostics, aerodynamics and fuel stability.







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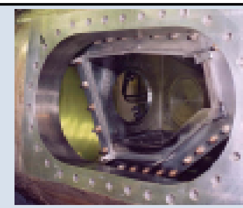
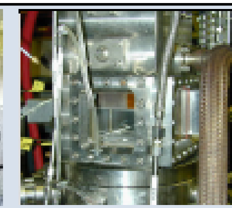
2 sector sub-atmospheric & HP Single Sector





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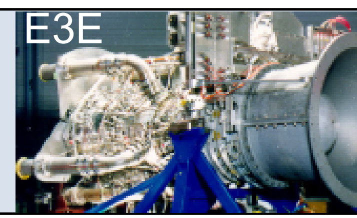
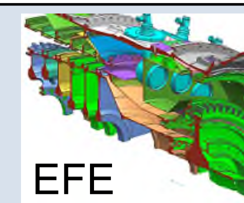
HP and sub-atmospheric annular & HP multisector

5

Engine Demonstrators





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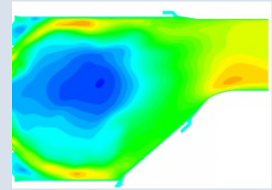

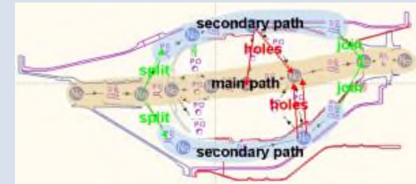

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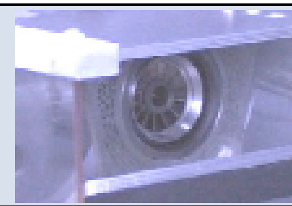

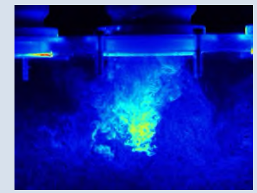

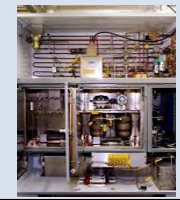

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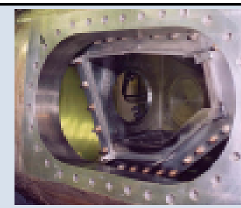

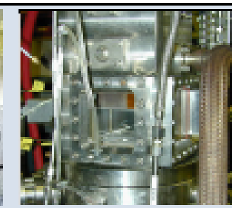

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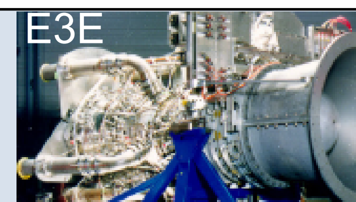

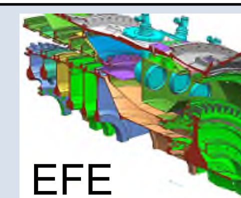

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Combustor Technology Development

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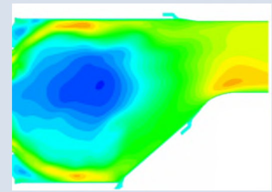
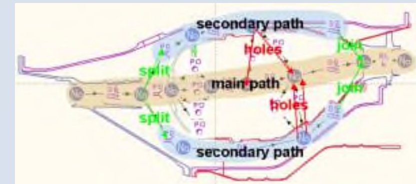
Low order modelling & CFD





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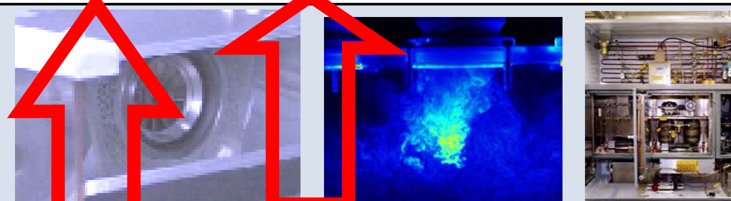

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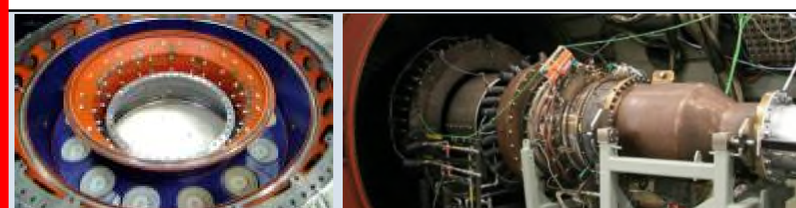

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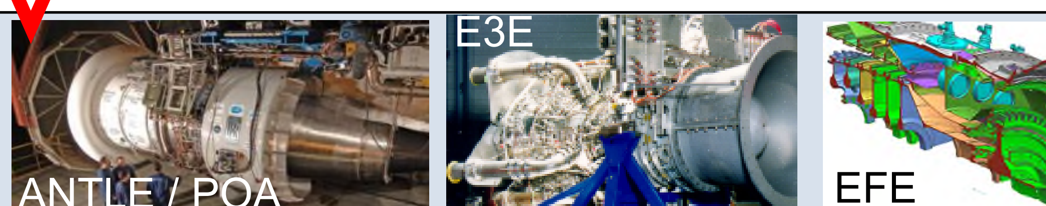

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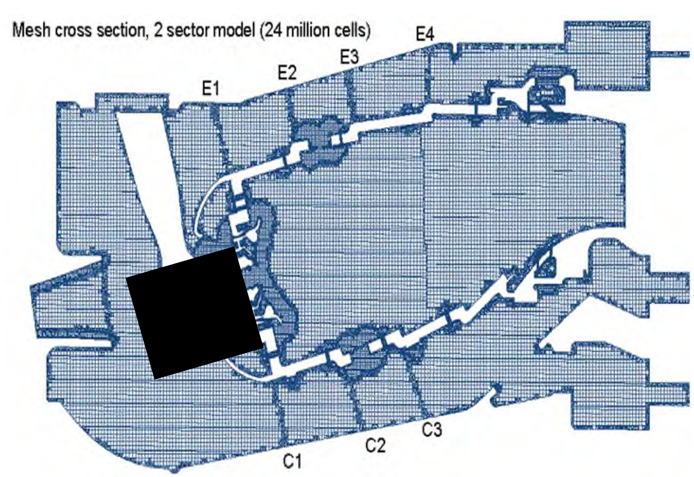
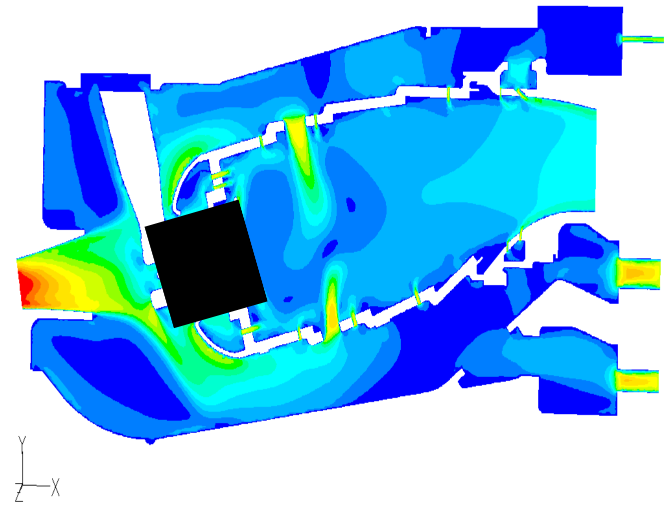
Introduction to combustion CFD for design

- Aero-engine combustor development is still dominated by rig testing
- However, CFD is now an integral part of the design and verification process, to support and complement rig and engine testing
- CFD is routinely used for assessing:
  - External aerodynamics
  - Temperature traverse
  - Injector design
  - Emissions trends (NOx, CO, UHC, soot)
  - Metal temperature
- CFD is also used to investigate more other phenomena:
  - Relight/extinction
  - Thermo-acoustics
  - Fuel coking
  - Tolerance to volcanic ash
  - ….
- For both established designs (i.e. rich burn) and novel concept (i.e. lean burn)
- For both main combustors and afterburners

External aerodynamics



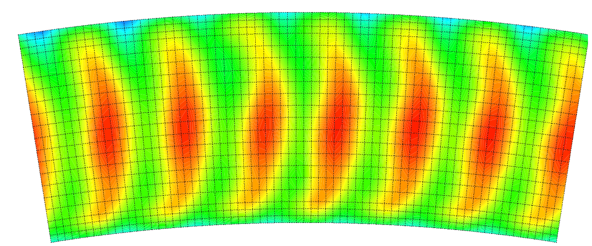
mesh



velocity magnitude

- •OGV exit velocity profiles from measurements
- •OGV exit turbulence profiles from Compressor CFD
- •Bleed flow splits from measurements
- • Atmospheric conditions
- •Steady RANS with realisable k-ε
- •~ 10 Million Hex dominant cells per sector
- •2nd order for all terms

measurements

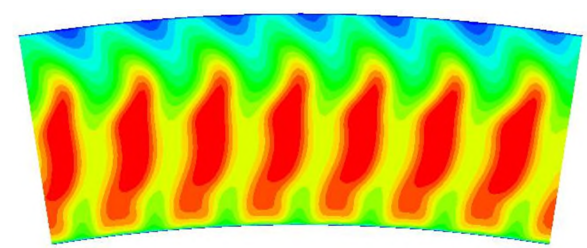


Non-dimensional velocity

1.500

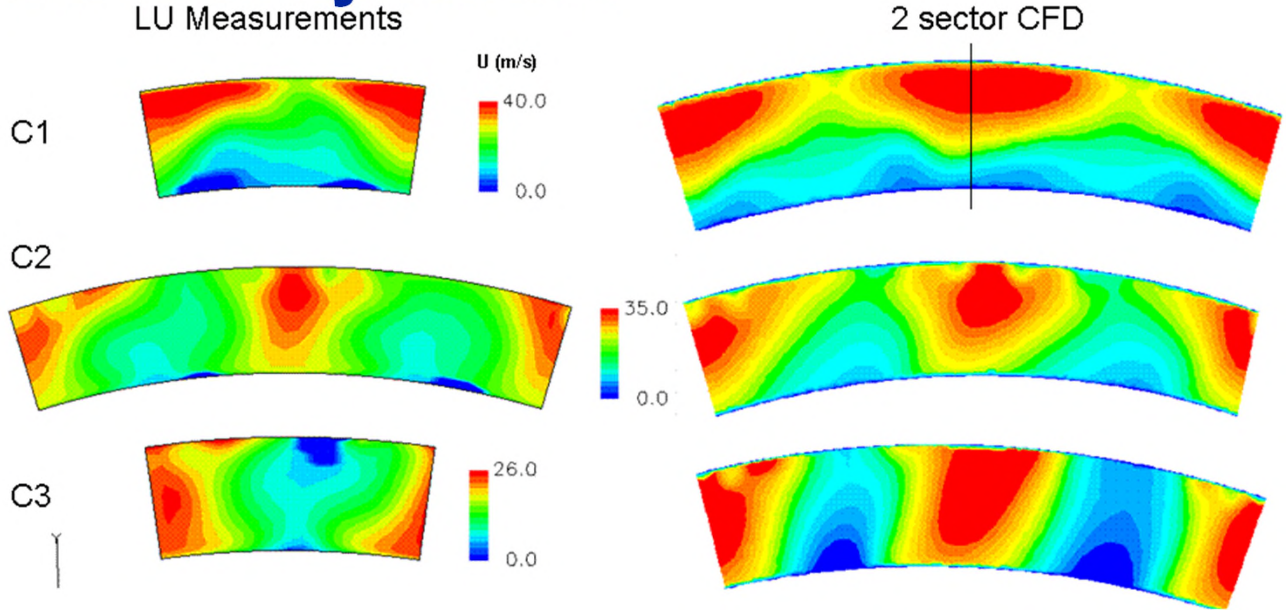
0.000

CFD



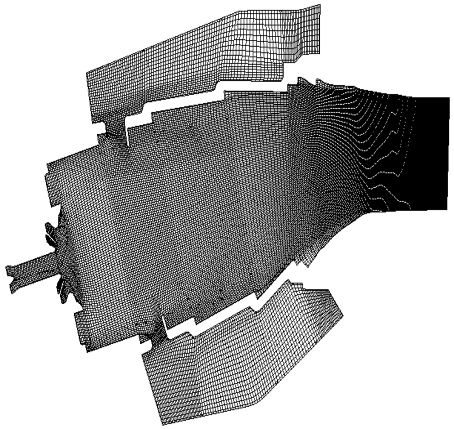
Prediffuser exit velocity

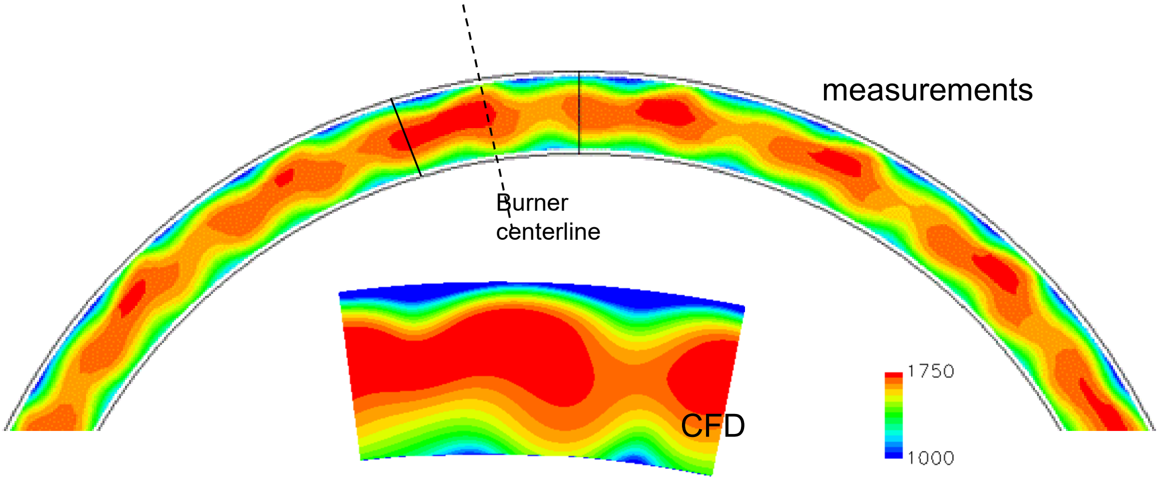
External aerodynamics



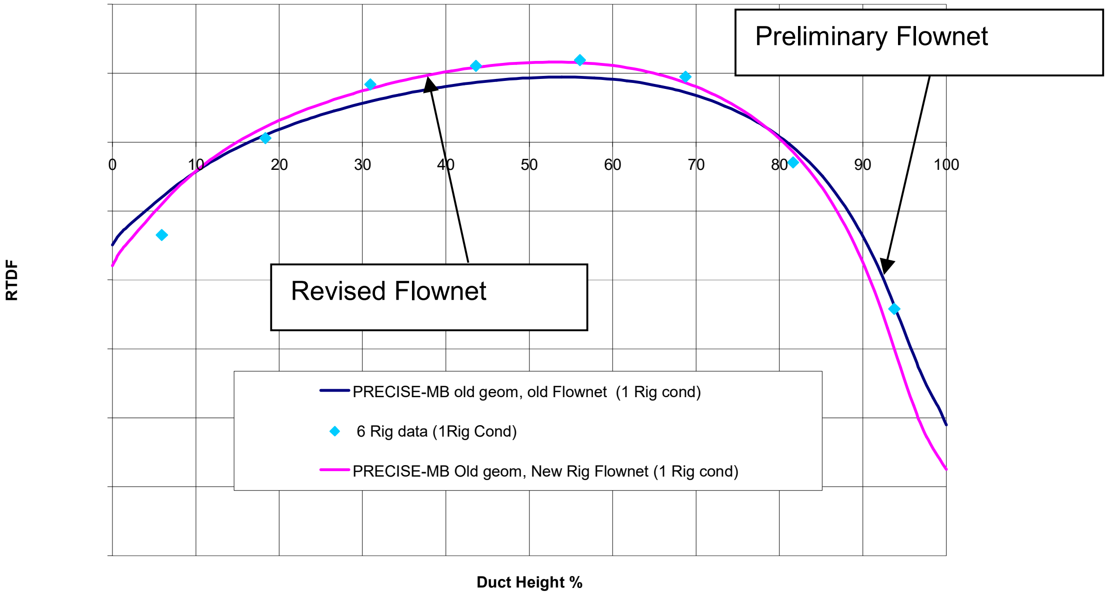
- General features of the aerodynamics are investigated
- Emphasis on feed to ports, injector and turbine flows
- Uncertainties affecting:
  - Geometry
  - Inlet profiles (time averaged and unsteady)
  - Cooling flows
  - Bleeds
  - Separations
- Full system model used to understand flow distribution and predict pressure losses
- Usually checked against detailed aerodynamics survey measurements

Temperature traverse

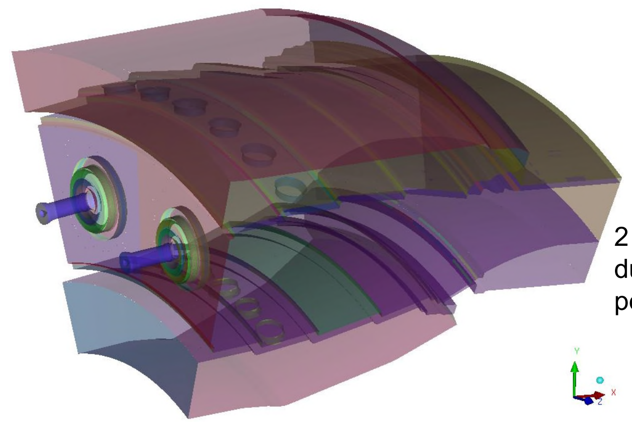




- Boundary conditions (2D profiles) from full system model and full annular isothermal test
- Realisable K-eps
- CSM with equilibrium chemistry
- Careful network modelling required
- RTDF and 2D map predicted reasonably well
- CFD used to predict and modify traverse

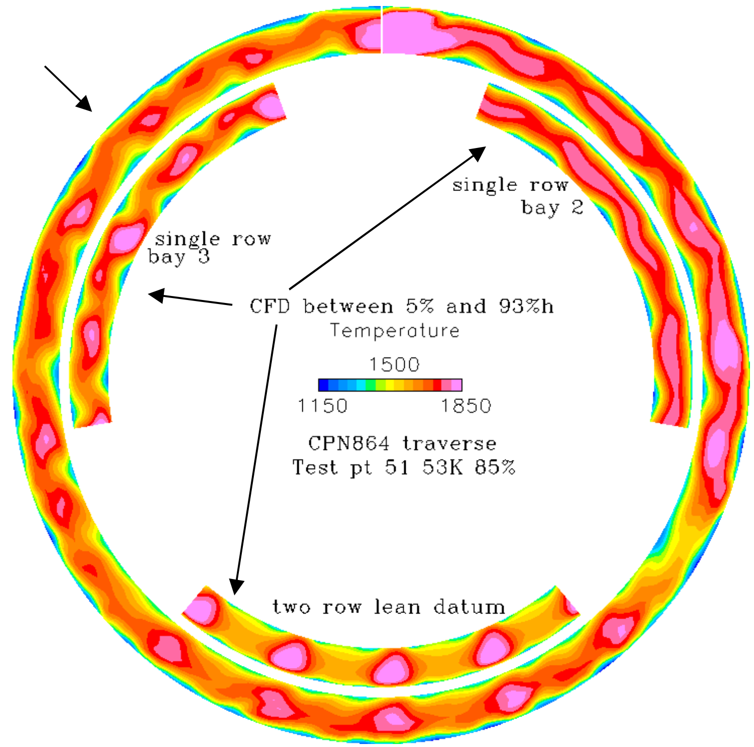


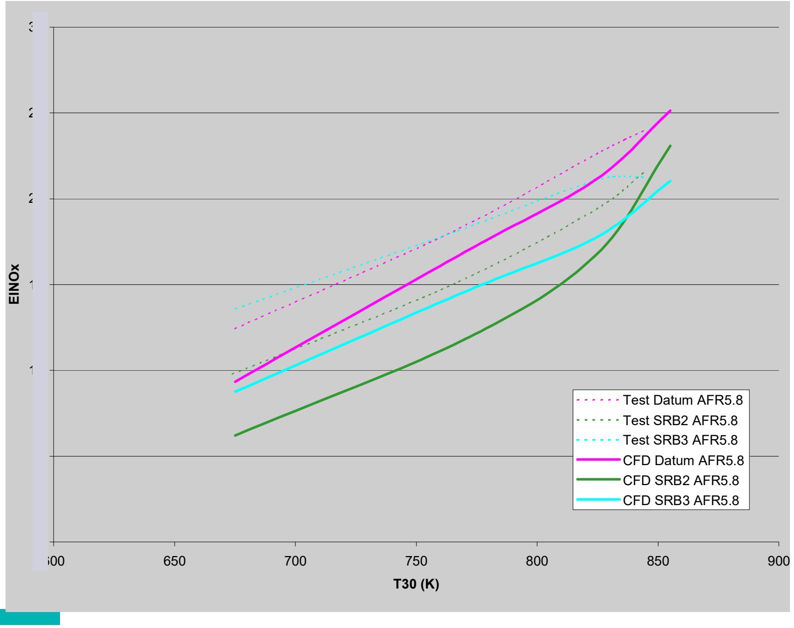
Emissions and traverse ranking



2 sector model
due to port
periodicity

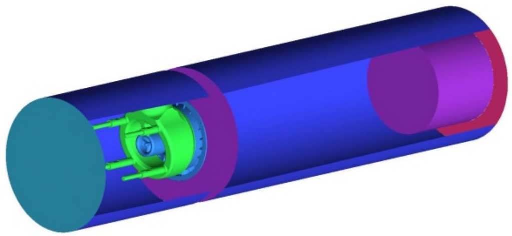
measurements





- RANS models used routinely to drive NOx down as long as prediction of DP/P and 2D T map is good
- DoE mapping

LES results – total velocity

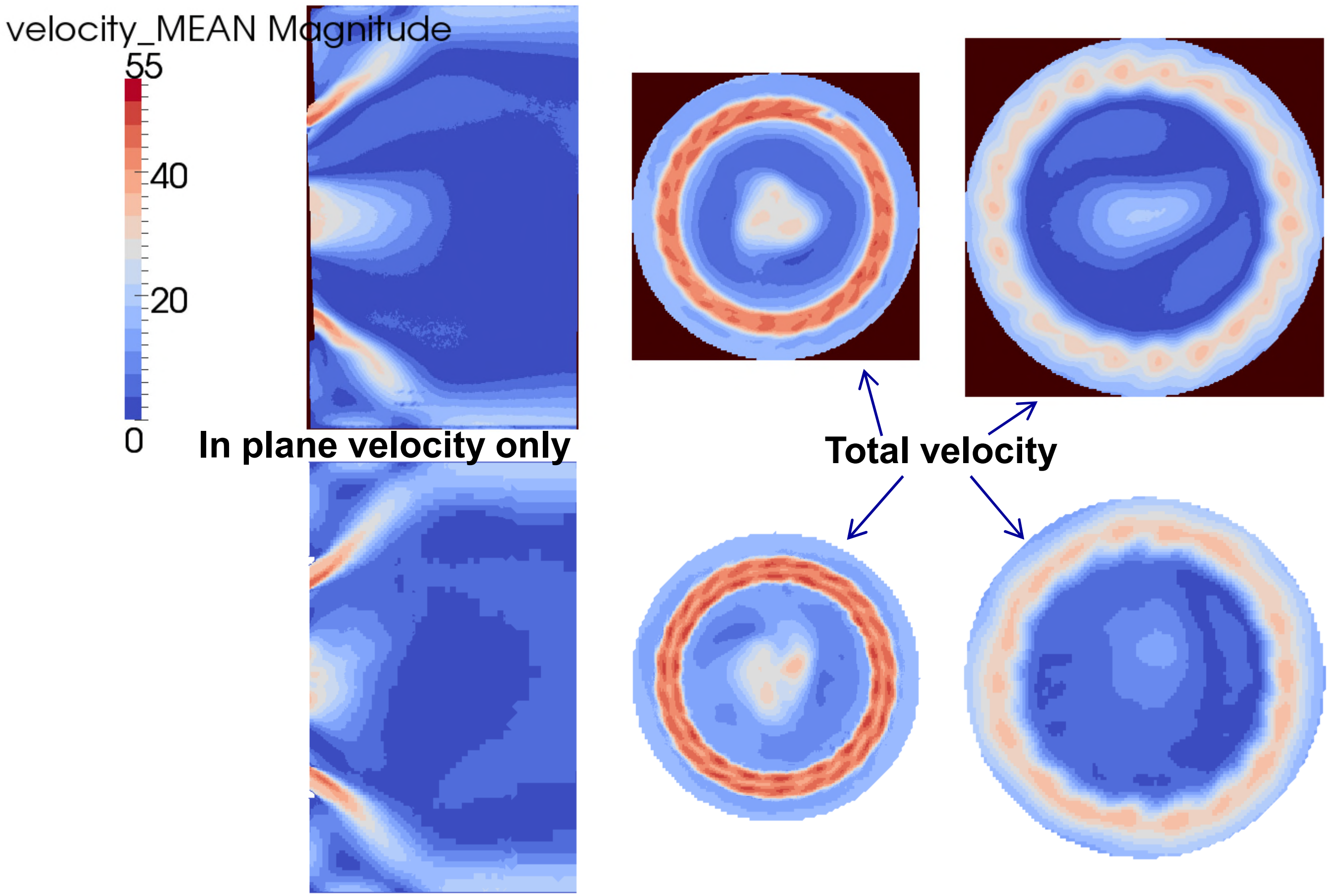


- LES or KE RNG for turbulence

2 cameras measurements | **3 cameras measurements**

PIV

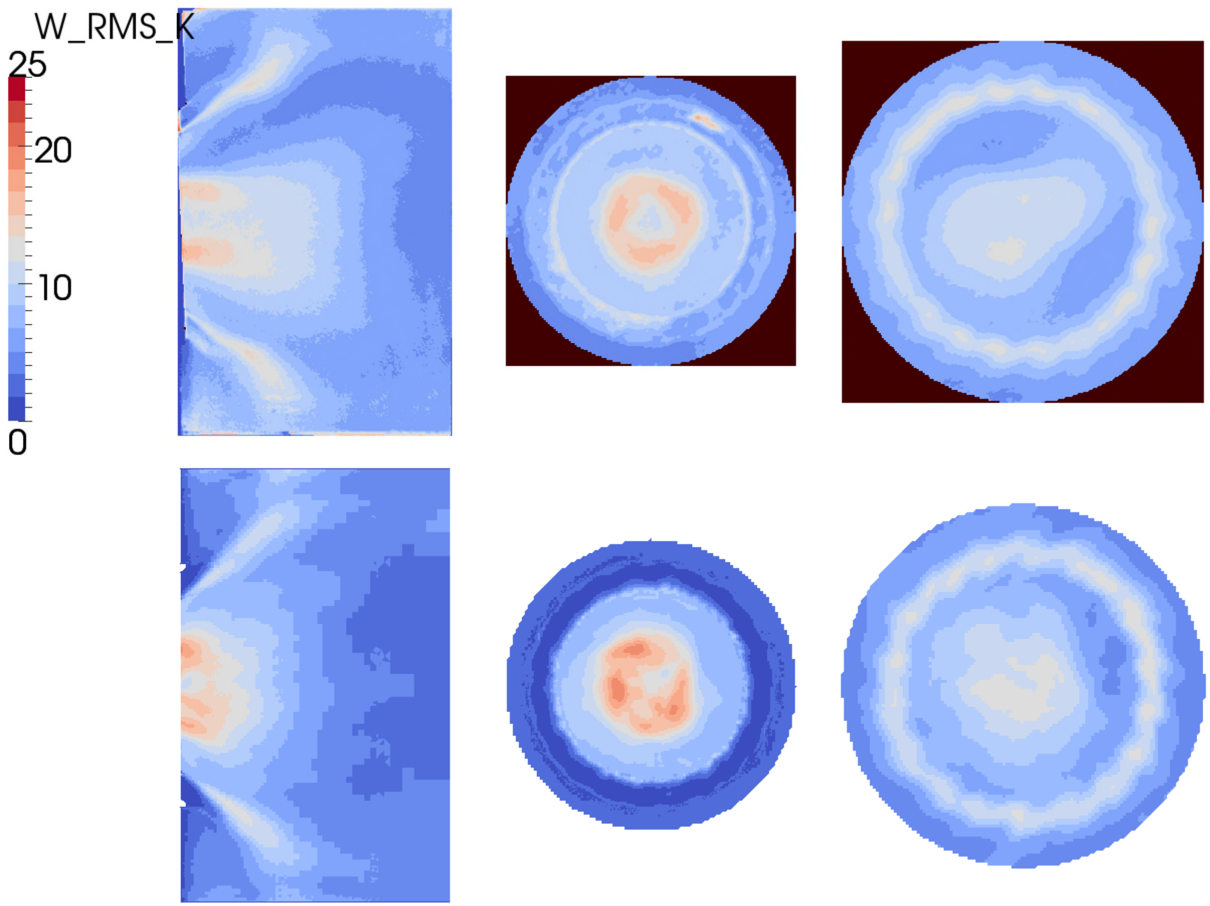
CFD



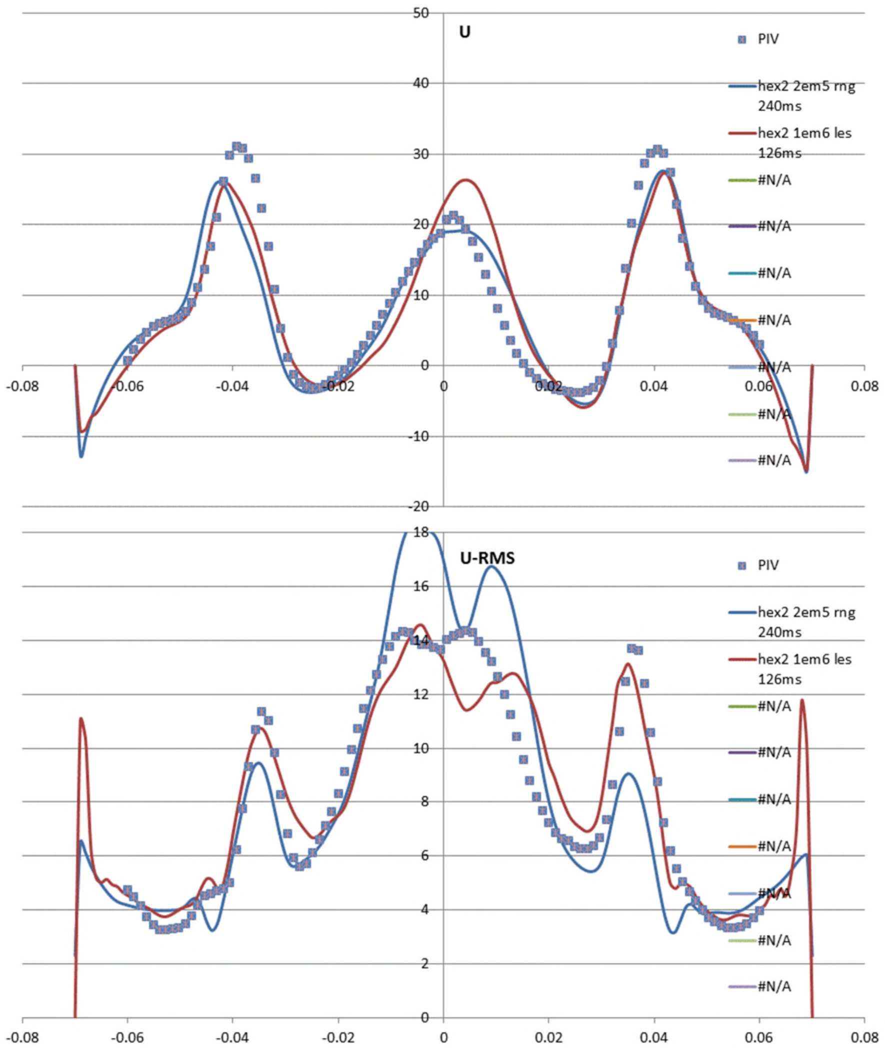
LES results – RMS of axial velocity

PIV

CFD



RANS vs LES for fuel injectors



- LES provides similar predictions to RNG k-eps
- The RMS is better predicted in the Mains region with LES

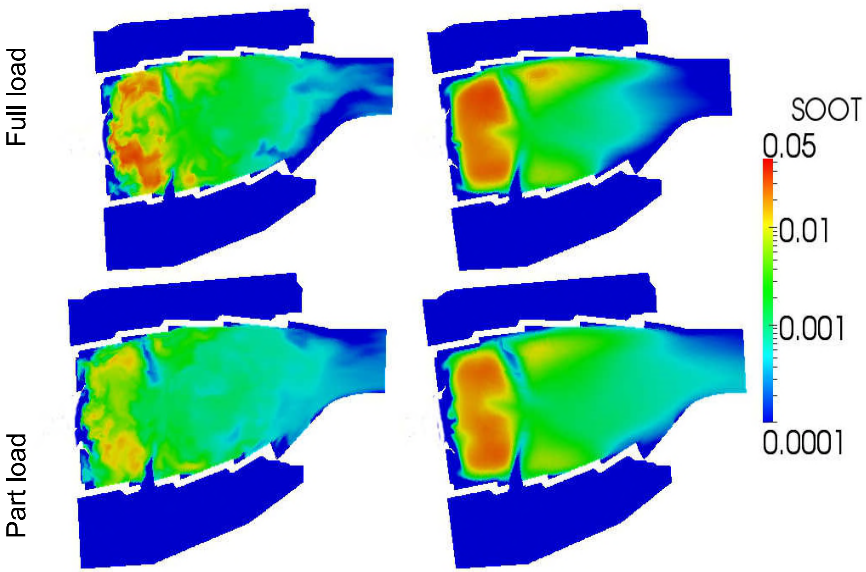
Soot trend prediction

- Standard 2-equation model used:

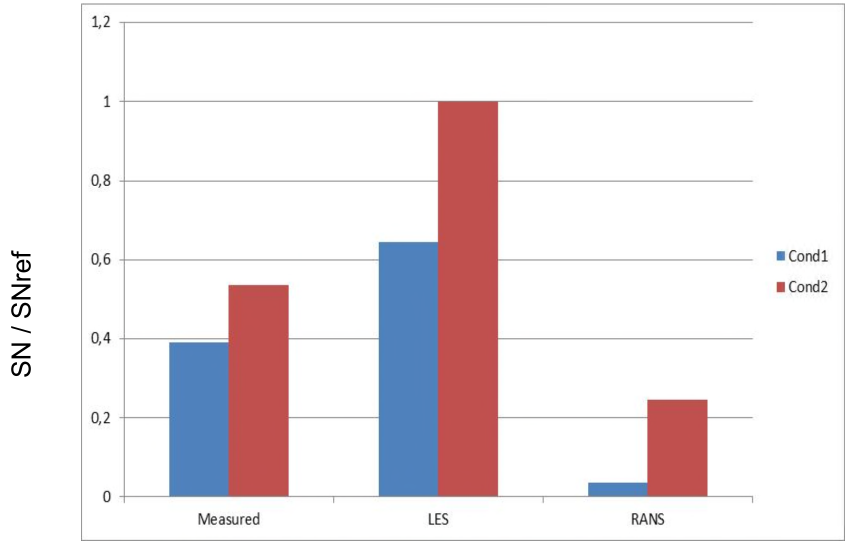
$$\bar{\rho}\frac{d(\tilde{N})}{dt} = \bar{\rho}\left(\tilde{R}_{nucl} - \tilde{R}_{coag}\tilde{N}^2\right)$$

$$\bar{\rho}\frac{d(\tilde{C}_m)}{dt} = \bar{\rho}\left(\tilde{R}_{sg}\tilde{N} + C_\delta \tilde{R}_{nucl} - \tilde{R}_{oxid}A\right)$$

- Flamelet Generated Manifold (FGM) combustion model
- Unsteady nature of soot production and oxidation better captured by LES

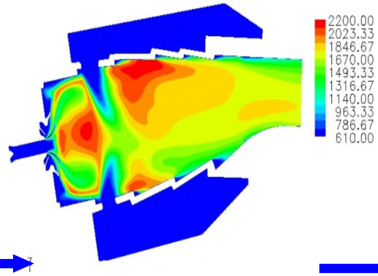


LES (instantaneous) RANS

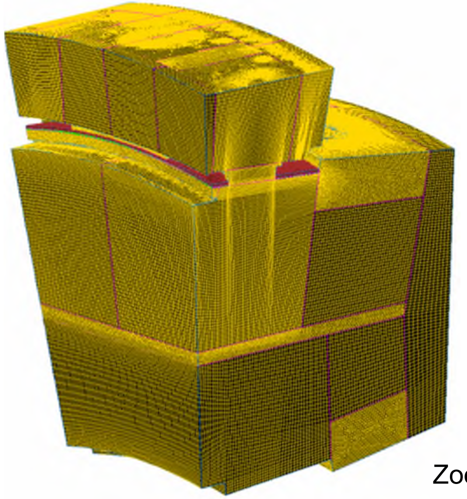


Metal temperature prediction

Tile lifing problem

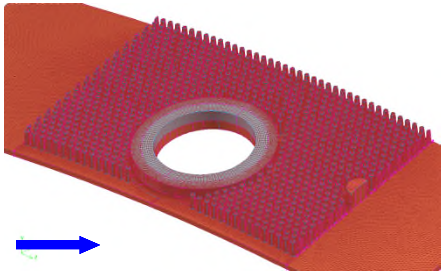


Reactive CFD (inclusive of soot and radiation by post-processing)

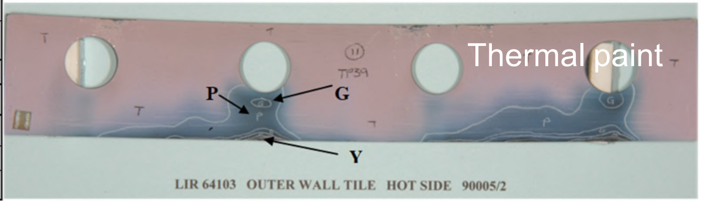


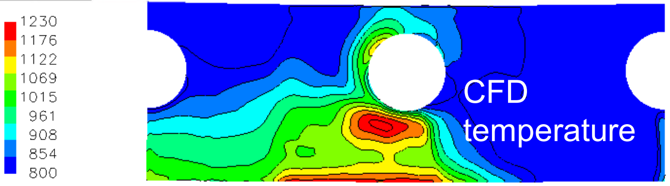
Zoomed-in CHT submodel

Explicit modelling of tile pedestals

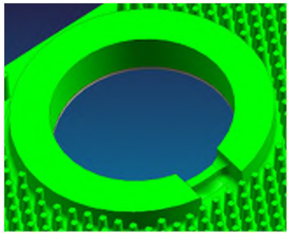


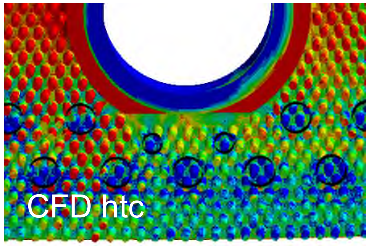
N	
T	Below 1130
P	1130
G	1180
M	1200
Y	1220
R	1240





Matching of datum's thermal paint

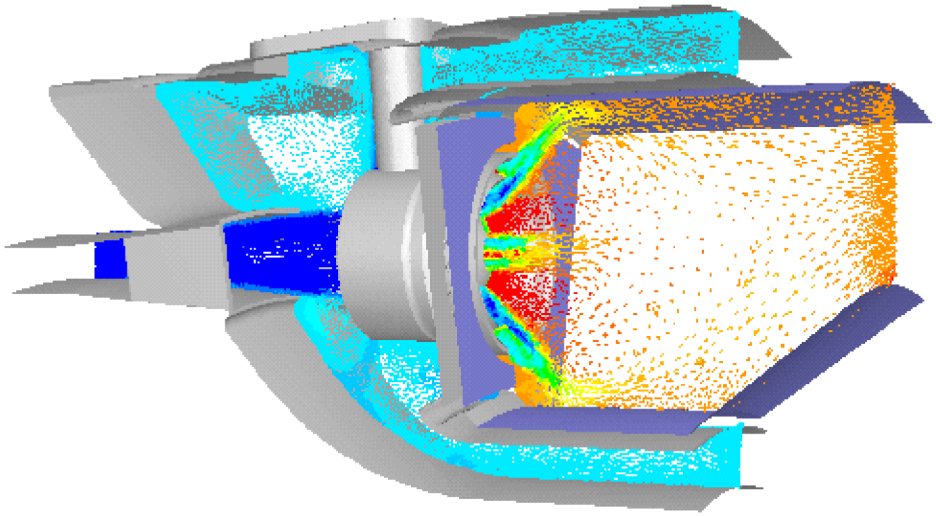




Analysis of range of design options

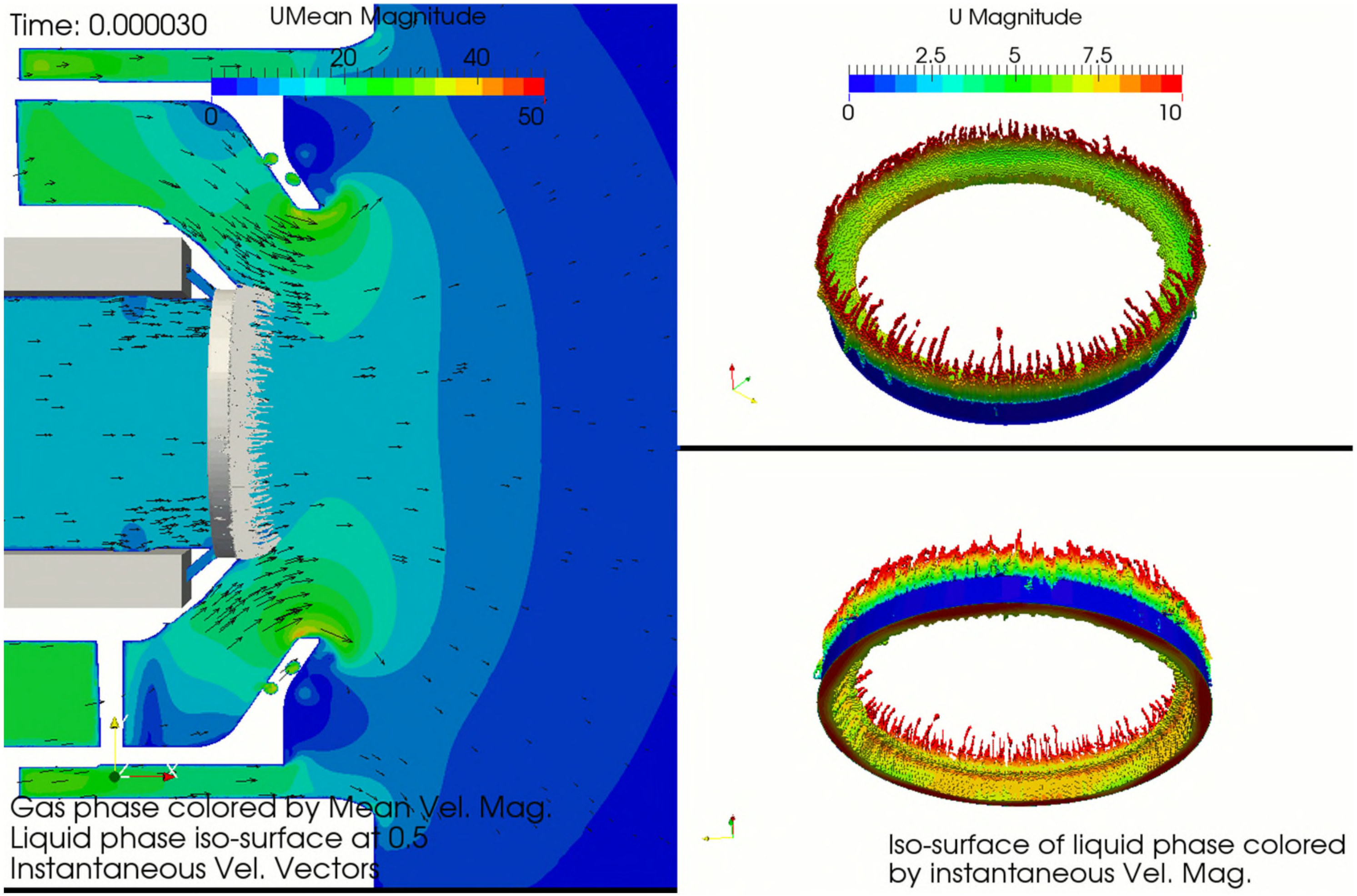
- <u>Redesign proved to hit target life via engine thermal paint</u>
- Metal temperature prediction still challenging (CFD difficult to tune), especially for primary zone

Role of spray modelling



- Fuel preparation can affect:
  - emissions (NOx, CO, UHC, soot)
  - temperature traverse
  - relight capability
  - rumble
  - metal temperature
  - weak extinction
- Sensitivities can be different for different parameters/combustors (e.g. rich vs lean burn)
- Primary and secondary break up are complex time-dependent phenomena, influenced by turbulence intensity and lengthscale

Detailed modelling of primary break up

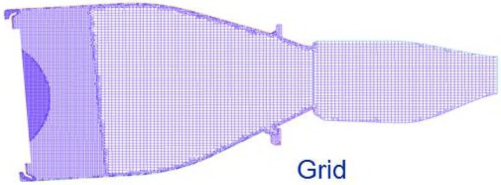


- Fuel placement can be studied in detail and impact the design of the fuel injector

The role of combustion modelling

- The choice of combustion model depends on the problem and required turn-around time
- Flamelet approaches are often used, especially to start with, as they are cheap to run
- In flamelet models, the chemistry is pre-tabulated and looked up at run time through a small number of parameters
- Some flamelet models have increased in sophistication: enthalpy, mixture fraction and progress variable and their variances are used in the Flamelet Generated Manifold approach (FGM)
- Finite rate chemistry approaches (i.e. chemistry calculated on the fly) have the advantage of accounting for the different timescales of reaction steps, but are more expensive computationally
- Conditional Moment Closure (CMC) used for diffusion flames (e.g. relight)
- Stochastic fields model is being used as well. The approach assumes no prescribed way to link turbulence and chemistry

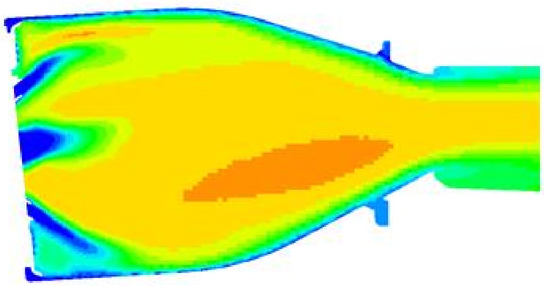
Modelling combustion for lean burn with LES

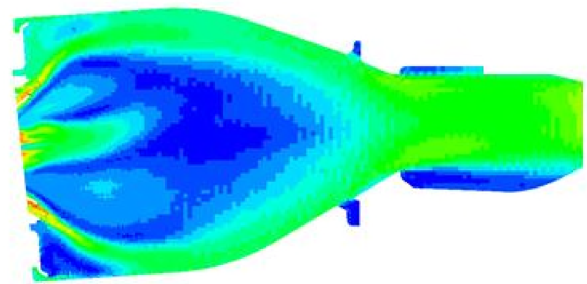


FGM

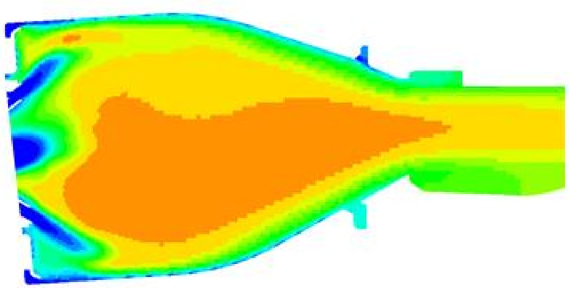
Time-averaged temperature

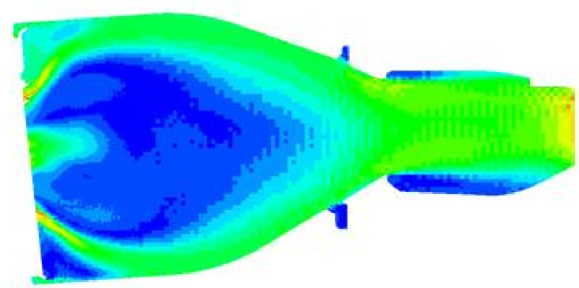
Time-averaged velocity magnitude





Stochastic fields
4 fields - dodecane chemistry

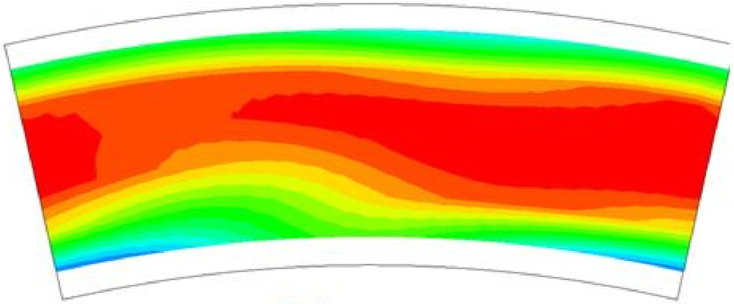




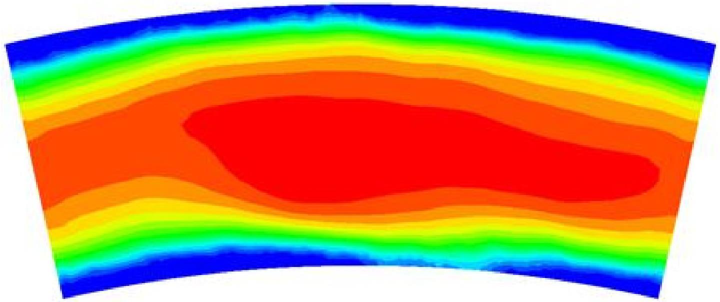
- Stochastic fields simulation much more expensive computationally (49 species transported)

Stochastic fields and FGM LES traverse

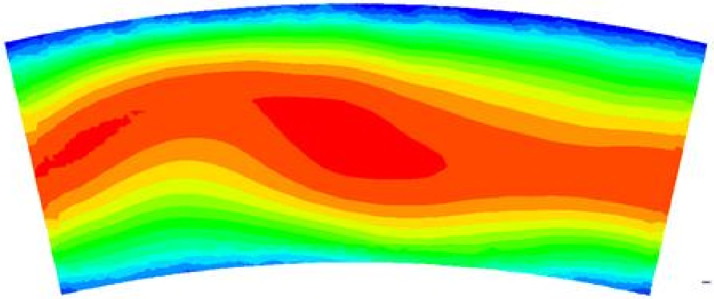
Temperature Distribution Factor



Test



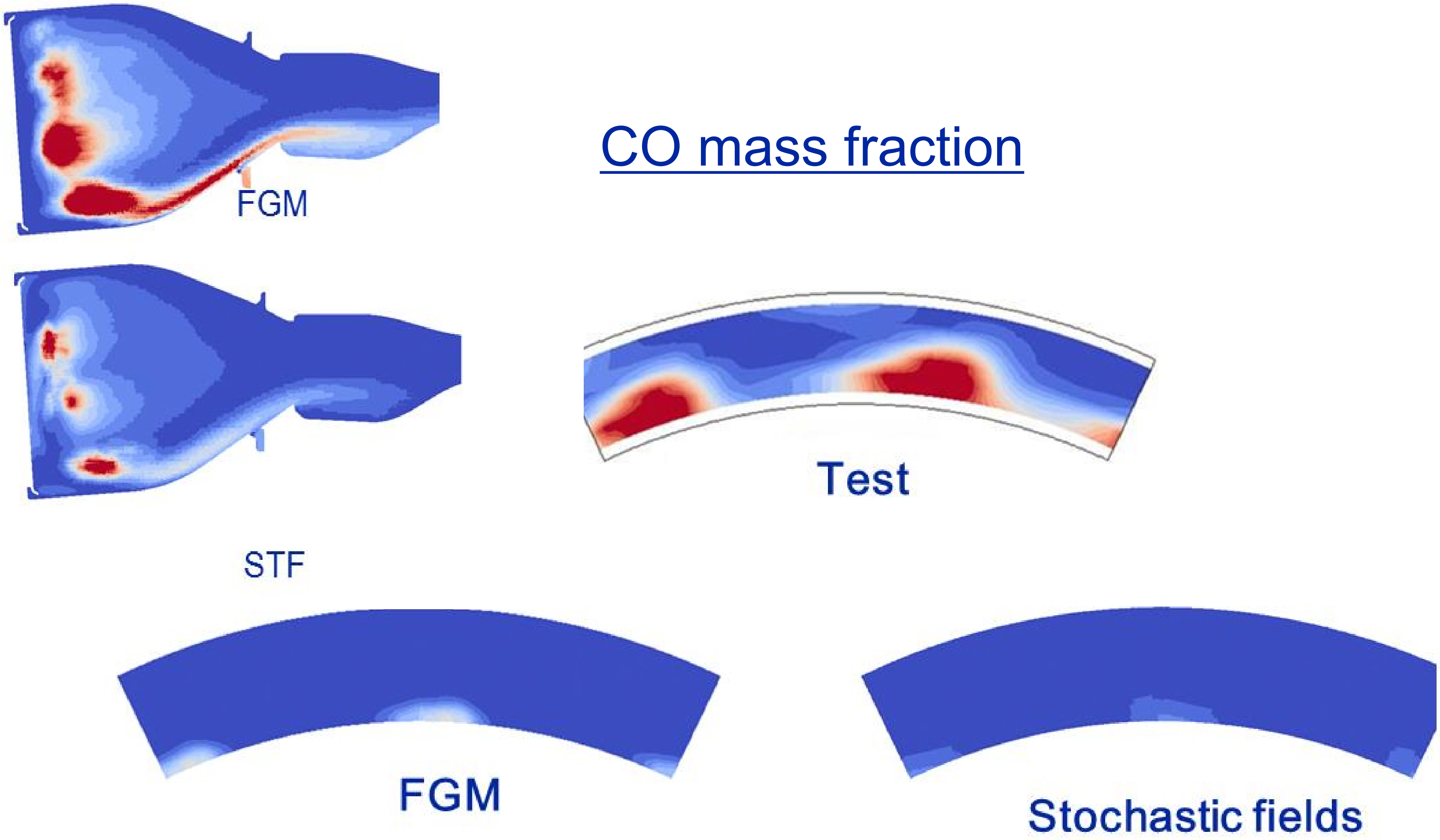
FGM



Stochastic fields

- Stochastic fields prediction slightly more accurate

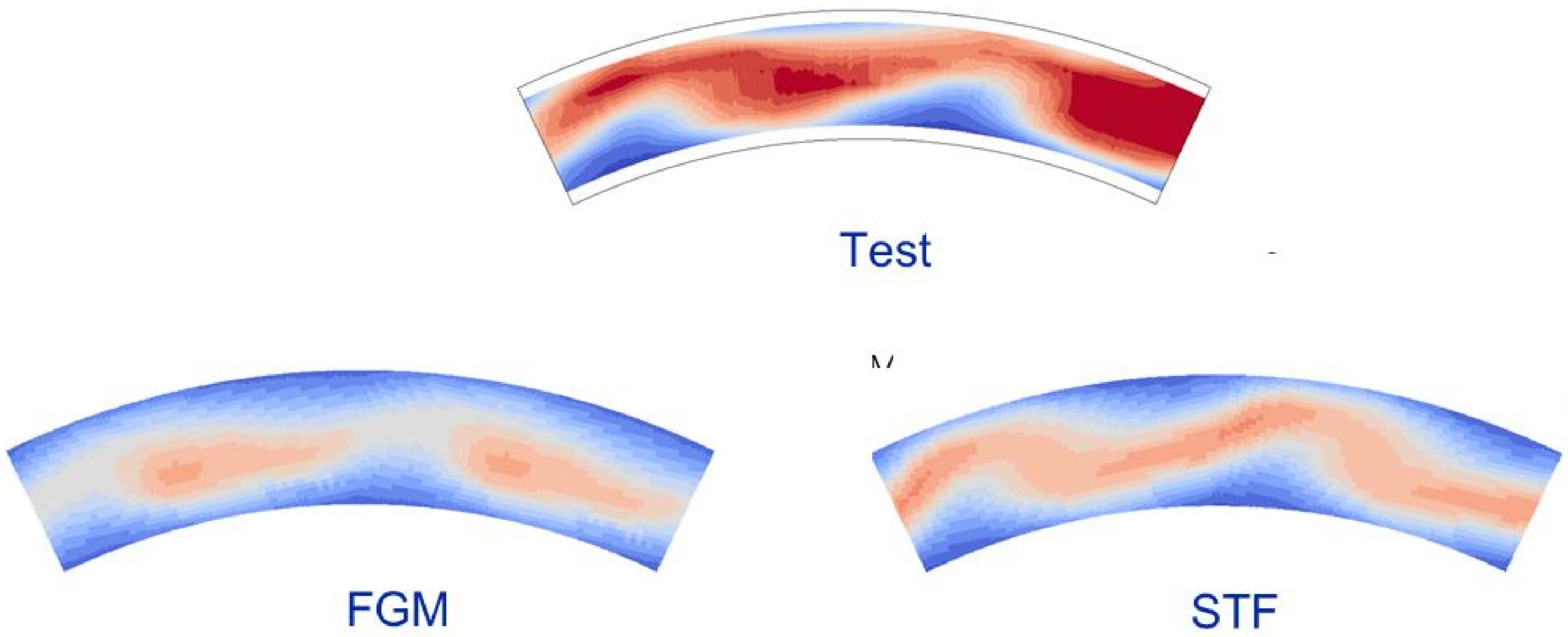
Stochastic fields and FGM LES CO



- Significant underprediction, similar maps produced by the two models

Stochastic fields and FGM LES NOx

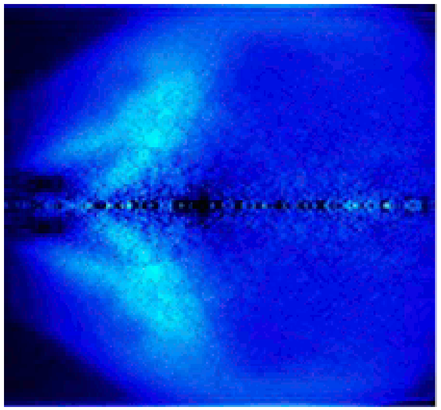
NOx mass fraction



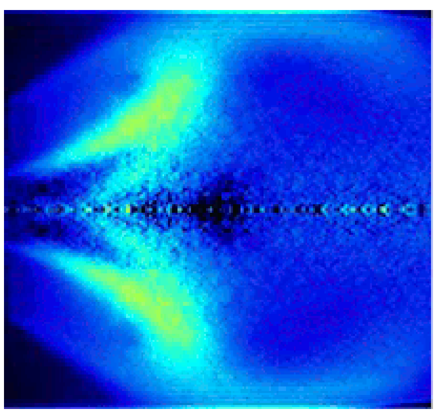
- Underprediction, 2D map predicted reasonably well, especially by the stochastic fields model

Relight

OH* chemiluminescence, Abel inverse

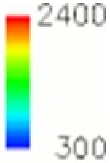


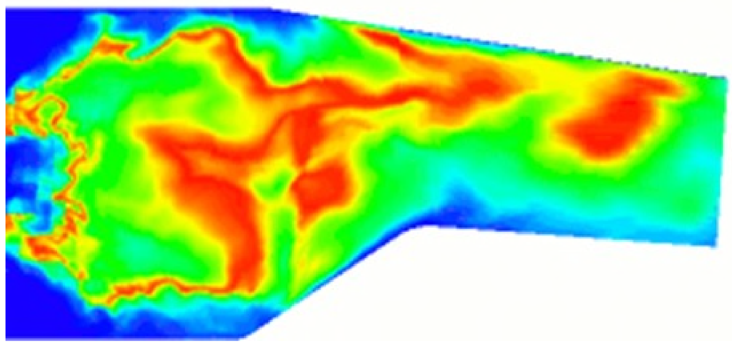
Q-air1, FAR 0.05



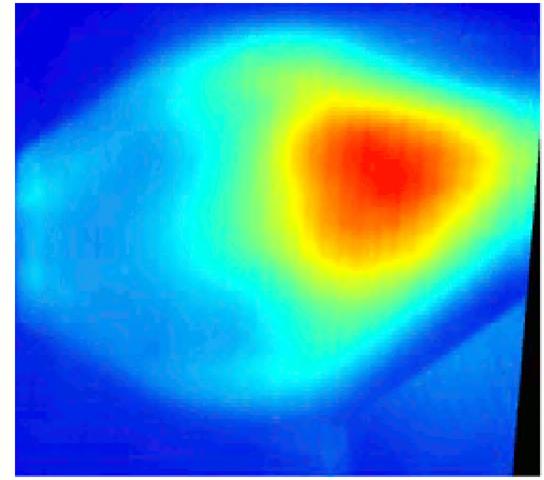
Q-air2, FAR 0.04

CMC model



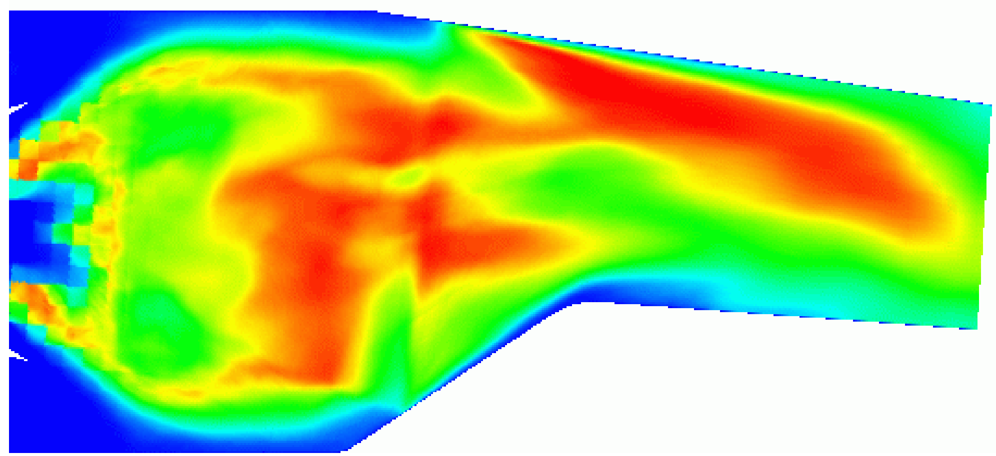


Time-resolved temperature



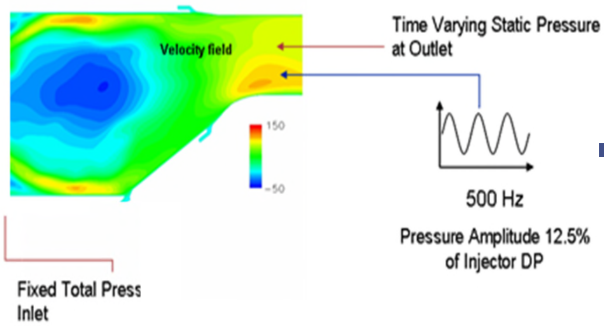
Flame luminosity

Time-averaged temperature



- Ignition mechanisms can be investigated

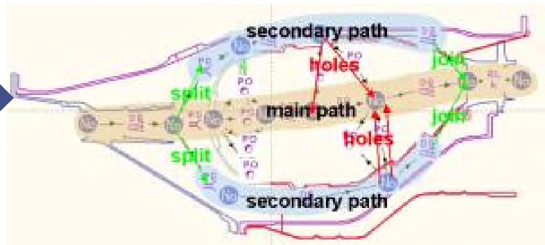
Thermo-acoustics



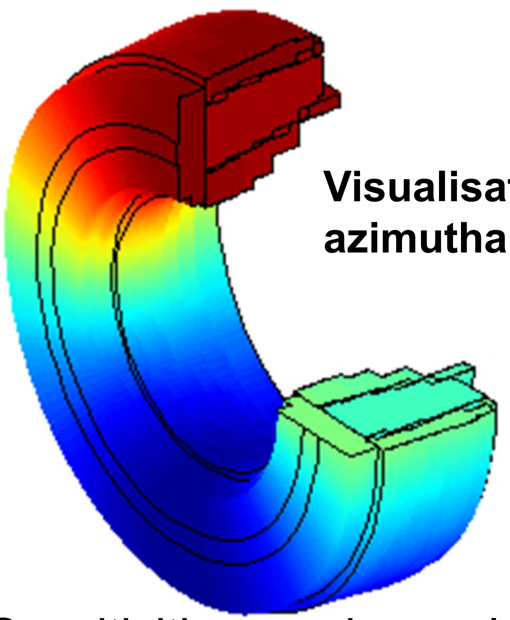
Forced CFD

$$\frac{\hat{Q}}{\bar{Q}} = T(\omega)\frac{\hat{m}}{\bar{m}}.$$

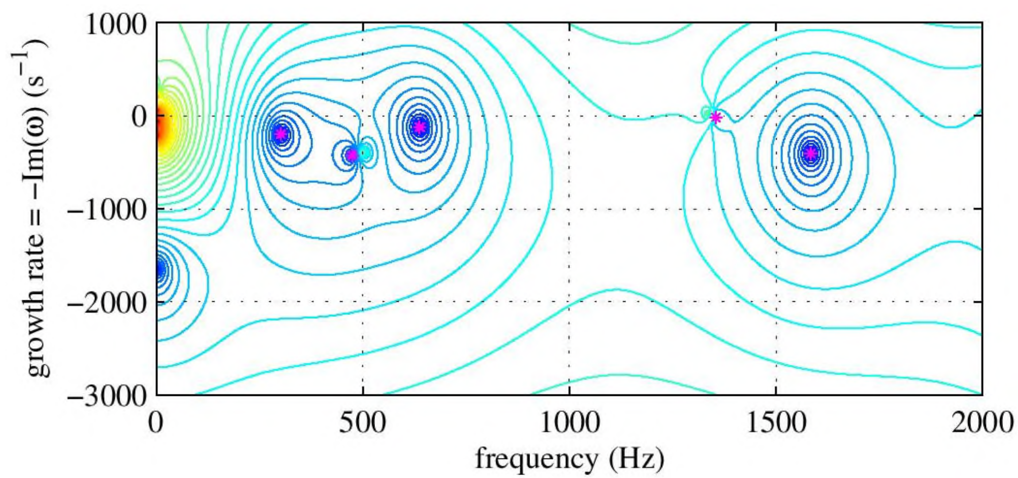
FTF



Low order modelling



Visualisation of azimuthal mode



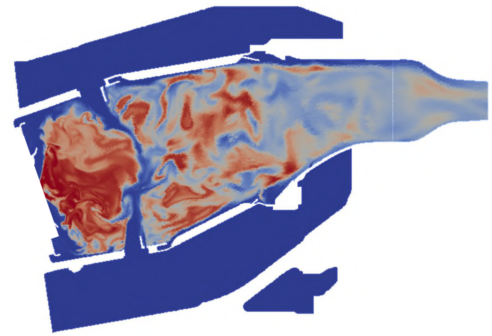
Mode instability analysis

- Sensitivities can be explored

Deriving LFR TFs from forced CFD

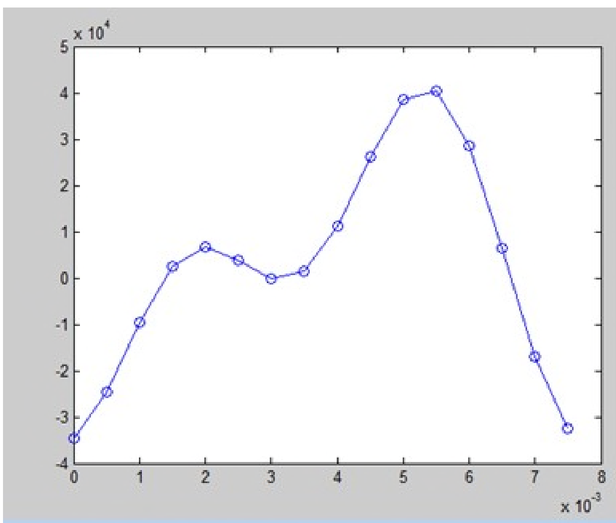
Inlet forcing (Input) → LES transfer function → Flame response (Output)

- Fuel is forced by step change
- Gain and phase of the FTF and TTF is computed and supplied to LOTAN



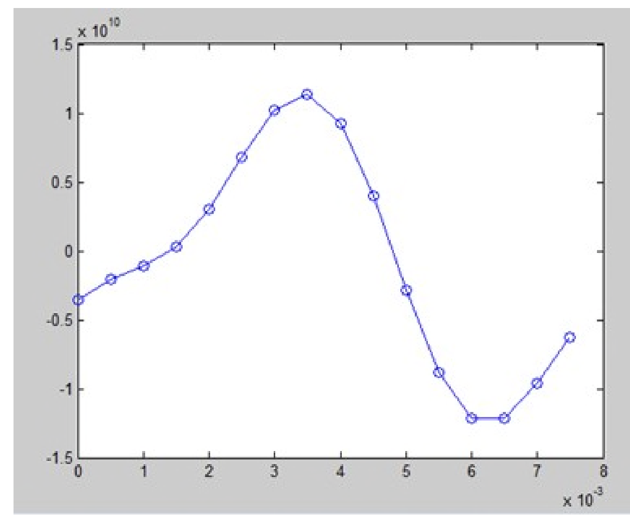
$$FTF(\omega) = \frac{\widehat{HR}_{volume}(\omega)}{\widehat{\dot{m}}_{fuel}(\omega)} \qquad TTF(\omega) = \frac{\hat{T}_{outlet}(\omega)}{\widehat{\dot{m}}_{fuel}(\omega)}$$

Outlet T



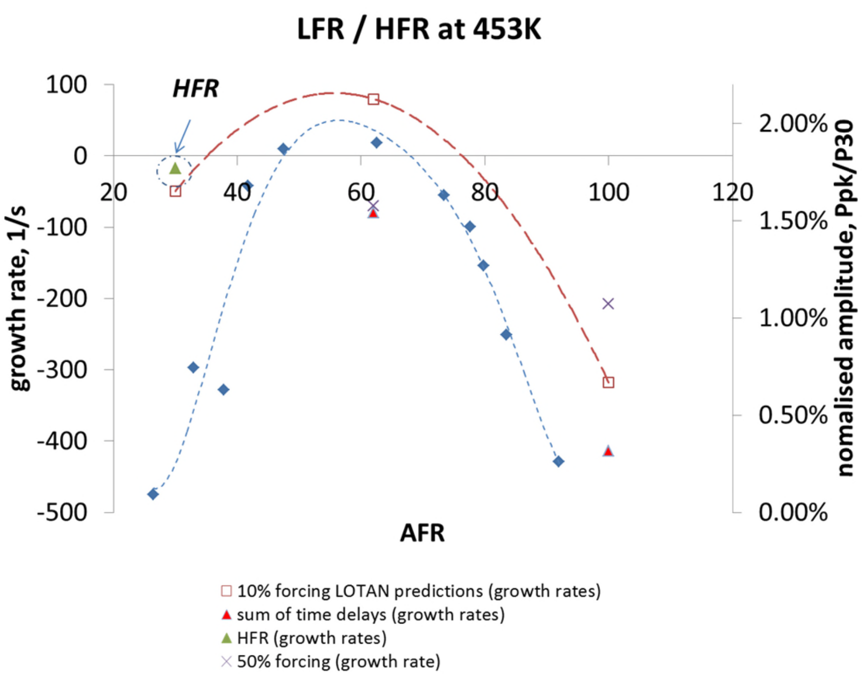
time

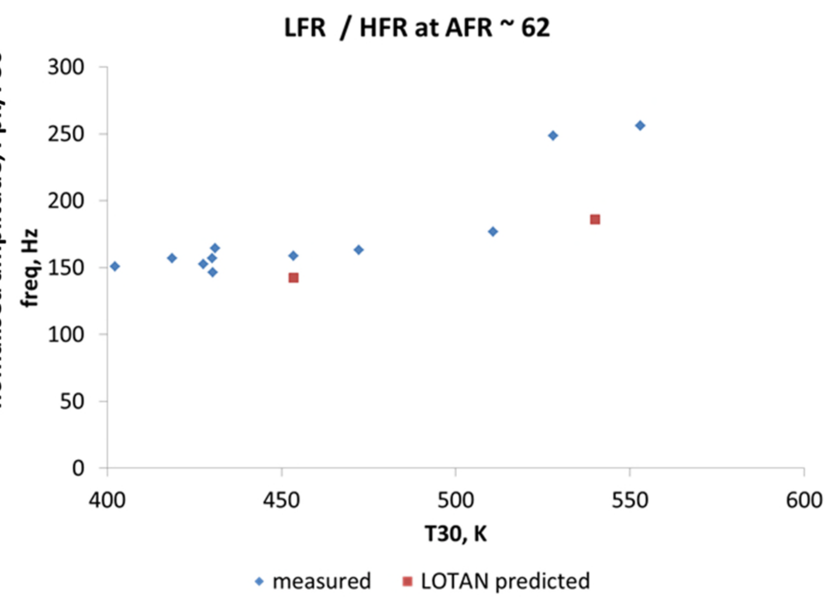
Heat release



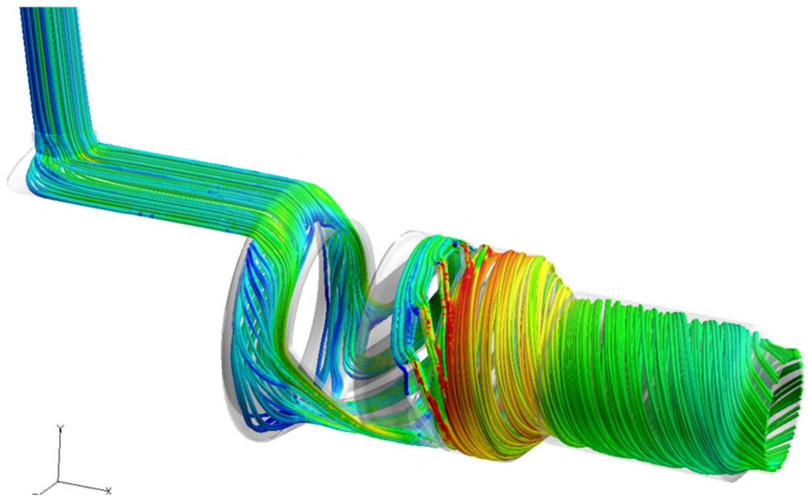
time

LOTAN predictions – growth rate and frequencies

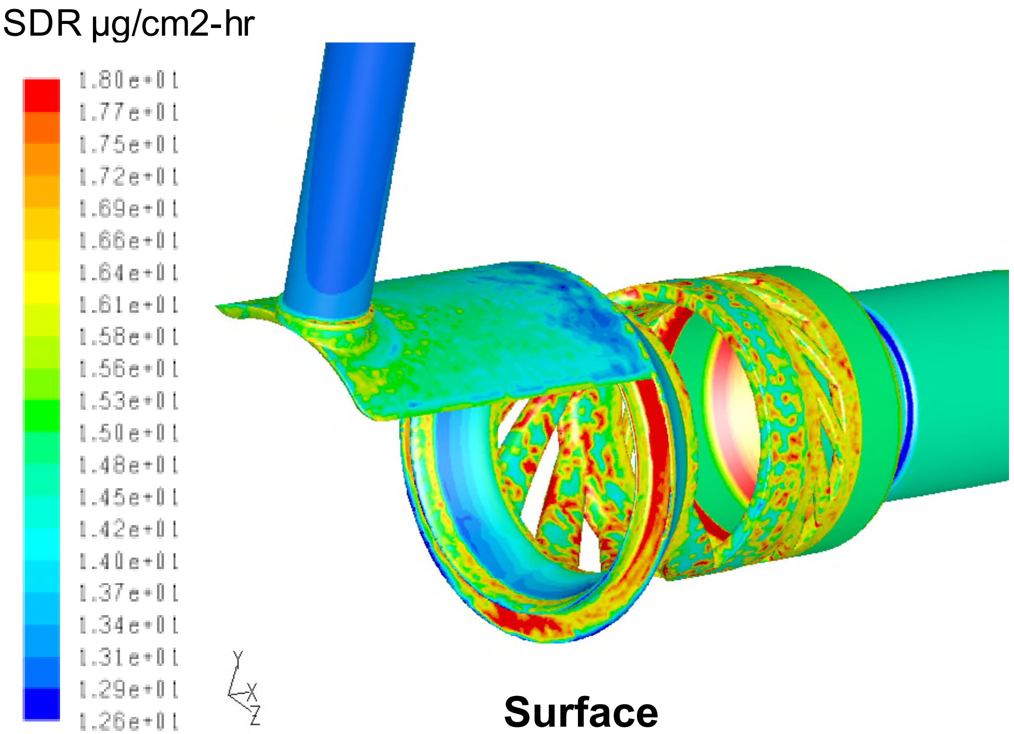




Fuel coking



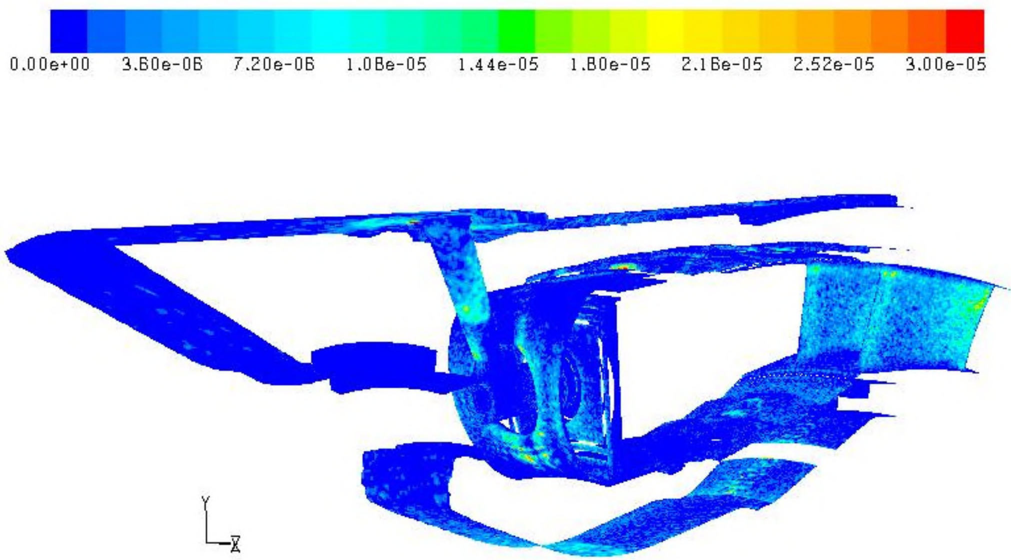
Streamline of fuel passages



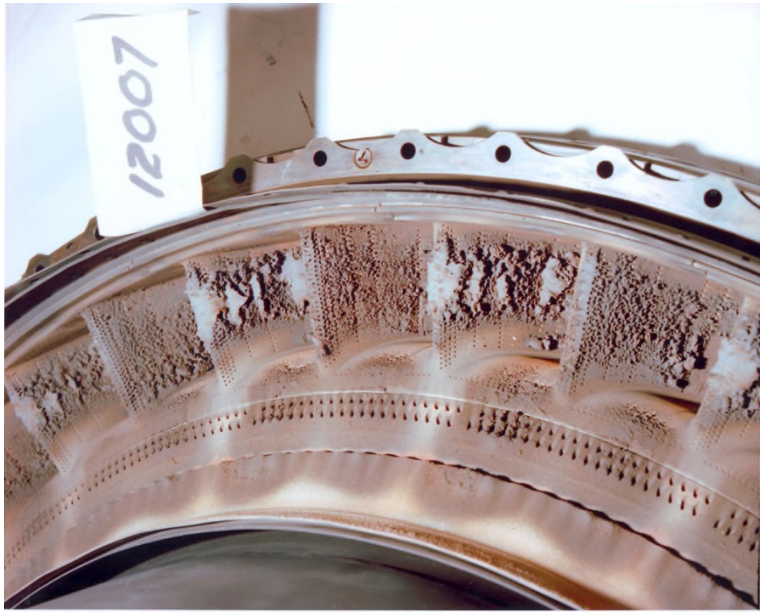
Surface deposition rate

- Coking prone parts of the injector fuel passages can be identified

Volcanic ash deposition



Capture efficiency



Damaged component

- Regions prone to deposition can be identified and different rates calculated

Summary

- Aero-engine combustor development is carried out by tight combination of experiments and simulations
- CFD is routinely used to support combustor design for:
  - External aerodynamics
  - Temperature traverse
  - Injector design
  - Emissions trends (NOx, CO, UHC, soot)
  - Metal temperature
- CFD is more and more used to investigate other problems as well
- Before use for product development, thorough validation of the methods is required, going from low to high TRL
- Co-operation between industry and academia key to move technology forward

Trends in gas turbine combustion CFD

- Massively parallel computations (the more cores the better?)
- LES as a routine design tool
- Multi-physics, multi-component simulations
- Continuous focus on interfaces (e.g. VR)
- Automation (faster!)
- Increasing research on rumble CFD
- Conjugate heat transfer modelling
- Alternative fuel modelling
- Usage of more detailed chemistry for soot predictions
- Eulerian or Lagrangian predictions of primary break up
- Open source
- Running on GPUs/hybrid platforms
- Use of AI techniques to tune models