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Cranfield University

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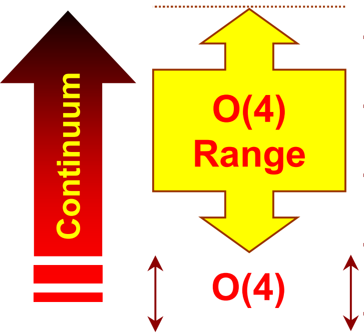
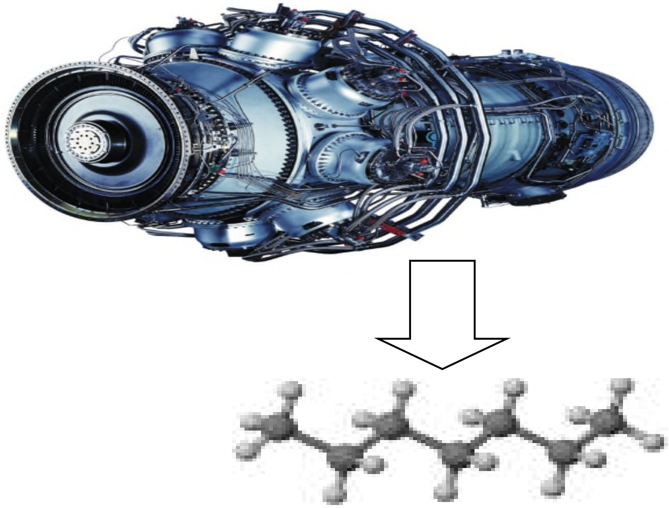
The Role of CFD in Combustor Design and Development (Part I)

Challenge: Several decades of relevant scales



- Typical range of spatial scales
  - Scale of combustor: **10 – 100 *cm***
  - Energy containing eddies: **1 – 10 *cm***
  - Small-scale mixing of eddies: **0.1 – 10 *mm***
  - Diffusive-scales, flame thickness: **10 – 100 μ*m***
  - Molecular interactions, chemical reactions: **1 – 10 *nm***
- Spatial and temporal dynamics **inherently coupled**
- **All scales are relevant** and must be resolved or modeled



CFD-based Modelling Techniques

- **RANS (Reynolds Averaged Navier-Stokes)**
  - Average the governing equations - model all scales
  - Modelling generally well developed
  - Inexpensive (relatively!) - remains standard for industrial problems

- **LES (Large Eddy Simulation)**
  - Filter the governing equations - modelling required at the sub-grid scale
  - Combustion physics and chemistry tends to happen on sub-grid scales
  - Now becoming applicable to industrial problems

- **DNS (Direct Numerical Simulation)**
  - Solve the governing equations directly - no modelling of the physics
  - Resolution of all scales required - high accuracy numerical methods
  - Computationally very expensive
  - Feeds modelling data to LES and RANS

Turbulence

"Big whirls have little whirls, That feed on their velocity;
And little whirls have lesser whirls, And so on to viscosity."
Lewis Fry Richardson

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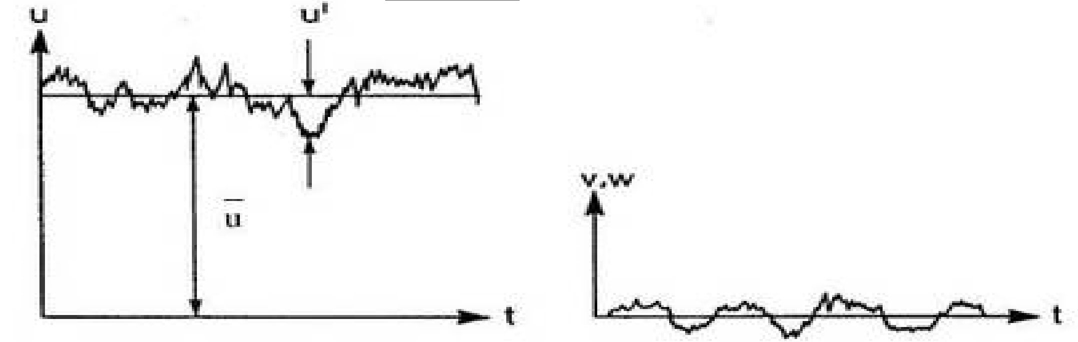
RANS



$$u=\overline{u}+u', \quad v=\overline{v}+v', \quad w=\overline{w}+w', \quad p=\overline{p}+p'$$

$$\rho\frac{D\overline{u_i}}{Dt}=F_i-\frac{\partial\overline{p}}{\partial x_i}+\mu\,\Delta\overline{u_i}-\rho\underbrace{\left(\frac{\partial\overline{u_i'u_j'}}{\partial x_j}\right)}_{Reynolds-stress}$$

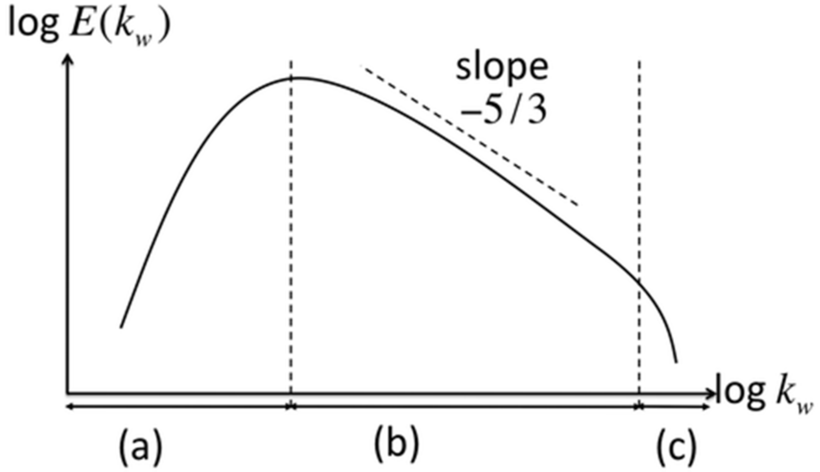
$$\tau_{ij}=\mu\frac{\partial u_i}{\partial x_j}-\rho\,\overline{u_i'u_j'}\quad=\mu\frac{\partial u_i}{\partial x_j}+\rho\left(\nu_T\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}k\,\delta_{ij}\right)$$

$$\nu_t=\left|\frac{\partial u}{\partial y}\right|l_m^2\quad\longrightarrow\quad\mu_t=\rho C_\mu\frac{k^2}{\epsilon}\quad\longrightarrow\quad\mu_t=\frac{\rho a_1 k}{\max(a_1\omega,\Omega F_2)}$$

LES

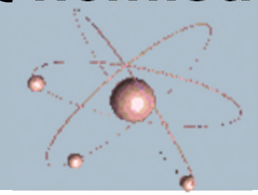
$$\overline{\phi(\boldsymbol{x},t)}=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\phi(\boldsymbol{r},t')G(\boldsymbol{x}-\boldsymbol{r},t-t')dt'd\boldsymbol{r},$$

G(**x**) or G(**k**) are Filtering Functions



Eddies in turbulent flows contain Energy resulting in a level of turbulent mixing and shear forces.
Kolmogorov's Energy cascade Theory: Energy is passed from eddies with larger wave numbers,
to eddies with smaller wave numbers.
(1941 paper 'The local Structure of Turbulence at High Reynolds Number',
in which he sites T. Von Karman and G.I. Taylor)

Sub-Grid Scale Turbulence Models are still required



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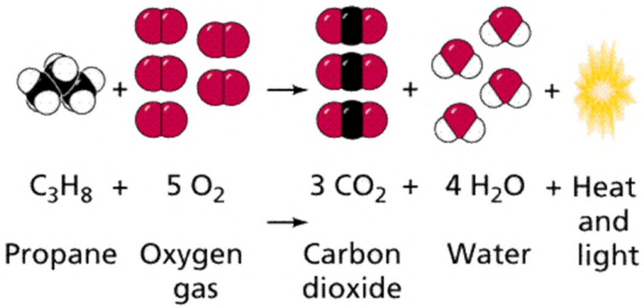
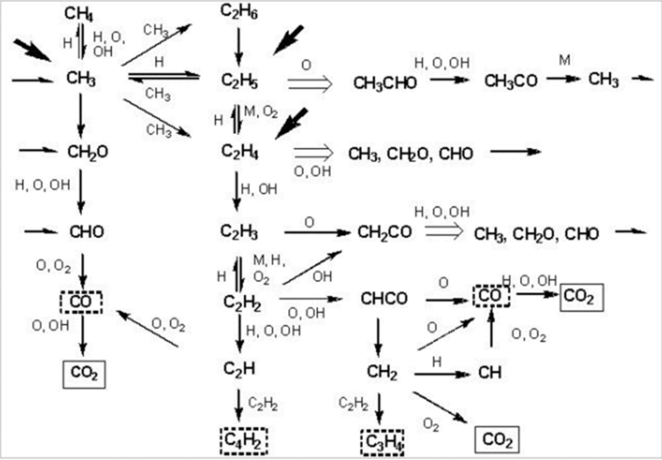
Global Reactions → One or more 'reactions' tuned to reproduce Thermo-Chemical effects



(FUEL + Oxidizer → Products)

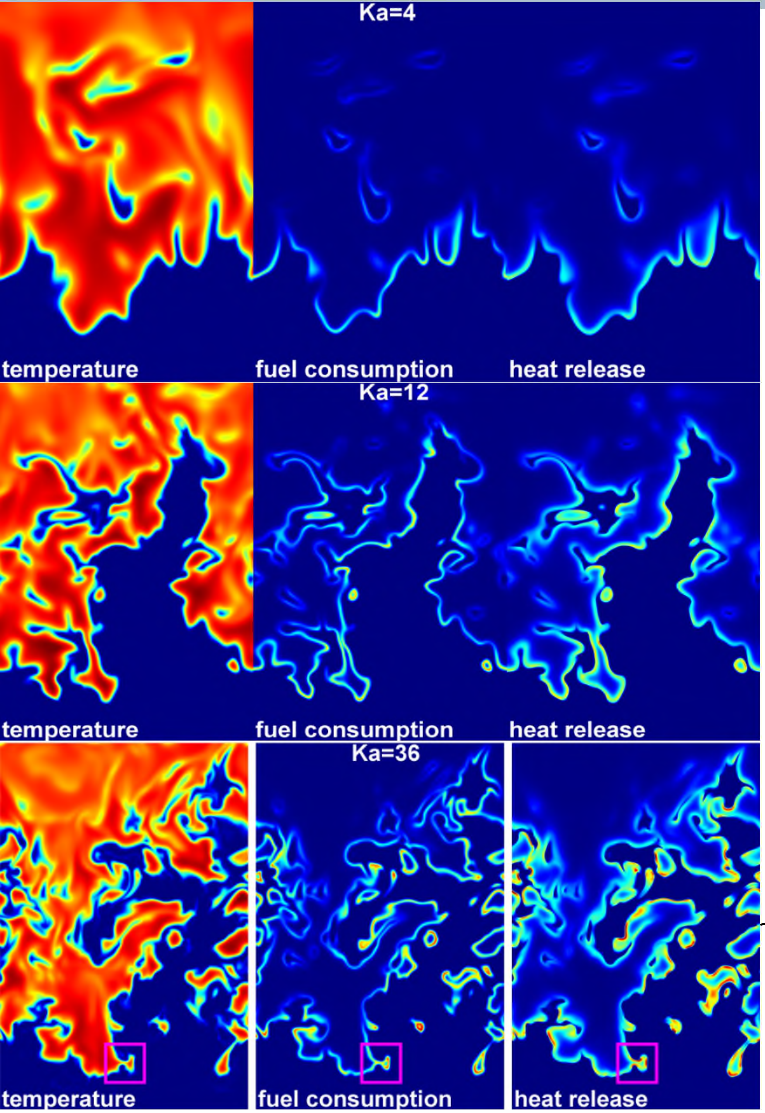
Detailed Chemistry → Chain-Initiating, Chain-Carrying, Chain-Branching...Chain-Terminating



Reduced Chemistry → Keep Important Pathways...even add a little NOx!

(R_1)	$H_2 \leftrightarrow 2H$
(R_2)	$H_2 + O_2 \leftrightarrow 2OH$
(R_3)	$2H_2 + O_2 \leftrightarrow 2H_2O$
(R_4)	$2CO + O_2 \leftrightarrow 2CO_2$
(R_5)	$2CH_4 + O_2 \leftrightarrow 2CO + 4H_2$
(R_6)	$2CH_4 \leftrightarrow 2CH_3 + H_2$
(R_7)	$2CH_4 + 3O_2 \leftrightarrow C_2H_2 + 6OH$
(R_8)	$2HCN + O_2 \leftrightarrow 2CO + H_2 + N_2$
(R_9)	$O_2 + N_2 \leftrightarrow 2NO$
(R_{10})	$O_2 + 2N_2 \leftrightarrow 2N_2O$

Turbulence Chemistry Interactions



Old School – Uses information from Turbulence Models

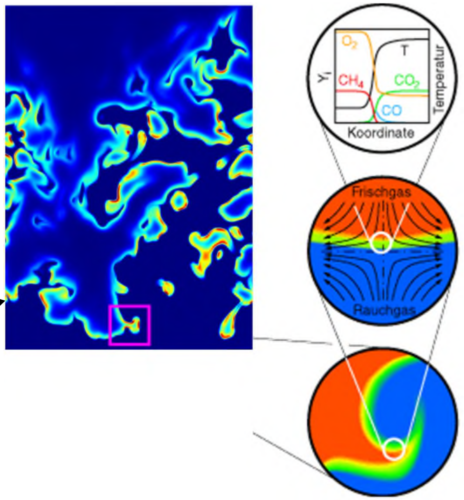
$$\tau = \varepsilon / k \qquad \text{Turb. Time Scale}$$

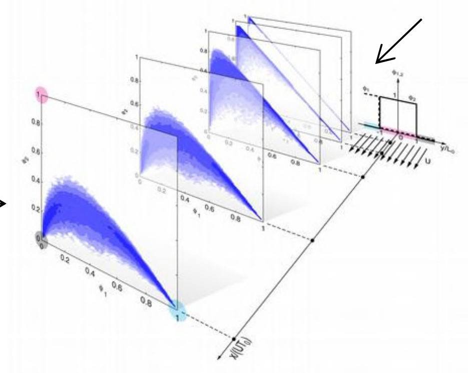
$$\varpi_f = -C_{EBU}\bar{\rho}\bar{Y}_f\,\varepsilon / k$$

$$\varpi_{ox} = -C_{EBU}\bar{\rho}\,\frac{\bar{Y}_{Ox}}{s}\,\varepsilon / k$$

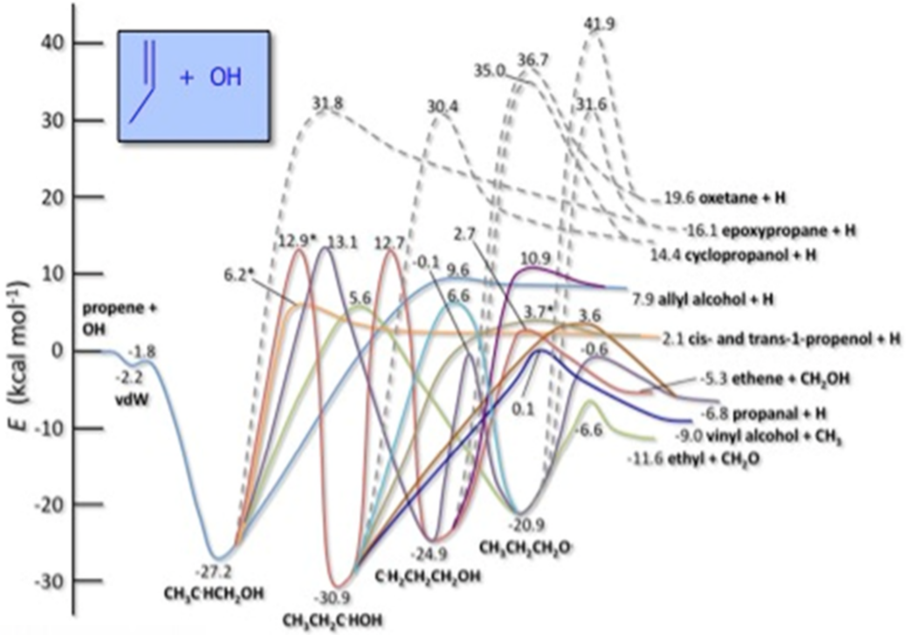
$$\varpi_{\mathrm{Pr}} = -C_{EBU}\bar{\rho}\,\frac{\bar{Y}_{\mathrm{Pr}}}{s+1}\,\varepsilon / k$$

Newer School – Flamelets





Where we need to be– More Detailed Chemistry



$$y_1' = -0.04y_1 + 10^4 y_2 y_3$$

$$y_2' = 0.04y_1 - 10^4 y_2 y_3 - 3\cdot 10^7 y_2^2$$

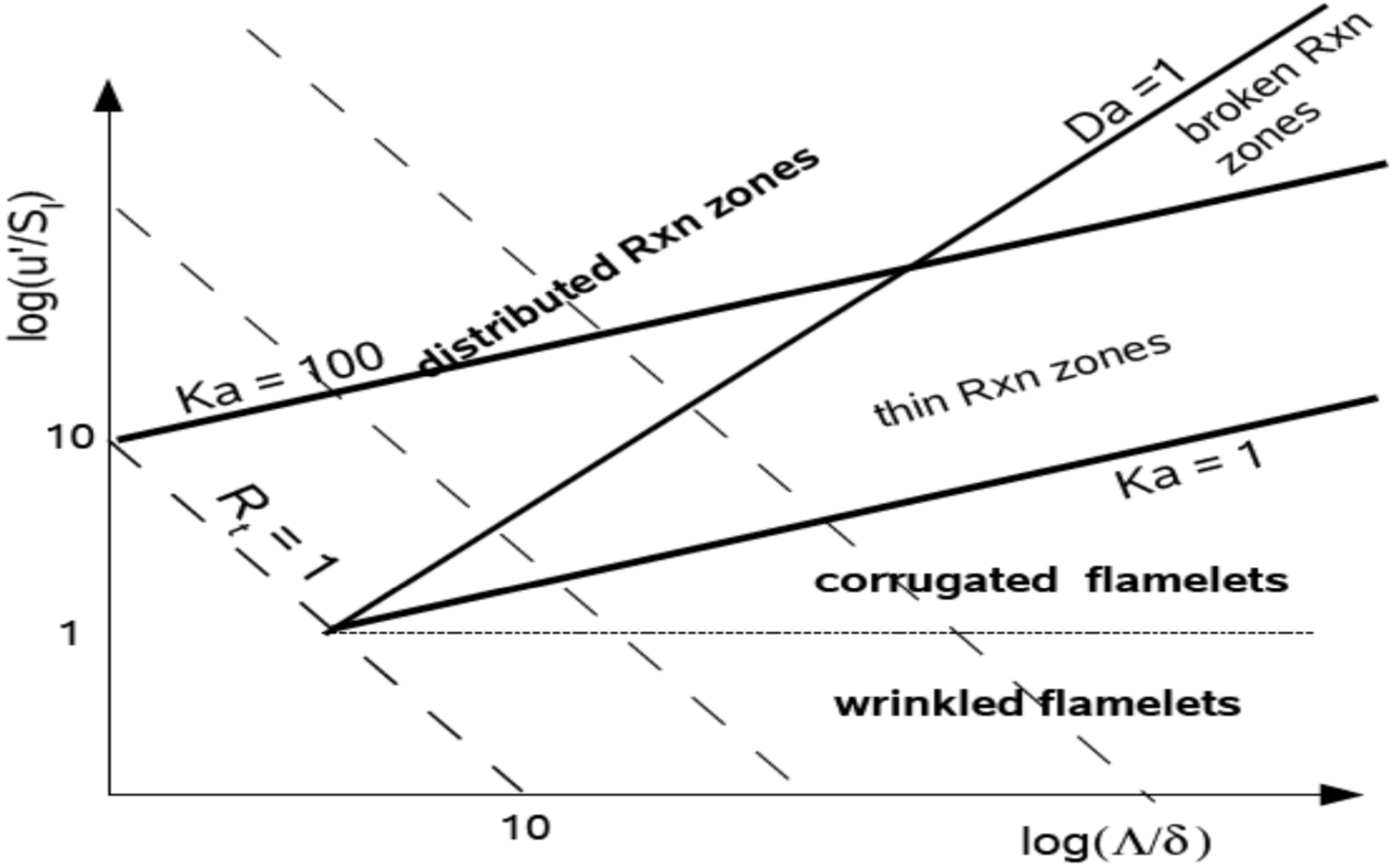
$$y_3' = 3\cdot 10^7 y_2^2$$

Combustion Regimes

$$Da = \frac{\tau}{t_c} = \frac{\Lambda/\delta}{u'/S_l}$$

$$R_t = \frac{u'\Lambda}{\nu} = \frac{\Lambda/\delta}{S_l/u'}$$

$$Ka = \frac{t_c}{\tau_\eta} = \left(\frac{\delta}{\eta}\right)^2 = \left(\frac{u'}{S_l}\right)^{3/2} \left(\frac{\Lambda}{\delta}\right)^{-1/2}$$



Flames

Combustion Models (The Usual Suspects)

Global Chemistry

- Westbrook-Dryer 2-step with Finite-Rate EBU

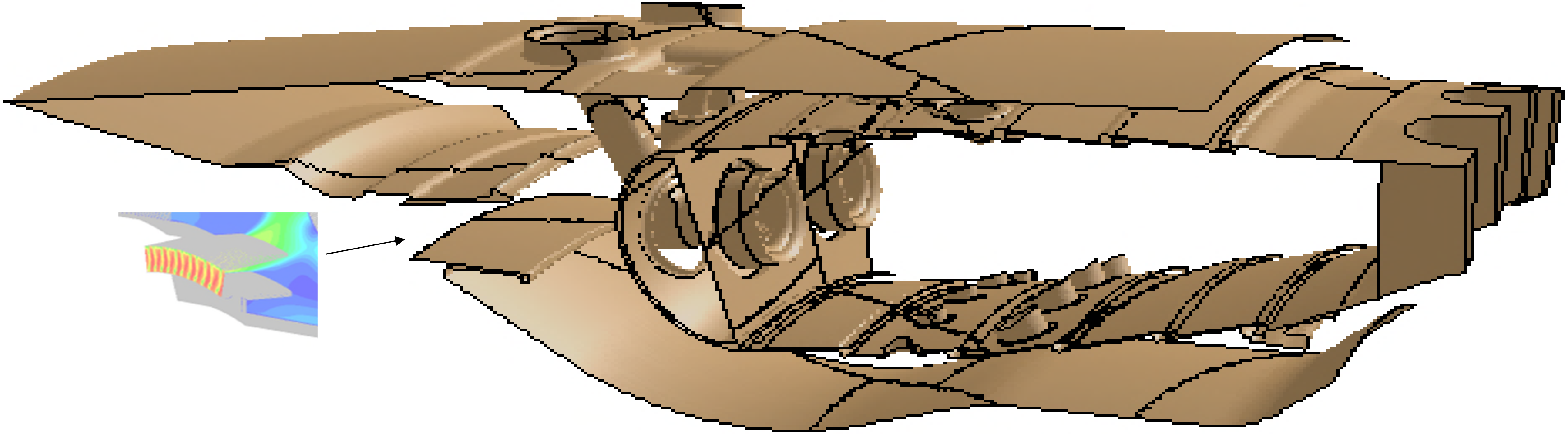
Detailed Chemistry

- Reduced Reaction Mechanisms
  - Species Transport with EDC/ISAT Chemistry Model
- Full Reaction Mechanisms
  - PDF/Flamelet Model

Equilibrium Chemistry

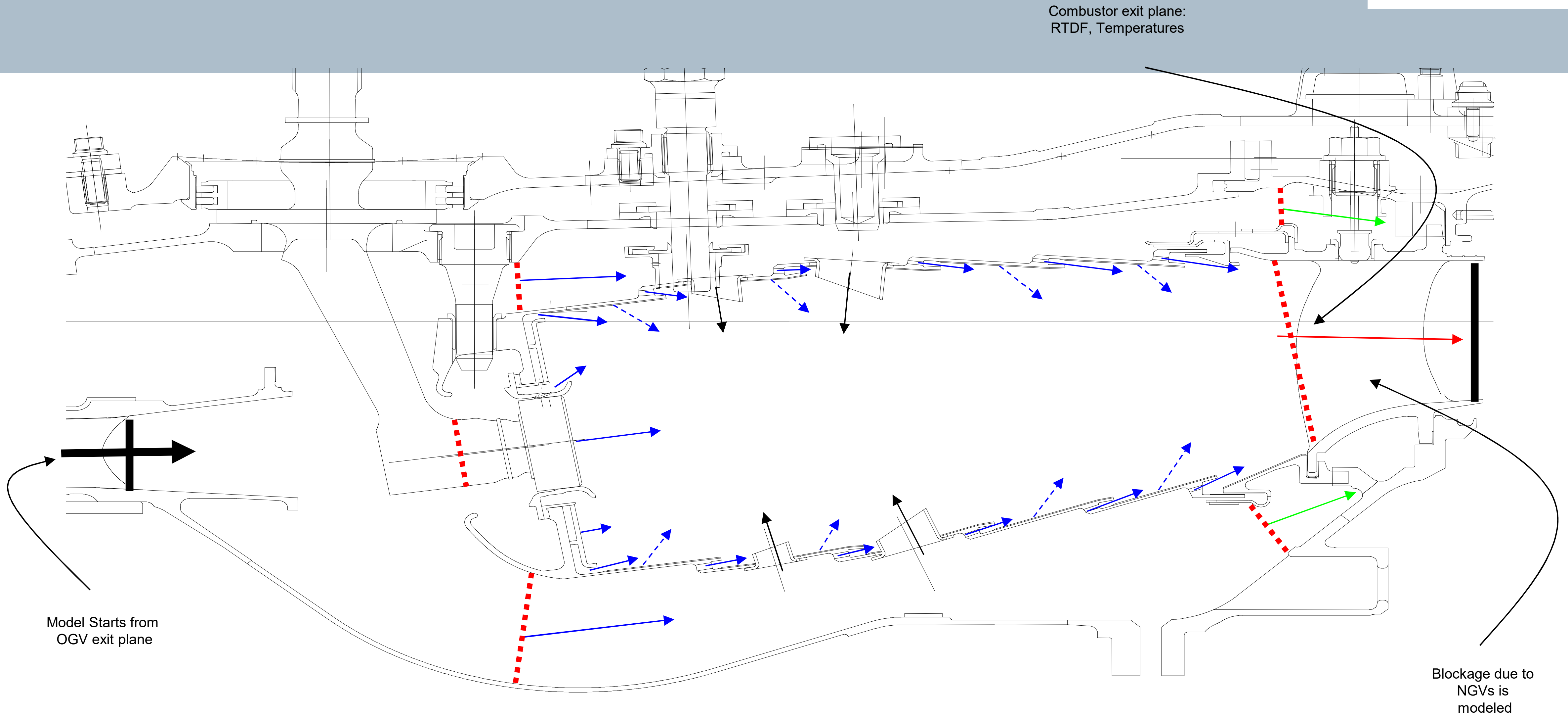
PDFs

T60 WLE



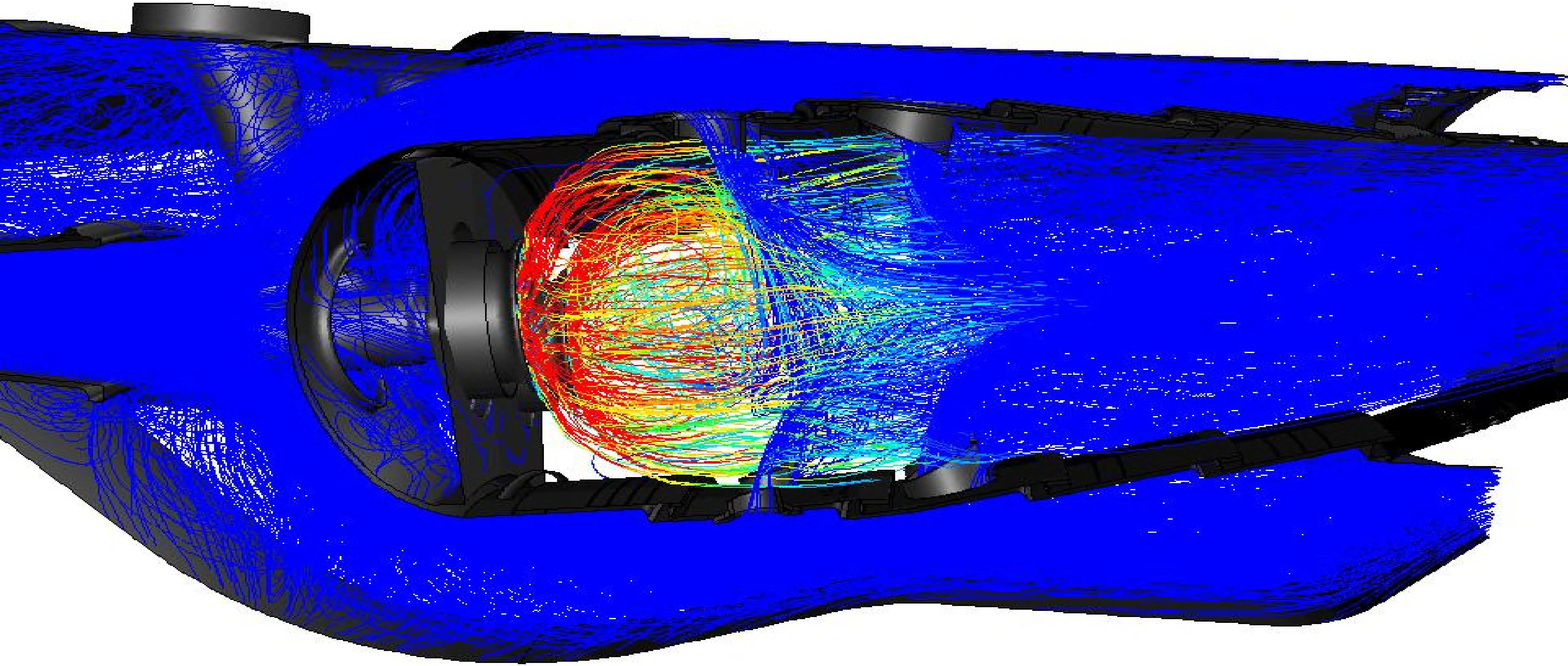
- 1/12 Sector model: to include 2 fuel injectors and mounting pin
- Full Combustion System from OGV to NGV
- Inlet Profile includes wake effects from OGVs
- Combustor Liner Thickness included → Conjugate Heat Transfer Modeled
- Full details of Injector air passages modeled
- Fuel supply passage not modeled
- Liner Effusion Cooling Implicitly modeled
- All Chute Flows and Film Cooling Flows Explicitly modeled
- Steady-State Reacting Flow and Unsteady Reacting Flow

CFD Bocos



Combustor exit plane:
RTDF, Temperatures
Model Starts from
OGV exit plane
Blockage due to
NGVs is
modeled

Flow colored by Stoichiometric Fuel Mass Fraction



Combustor Gas Temperatures (Injector Plane)

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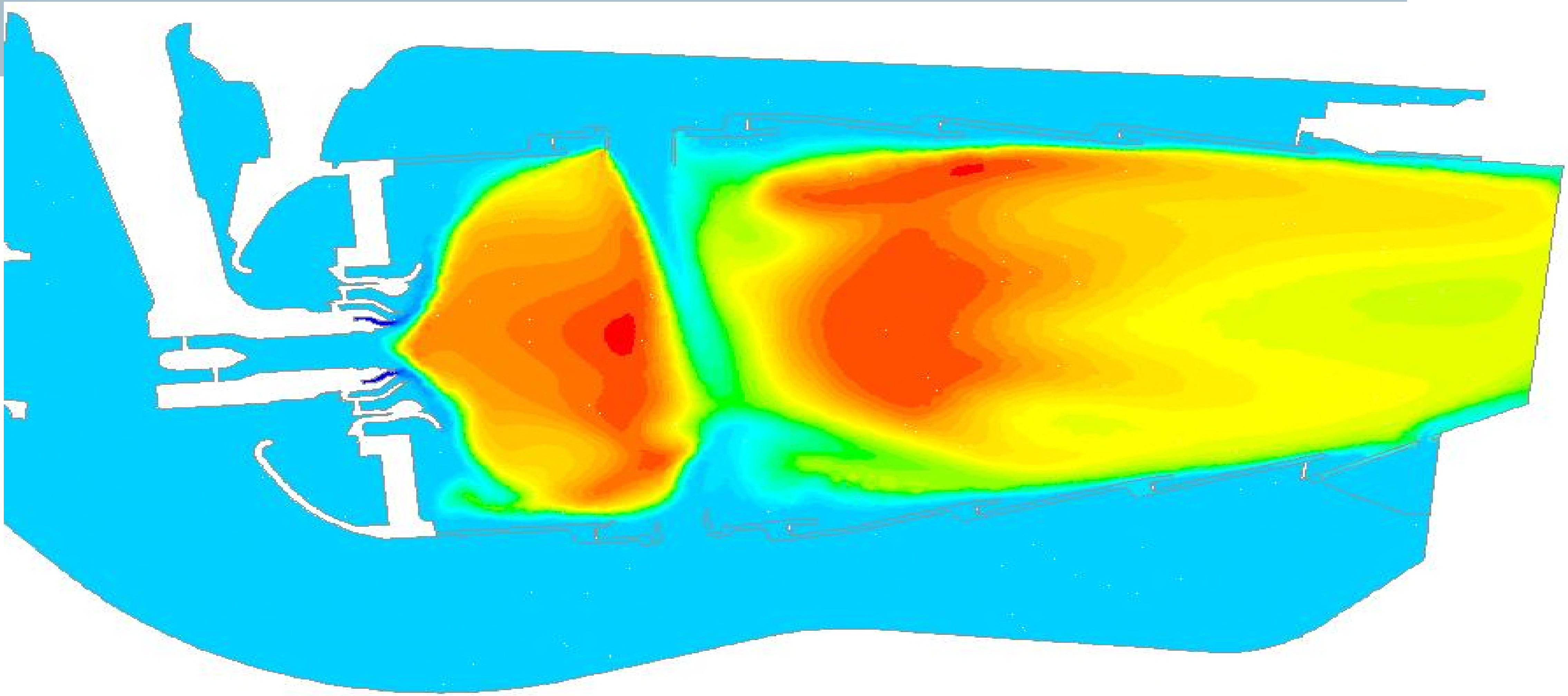
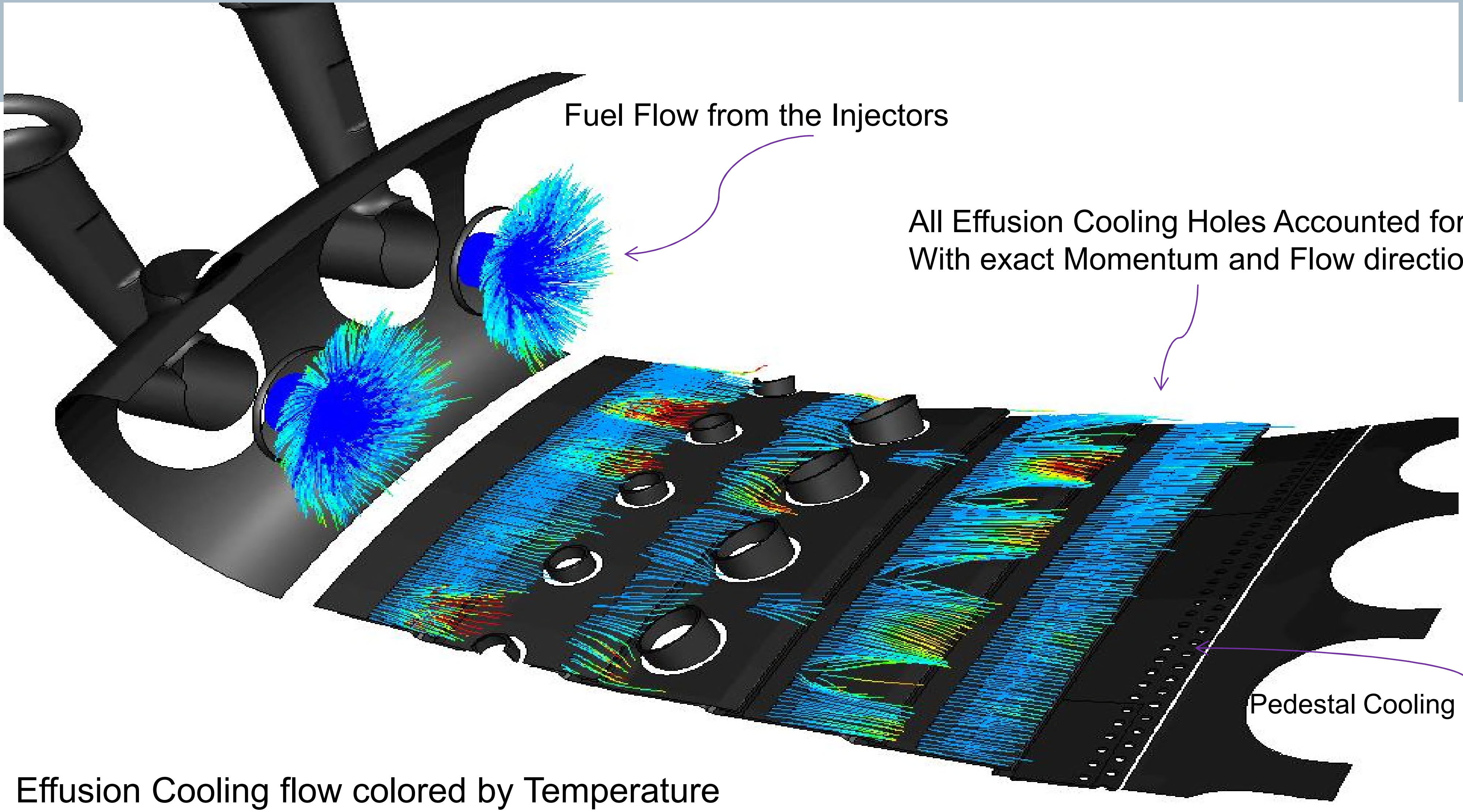


° K

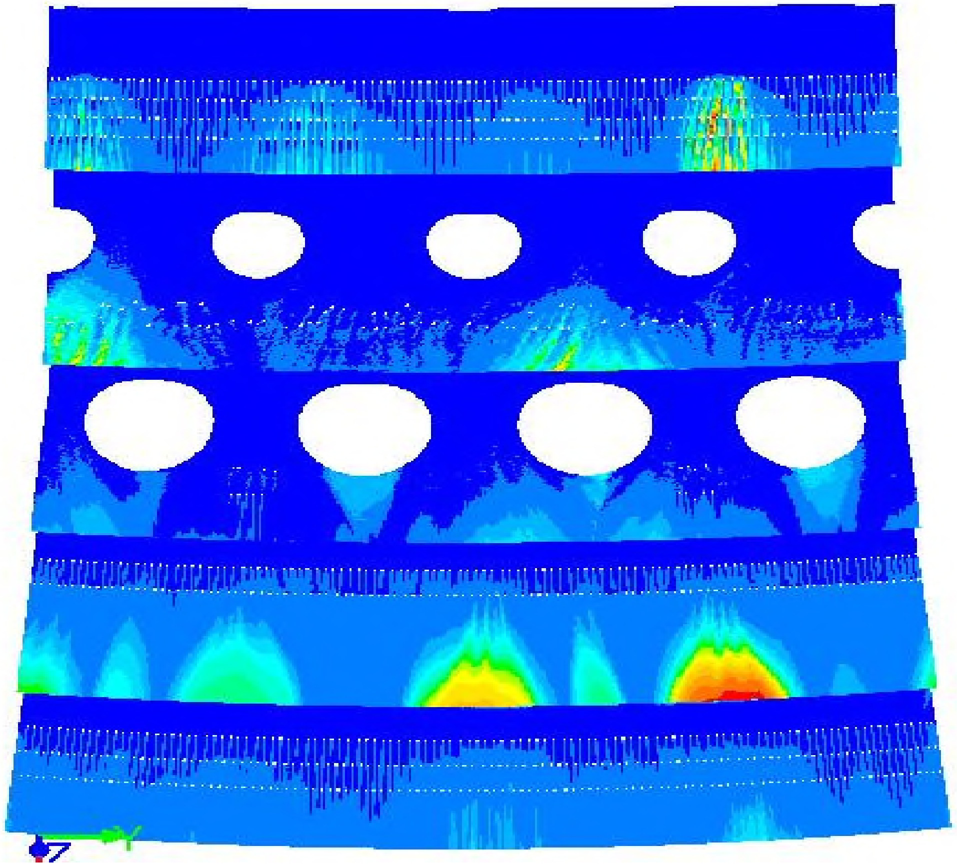
K

Liner Effusion Cooling Model



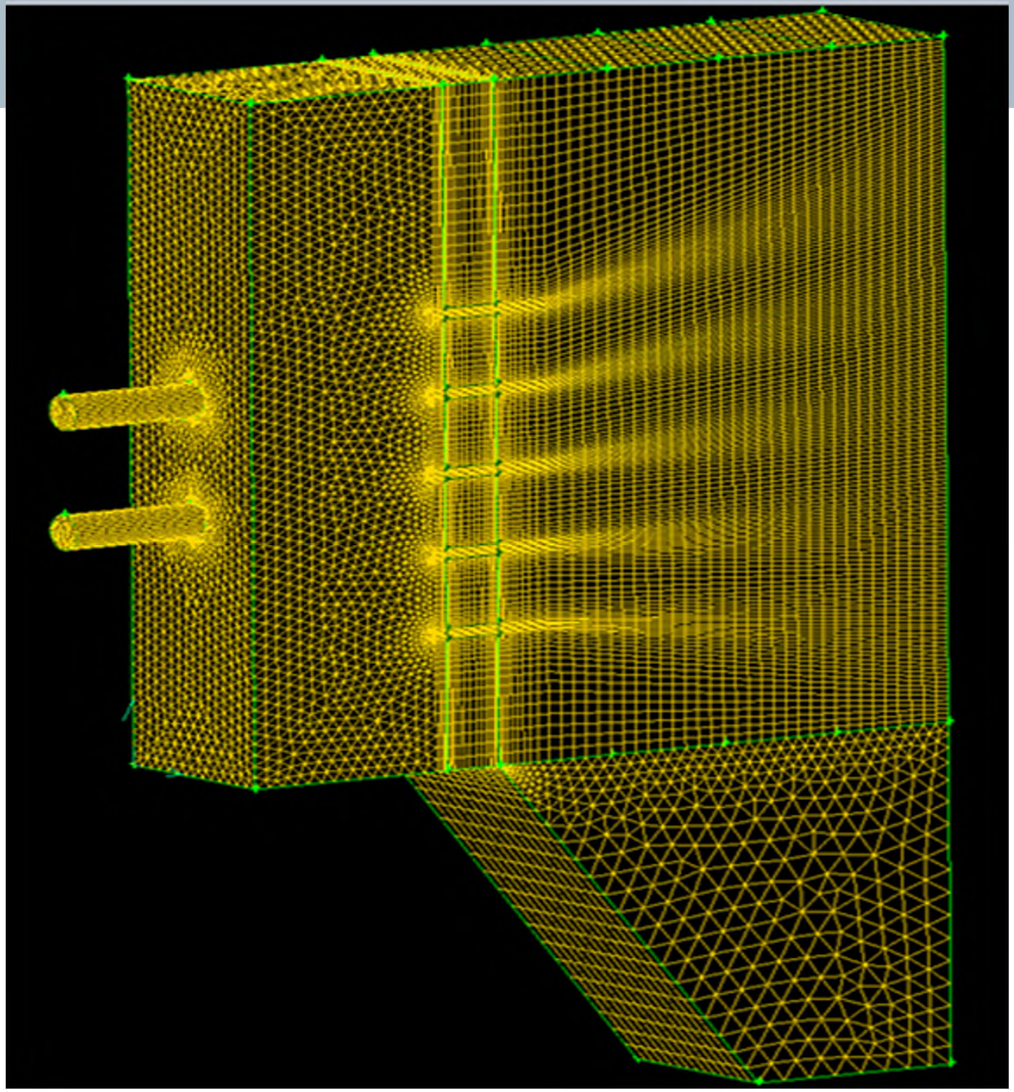
Effusion Cooling flow colored by Temperature

Combustor Liner Wall Temperatures
Thermal Paint Validation



Methods Development and Validation…

Simplified Representative Test-Case



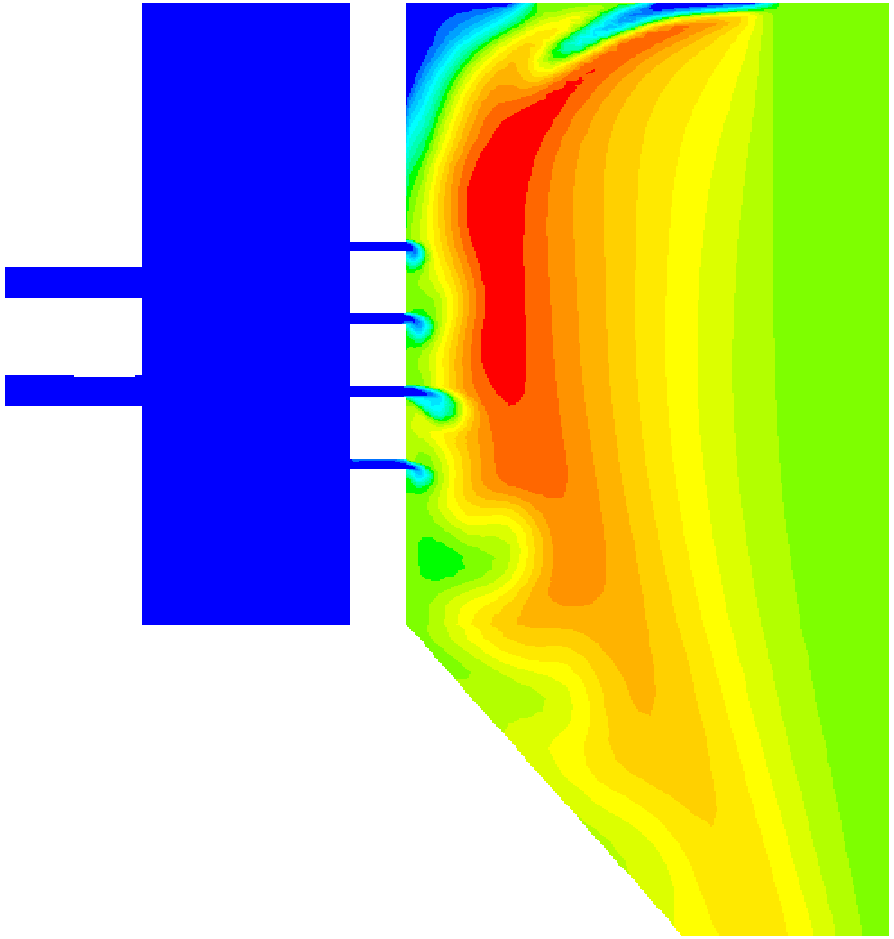
Fluid And Solid Meshed

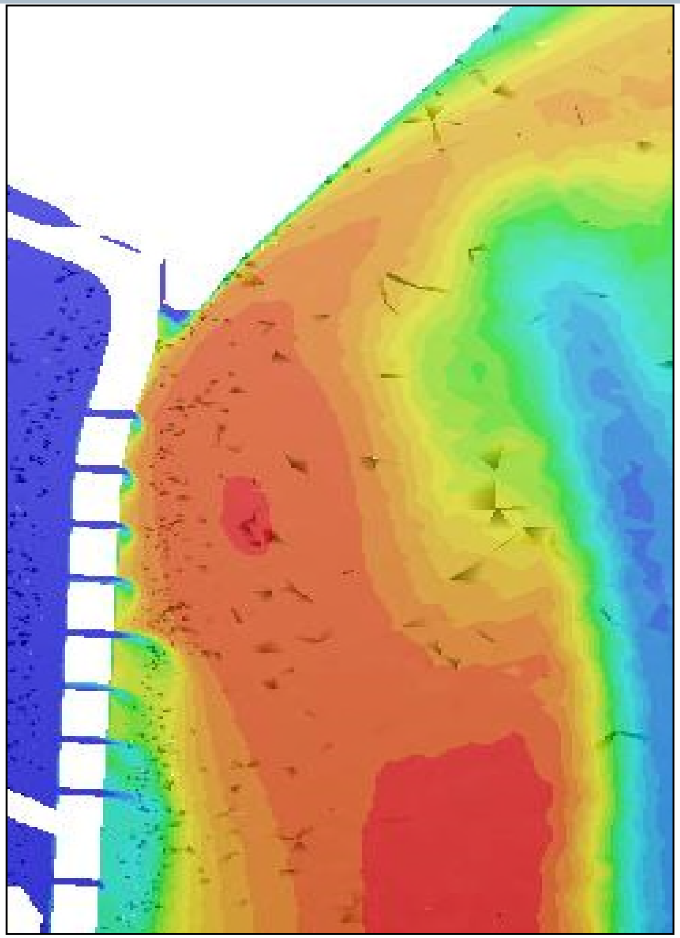
Mesh ~500k cells

Similar Mesh Density as Combustor

Boundary Layers Used for Gas-Solid Boundaries

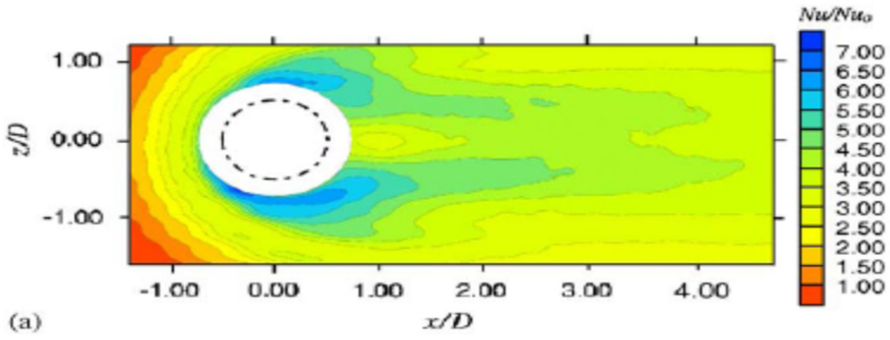
Test-Case Temperature Field



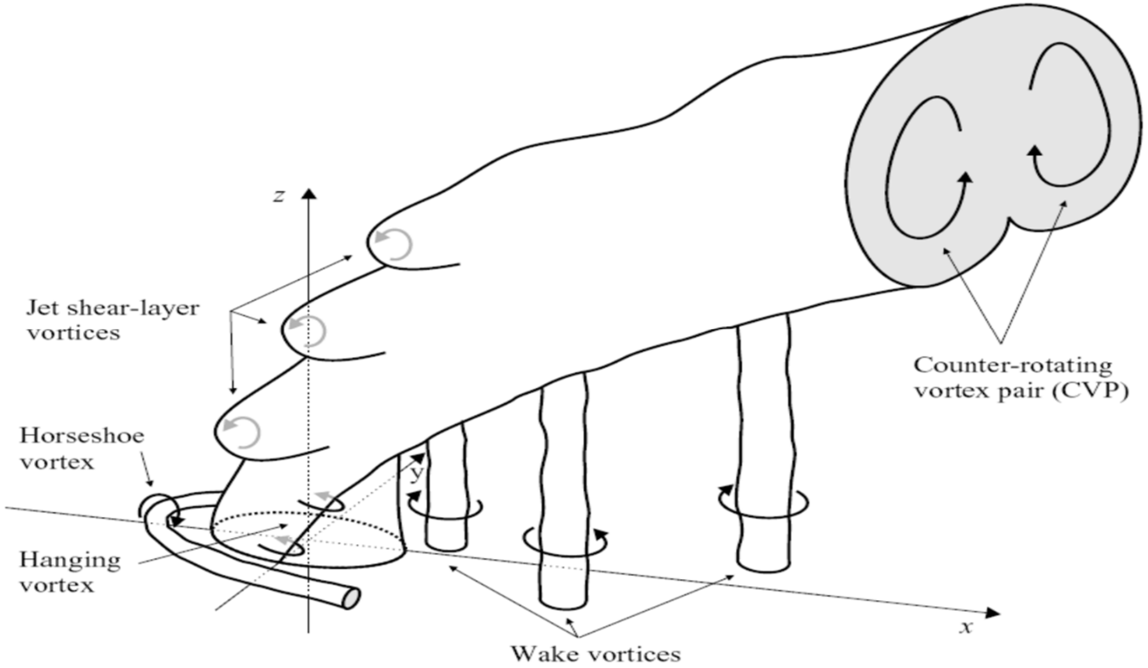


Heat Transfer Coefficient (HTC)

Experimental evidence of HTC enhancement due to cooling flow



Colours in a complex fluid flow - Giovanni Maria Carlomagno



A turbulent jet in crossflow analysed with proper orthogonal decomposition
KNUD ERIK MEYER1, JAKOB M. PEDERSEN1 AND OKTAY O¨ZCAN2

Hot-side HTC

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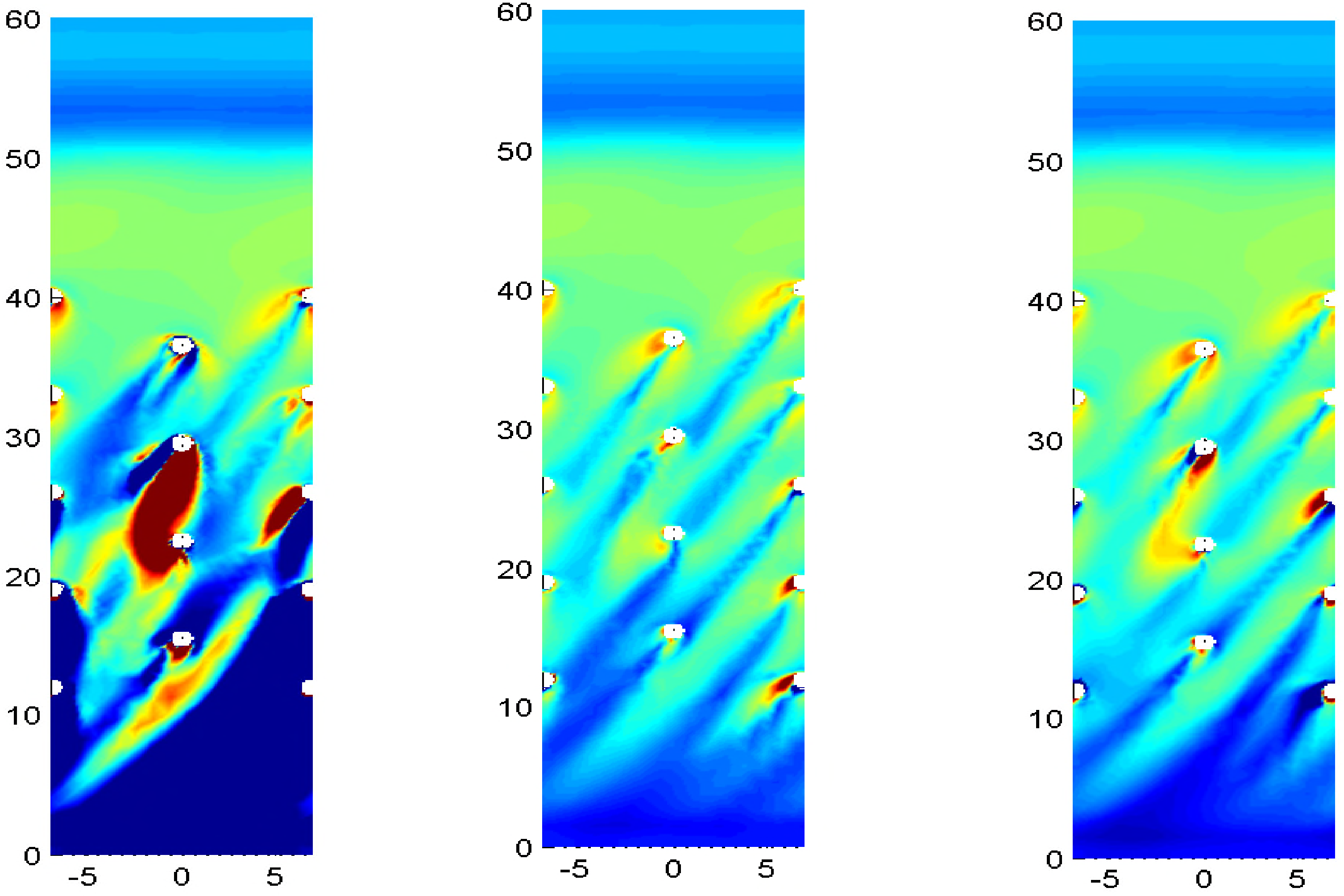
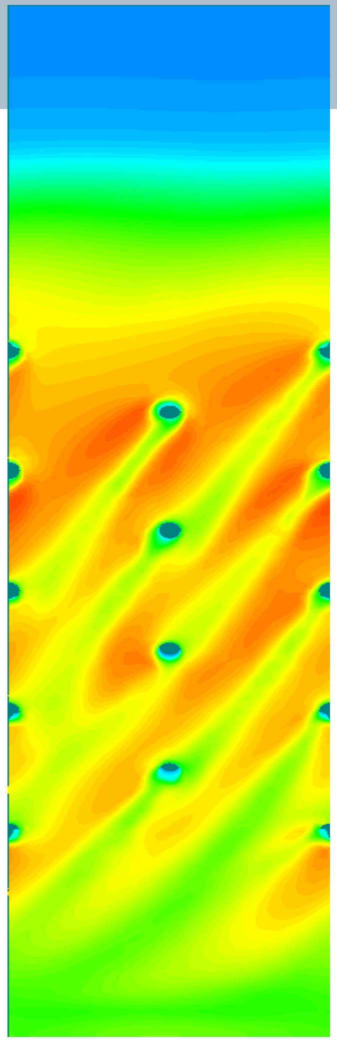
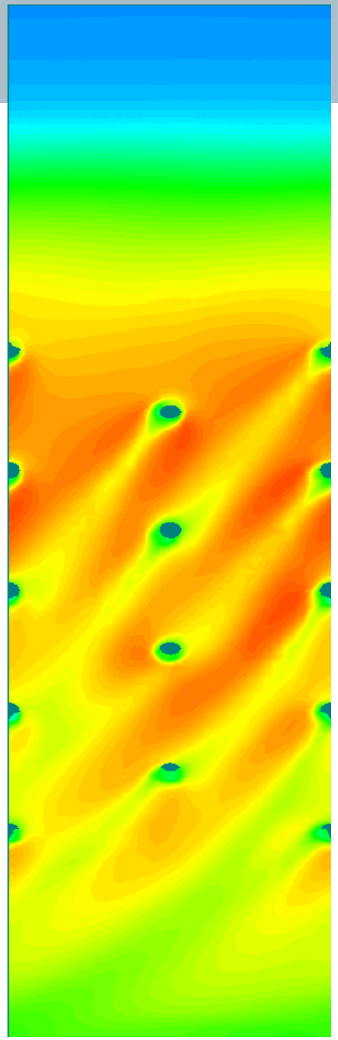


$$HTC = \frac{q}{\left(T_f - T_m\right)}$$

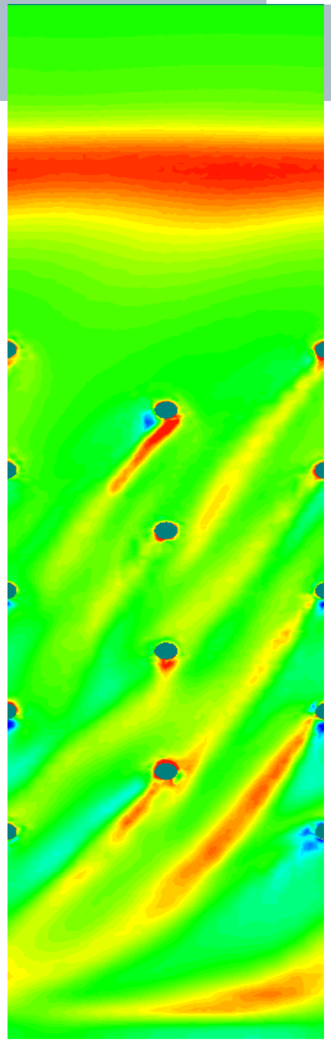
Conjugate CFD .Vs. Thermal Code + CFD

Thermal
+
CFD
input





Conjugate
CFD

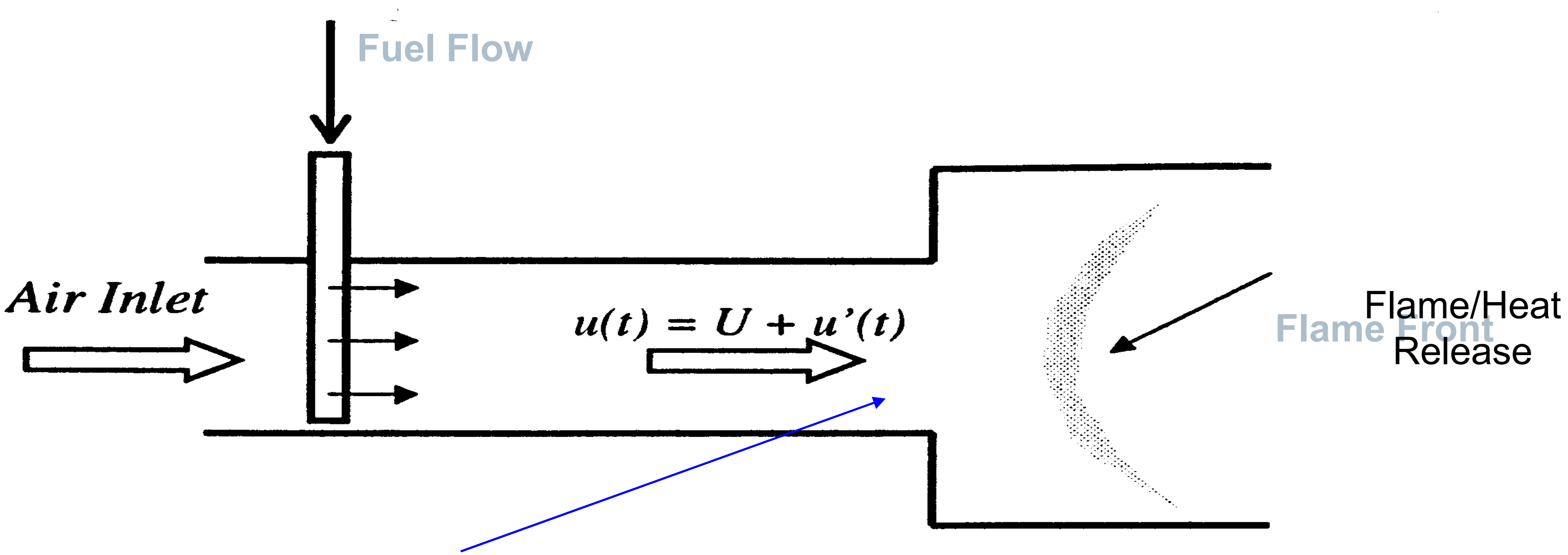


Differences

Combustor Noise:

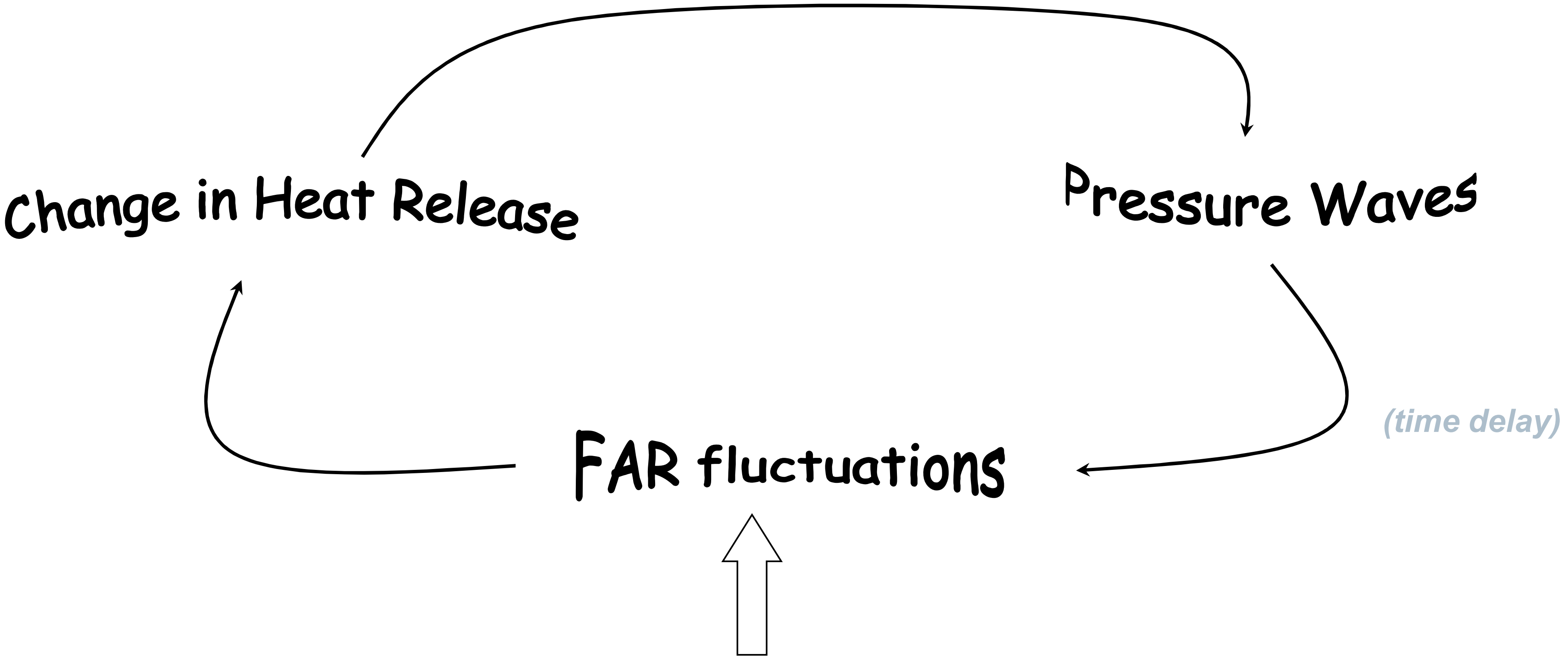
Thermo Acoustic Instabilities

DLE in its simplest form



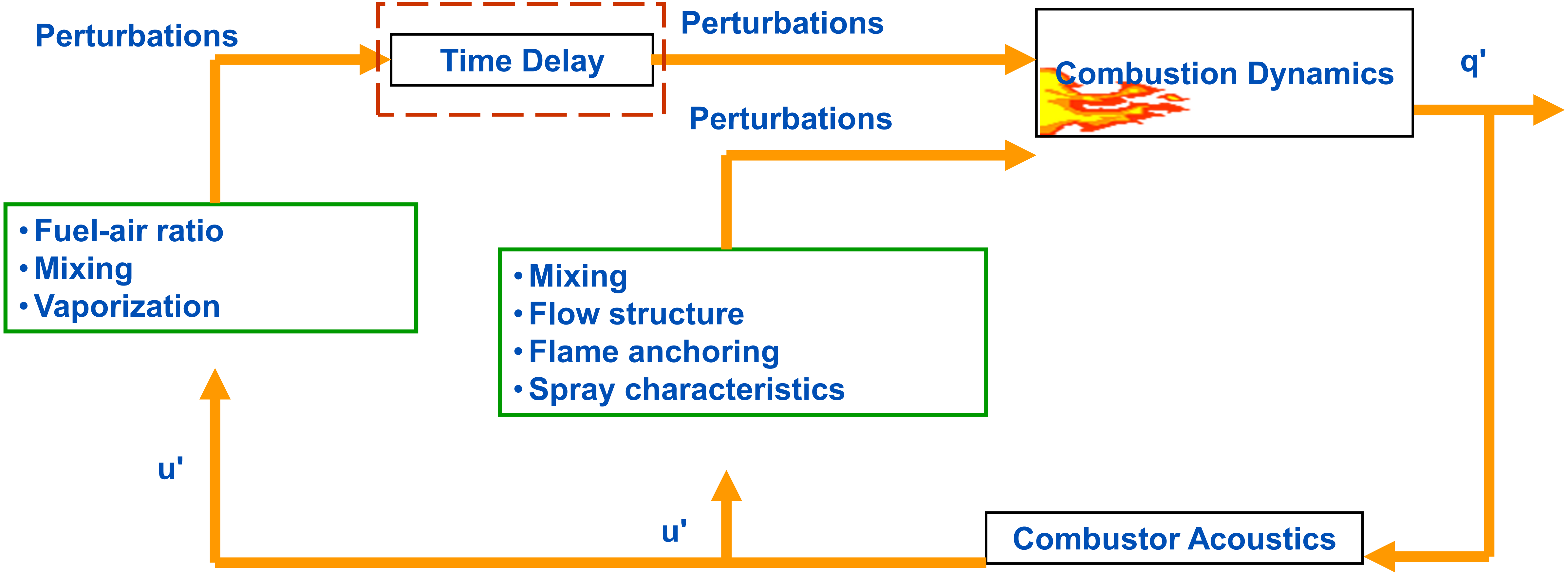
Flashback?
Autoignition?
Noise?

Dominant Mechanism behind Combustion Noise

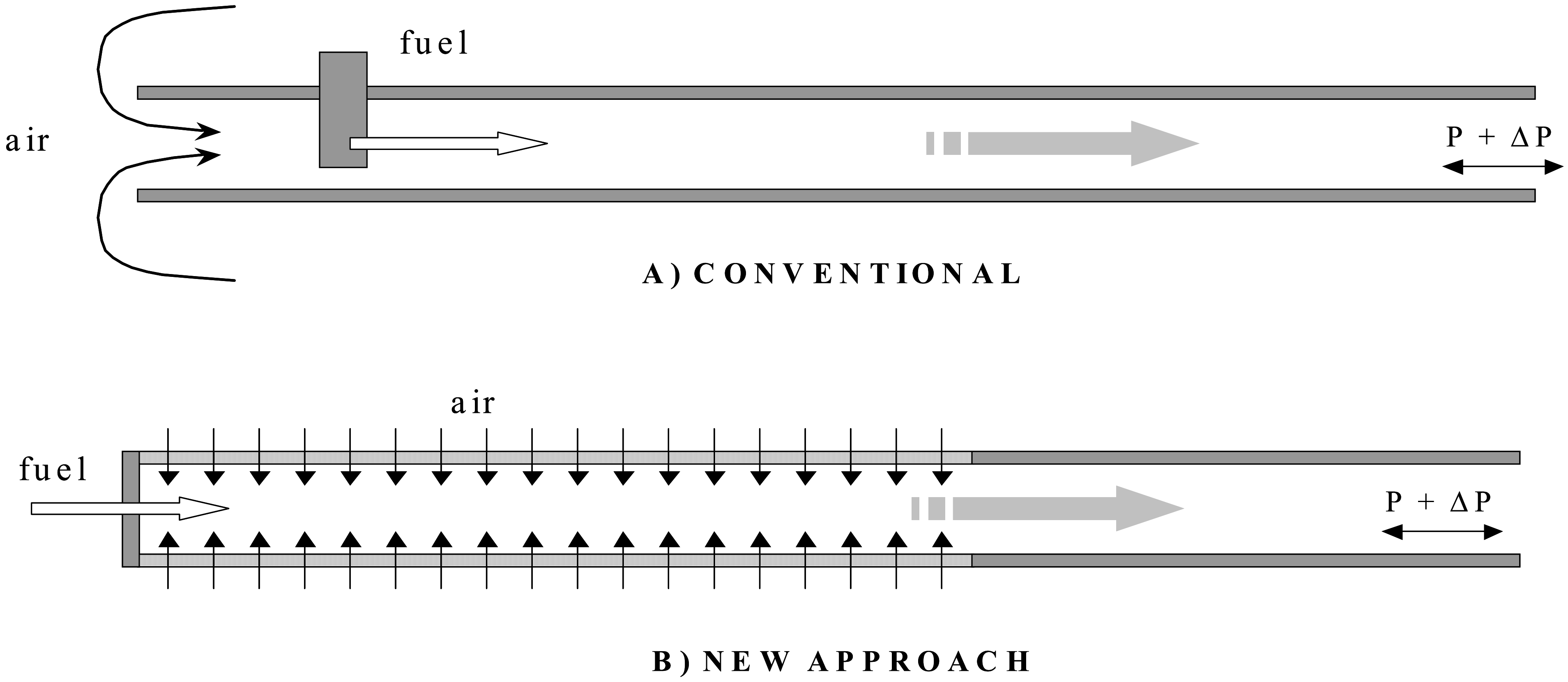


These originate from the presence of **mixing ducts**.
Can they be eliminated by passive design?

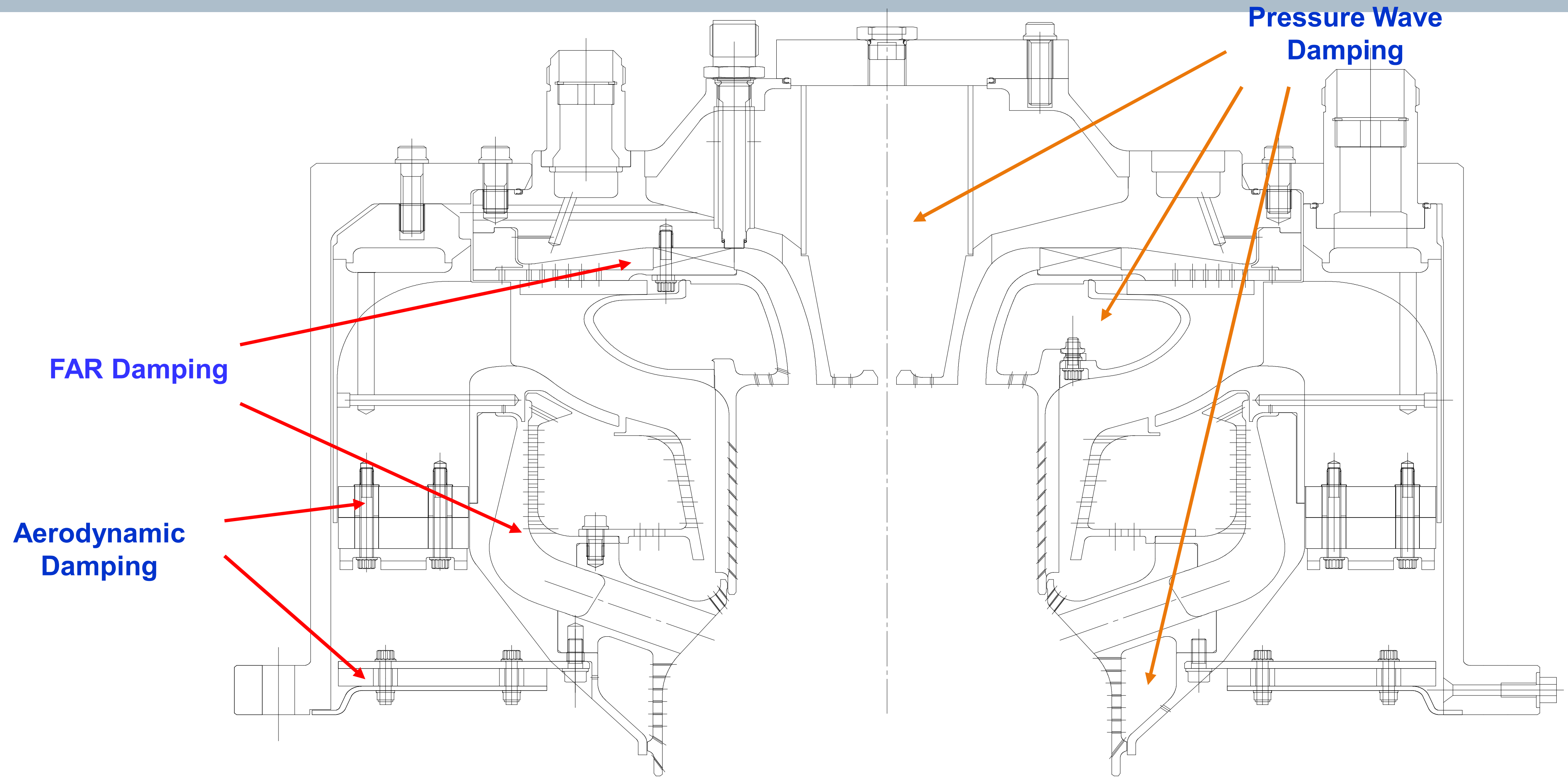
Combustion Instability Study & Modeling

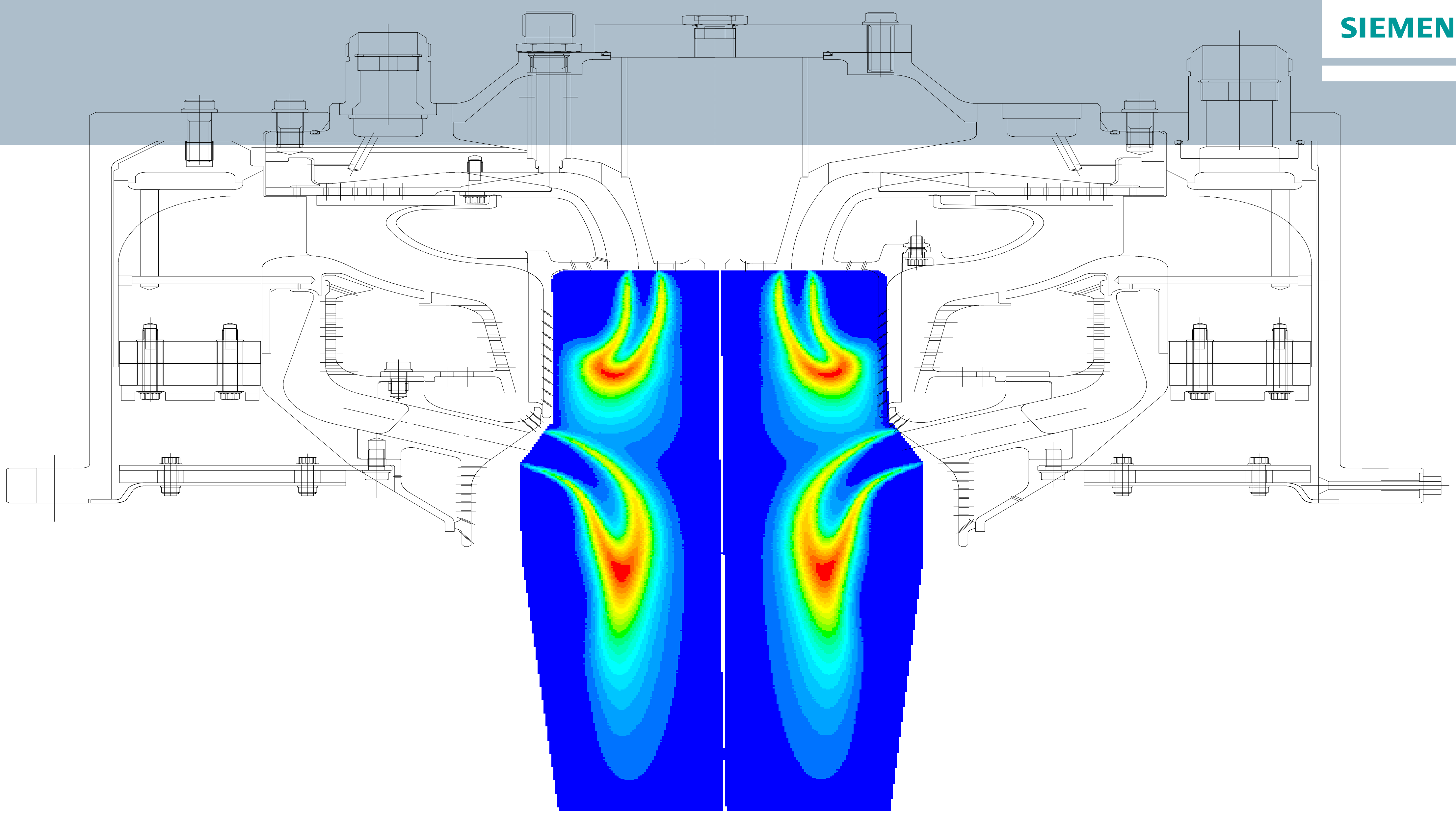


Development of a new fuel-air mixing approach



Implementation of Damping Technologies





Questions?

Thank You!