Lecture 3

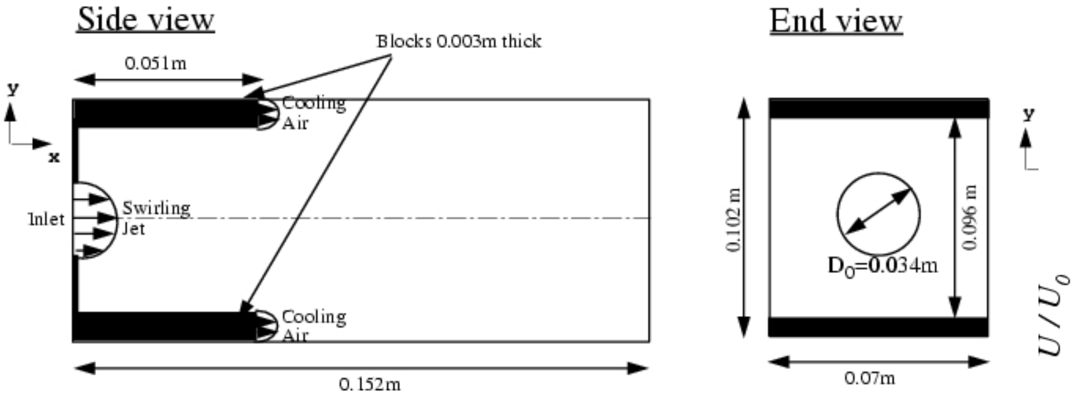
Combustion in CFD for Gas Turbine Combustors

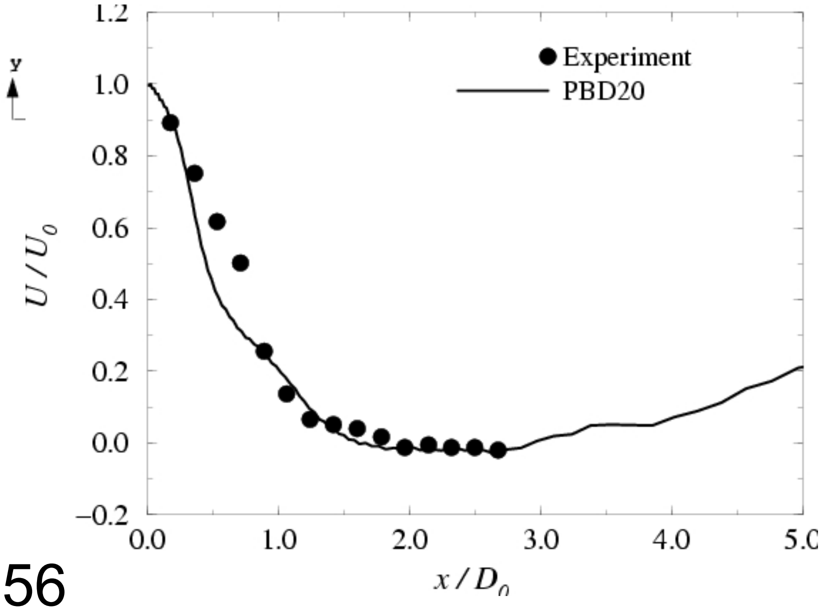
- Premixed and non-premixed (gaseous) combustion
  - Spray GTs discussed in Lecture 7
- Dump combustors with swirl
  - Operational and laboratory combustors
- Complex geometry, Multiple injectors coupling
- Different numerical strategies by different groups
- Different models by same and/or different groups
- Acknowledgements
  - Christer Fureby, FOA, Sweden

Why LES for Engineering Applications?

- Complex geometry and complex design optimization goals
- New designs will operate at the "edge" of combustion limits
  - Ignition, Lean blow out (LBO), Combustion instability (CI)
  - High pressure and/or supercritical combustion
  - Pollutant (CO, NOx, UHC and soot) emission
  - Fuel-flexible combustion without changing design
- *Many physics of interest are dominated by unsteady effects*
  - *To explain why mean predictions improved (or not) excursions about the "mean" needs to be captured*
  - *Predicting transitions (e.g., LBO, CI) requires simulation to physically move from one operating regime to other*

LES of Combustion in GE LM6000 using G-equation
Kim and Menon (1999, 2000)

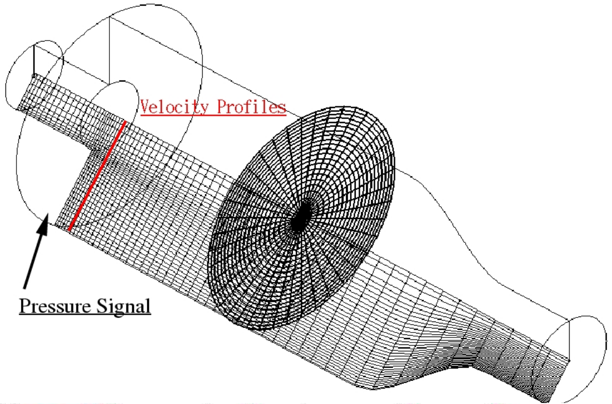


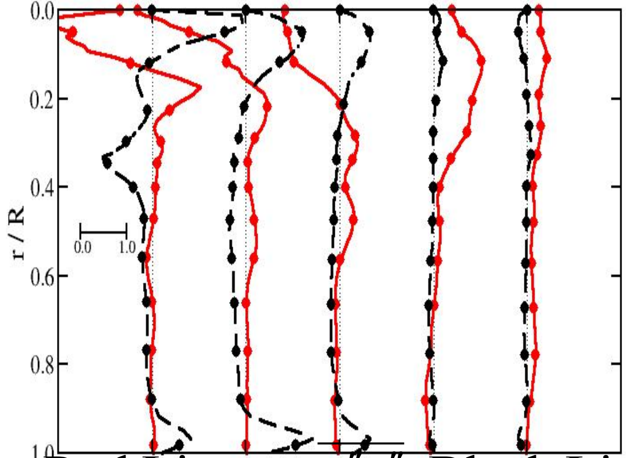


Premixed Methane-Air Combustion
Re = 350,000, Inlet Swirl Number=0.56
T_in = 688 K, P_comb = 6.5 atm
Resolution ~500,000 grid points
Dynamic subgrid kinetic energy model
Dynamic Flame Speed (G-equation) model

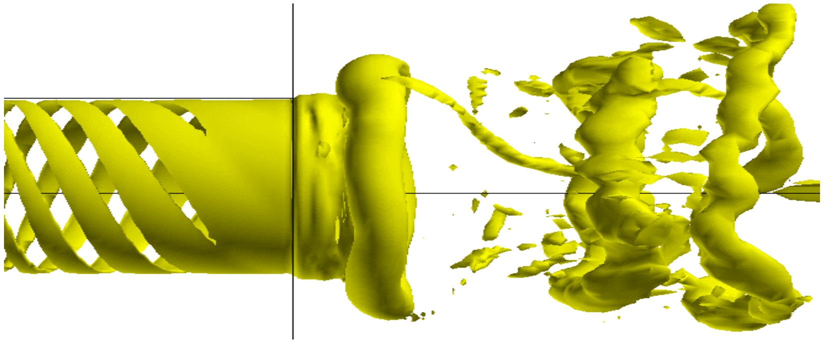
Centerline Mean Axial Velocity variation

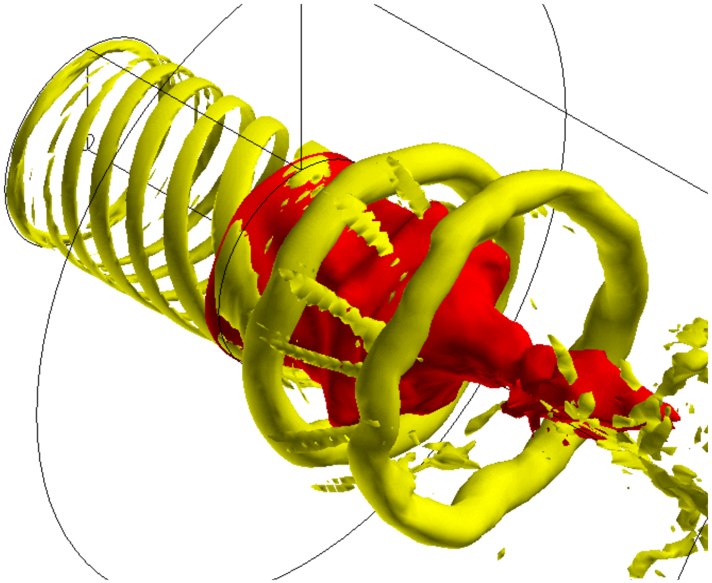
LES of Swirl Dynamics in LM6000 using GLES





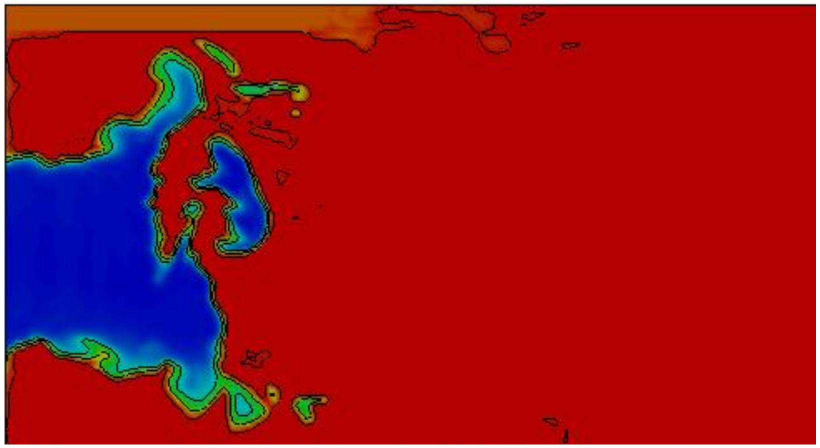
Red Lines : $-\overline{u''v''}$; Black Lines : $\frac{\partial \overline{u}}{\partial y}$





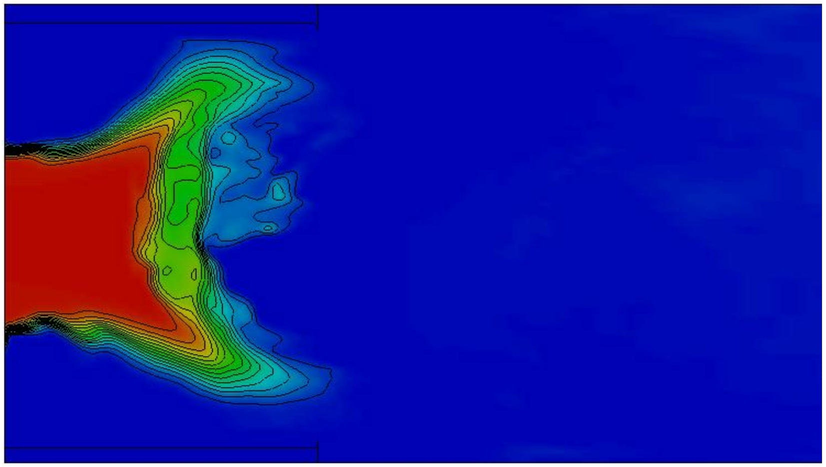
Counter-gradient diffusion can be predicted by LES

Instantaneous Contours in LM6000



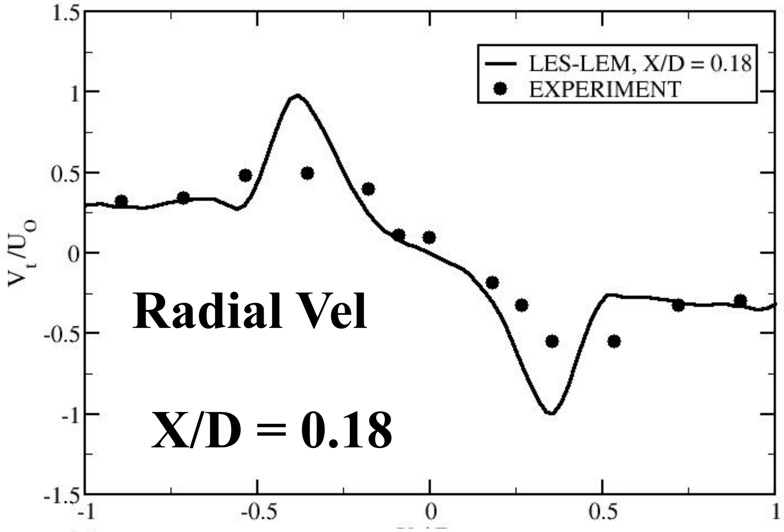
Temperature

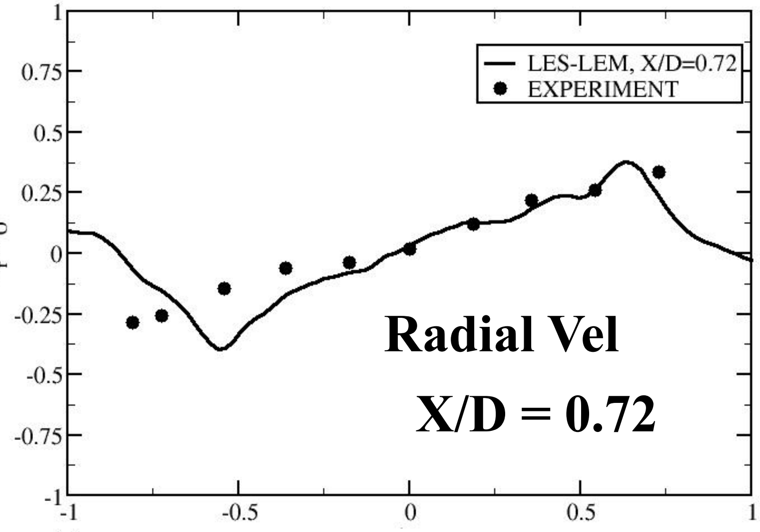
Flame captured within 2 LES Cells using LEMLES

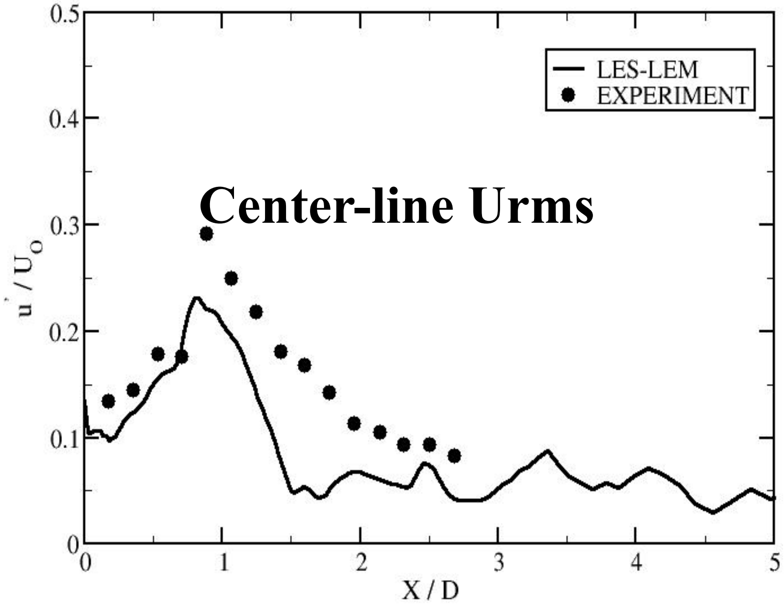


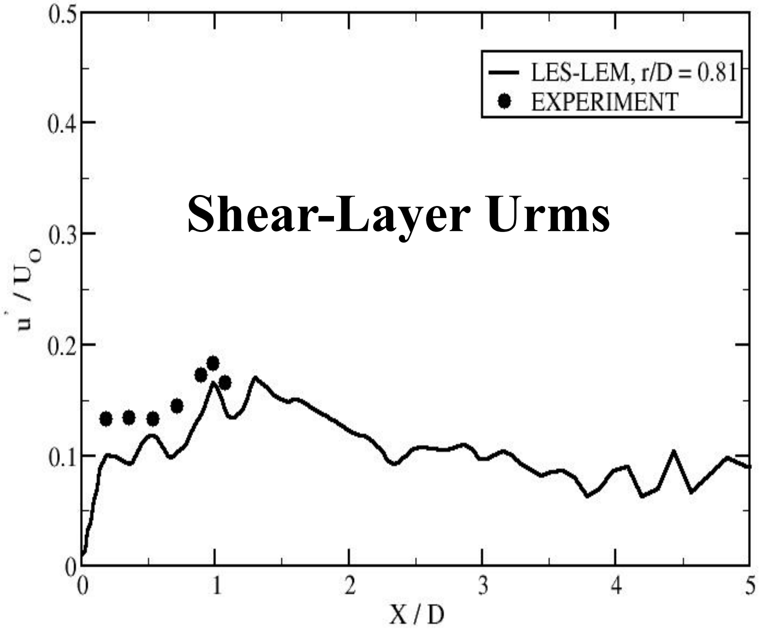
Methane Mass fraction

LEMLES of LM6000

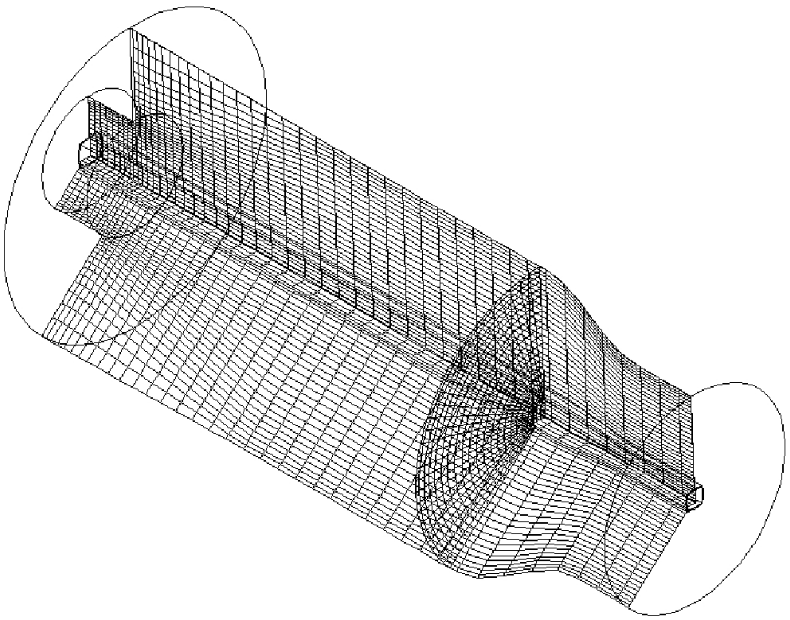








Regimes in the Combustion Zone



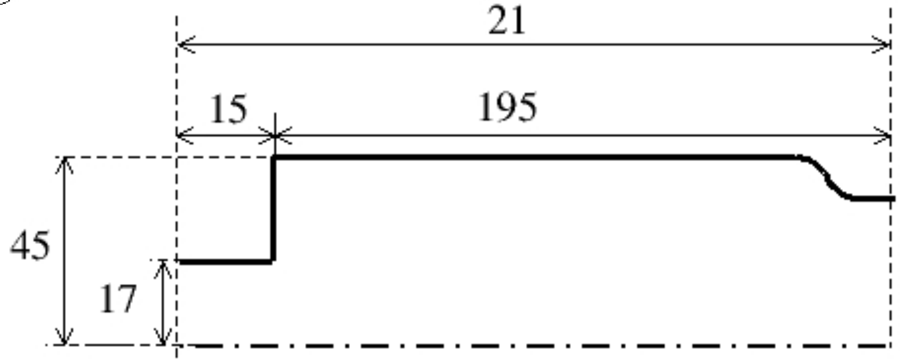
$T_{inlet} = 644K$

$P_{inlet} = 6.1$ atm

Swirl No = 1.1

$0.45 < \phi < 1.0$

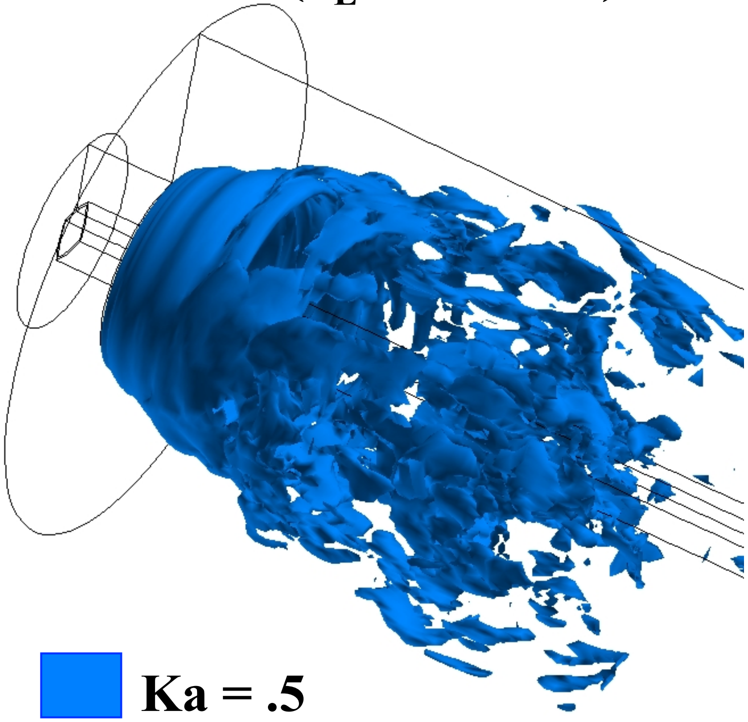
140x75x81 outer cylindrical
140x21x21 inner Cartesian
18 LEM cells per LES cell
- resolve nearly all scales



Dimensions are given in mm

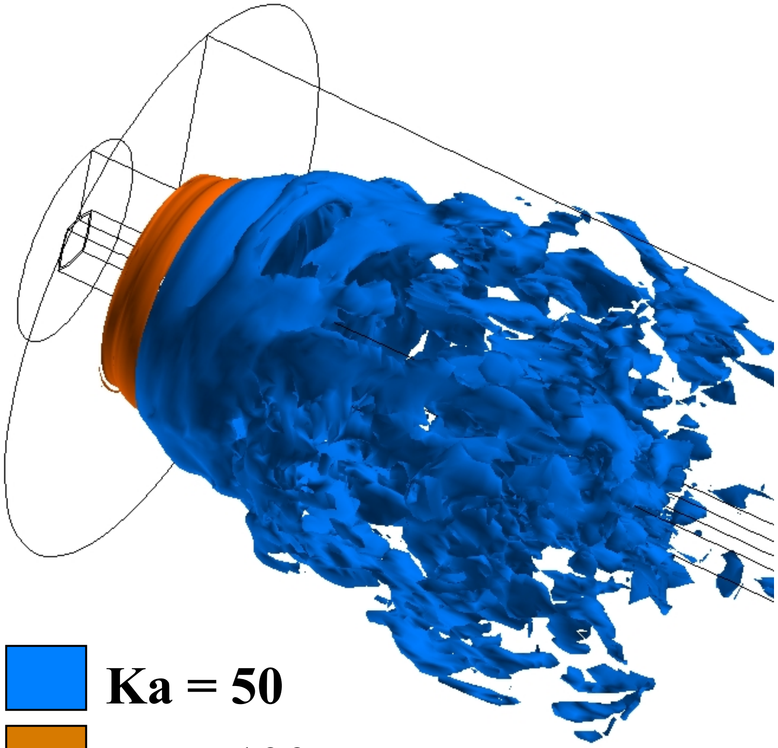
Combustion regimes

$\Phi = 1.0$ ($S_L = 0.8$ m.s^{-1})



🟦 **Ka = .5**

$\Phi = 0.45$ (SL = 0.09 m.s-1)

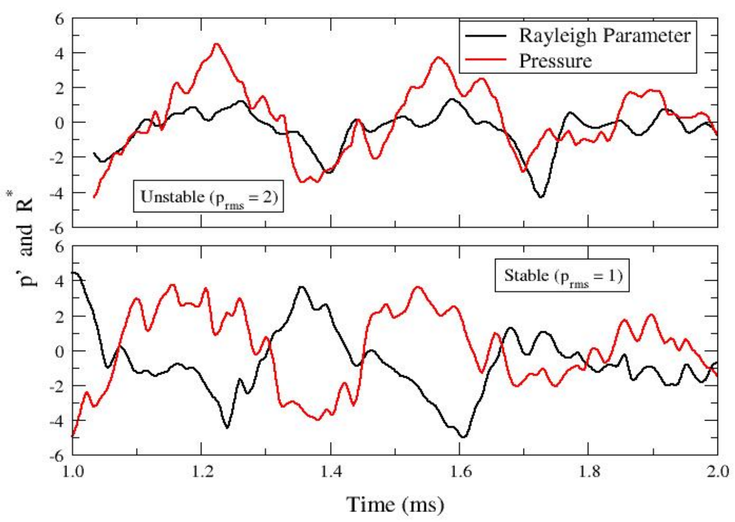


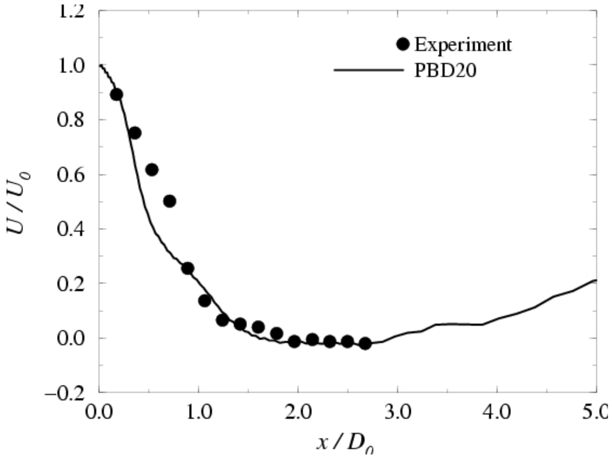
🟦 **Ka = 50**

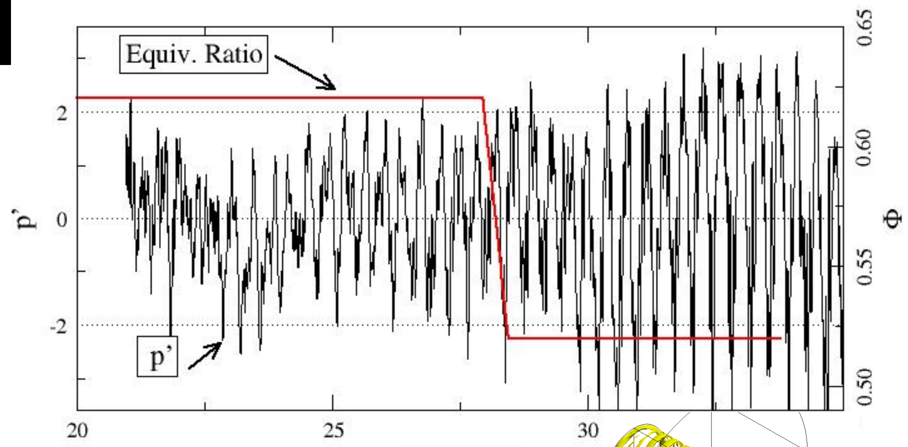
🟧 **Ka = 100**

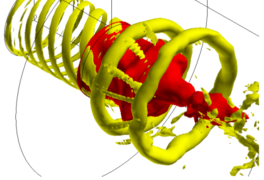
- **Ka depends strongly on S_L**
- **Only very lean flames can propagate in the BRZ regime**

Combustion Instability by Fuel Modulation



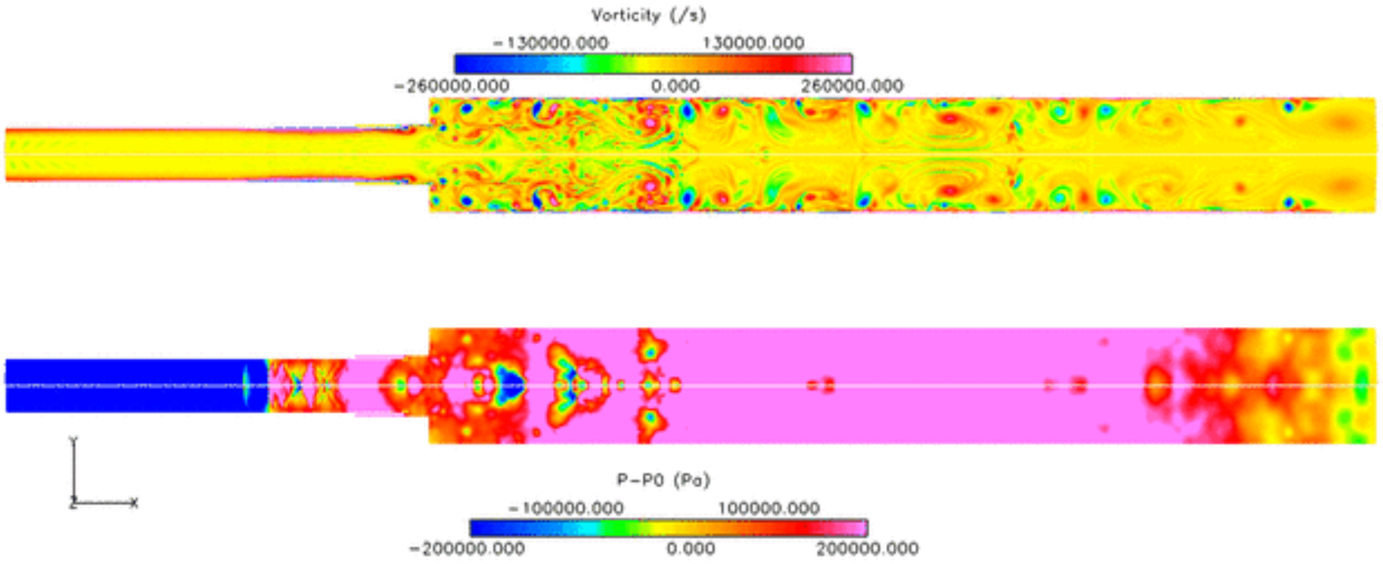


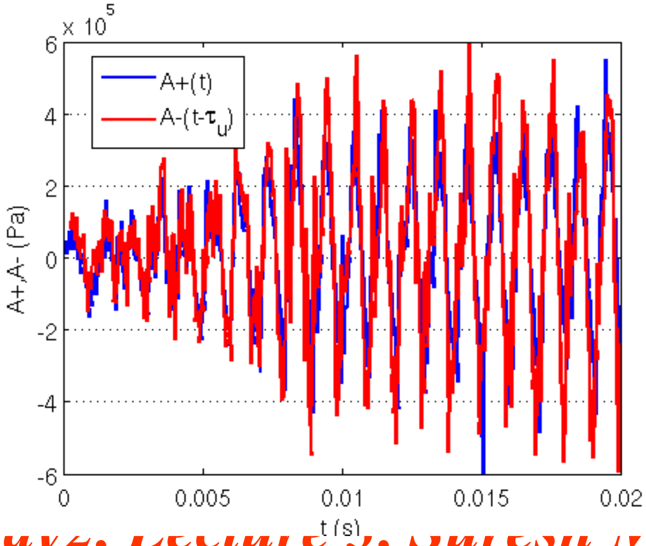




GE LM6000 (Comb Symp 2000; JSC, 2000)

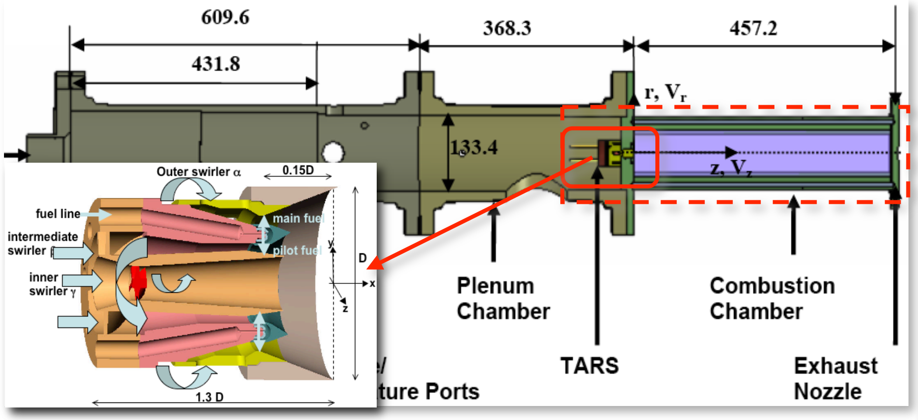
Combustion Instability in Shear-Flame GOX-GH2 Anchored Combustor





- Transition to CI simulated using physics based BCs without any model changes
- Acoustic reflections from inlet is critical and essential to capture
- Experiments: (Yu et al., 2008)

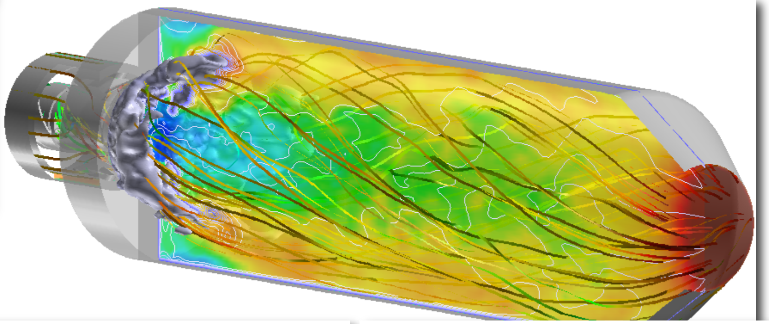
The Triple Annular Research Swirler

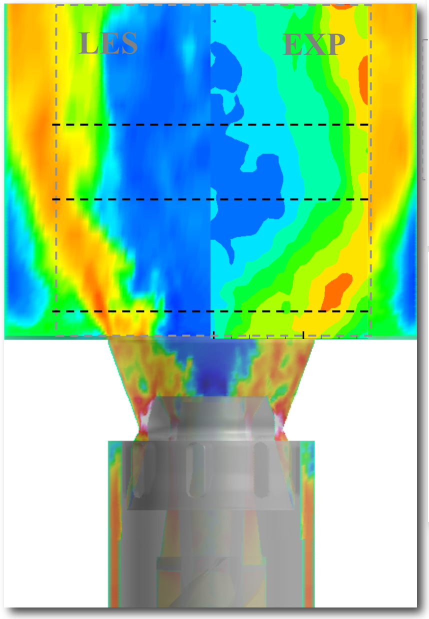


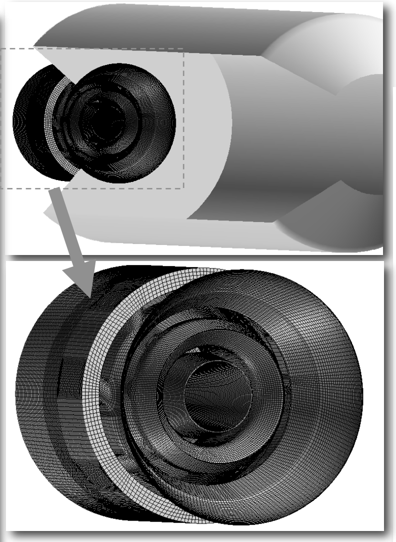
TARS S304545

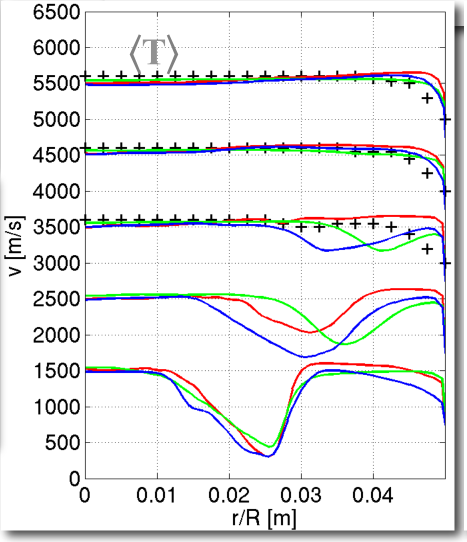
D=50 mm, Re≈50,000, ϕ≈0.5

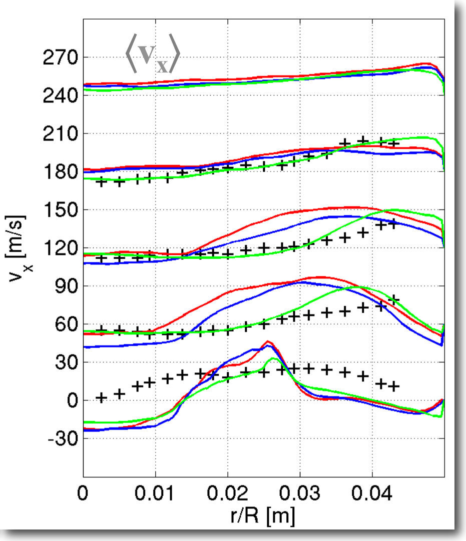
Exp. by Li G. & Gutmark E.









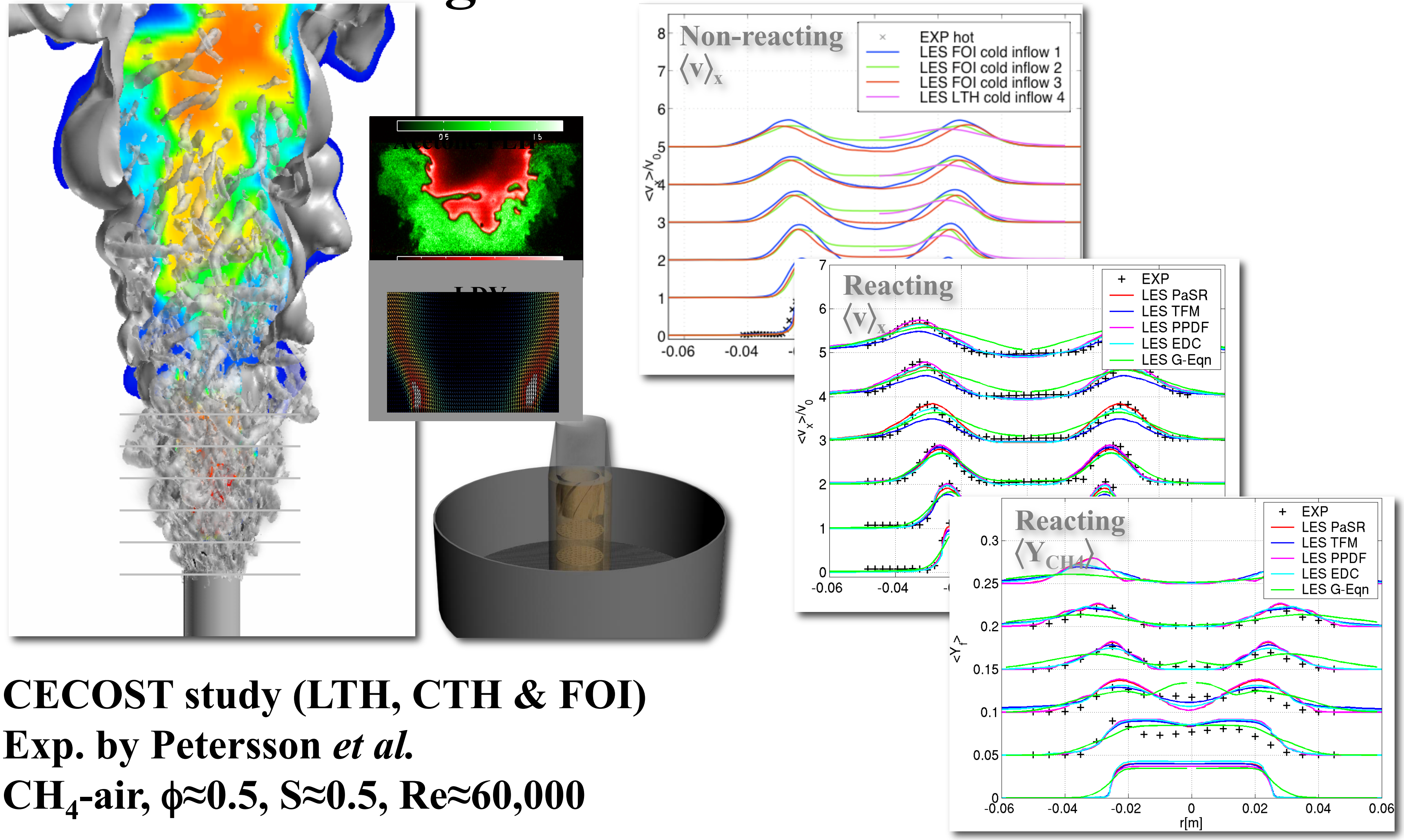


Li G. & Gutmark E.; 2006, AIAA.J., 44, p 444

Fureby C., Grinstein F.F., Li G. & Gutmark E.; 2006, 31st Int. Symp on Comb.

Courtesy C. Fureby

Cheng's Low Swirl Burner



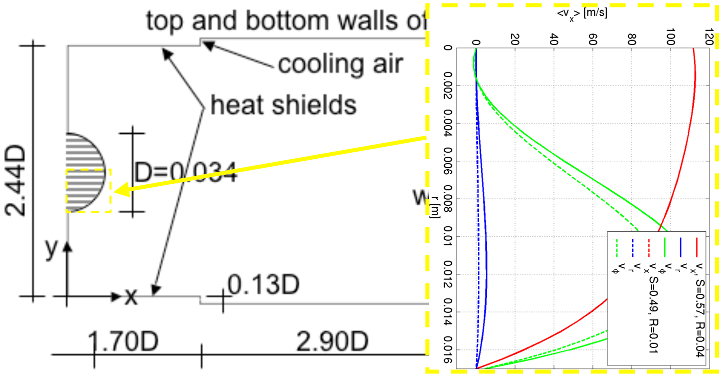
CECOST study (LTH, CTH & FOI)
Exp. by Petersson *et al.*
CH_4-air, $\phi \approx 0.5$, $S \approx 0.5$, $Re \approx 60{,}000$

Petersson et al, Appl. Optics, 2007
Nogenmyr et al.; 2008, Comb. Flame.
Nogenmyr et al.; 2008, AIAA 2008-0513.

Courtesy C. Fureby

The GELM 6000 Laboratory Combustor

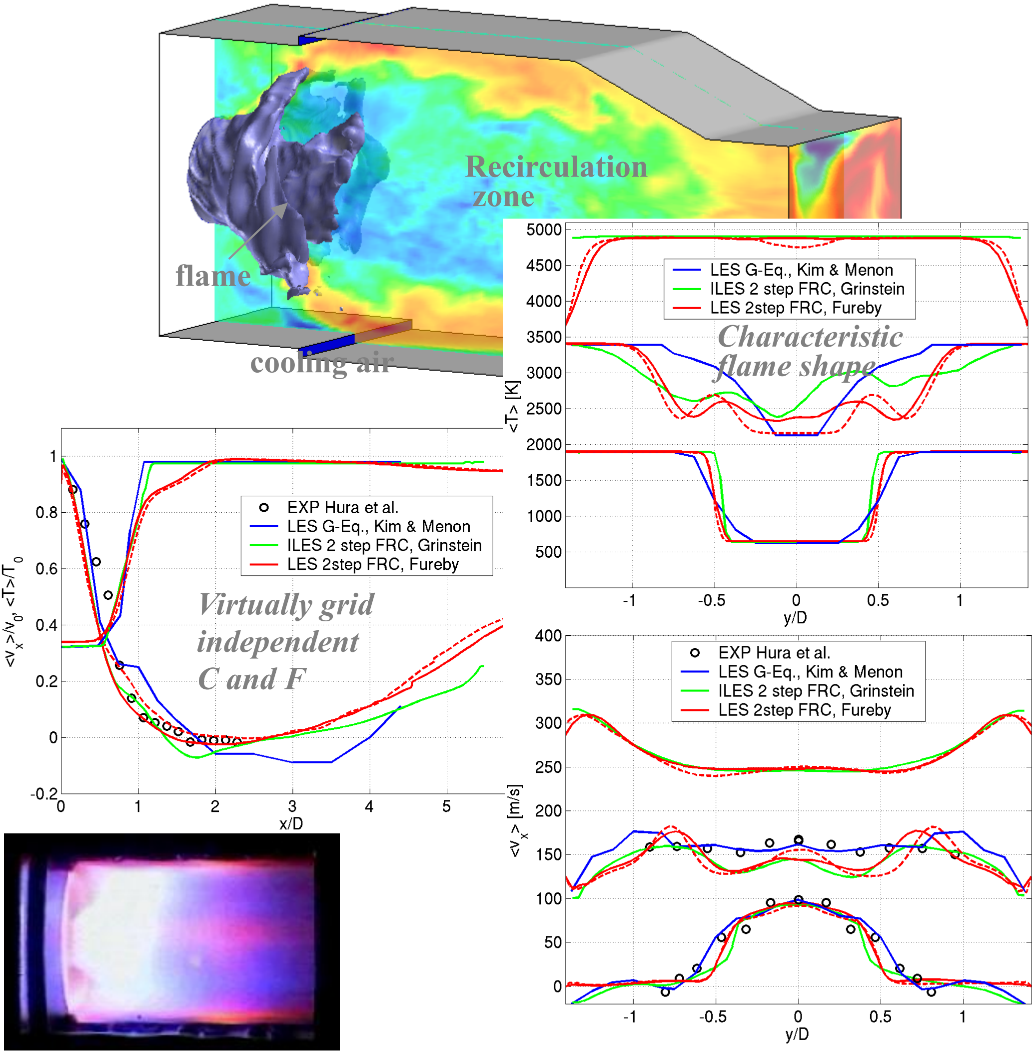
Rectangular combustor developed by GE (Hura *et al*, 1998) to emulate GE LM6000/2500



RANS by GE
LES by GaTech, FOI, Fluent, …

Swirlers excluded, modeled by inflow profiles provided by GE

Grids: 0.6, 1.2 & 2.4 Mcells
CH_4/air, ϕ≈0.56
Re=320,000, S≈0.56

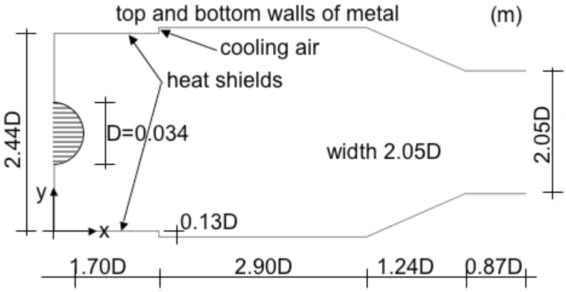


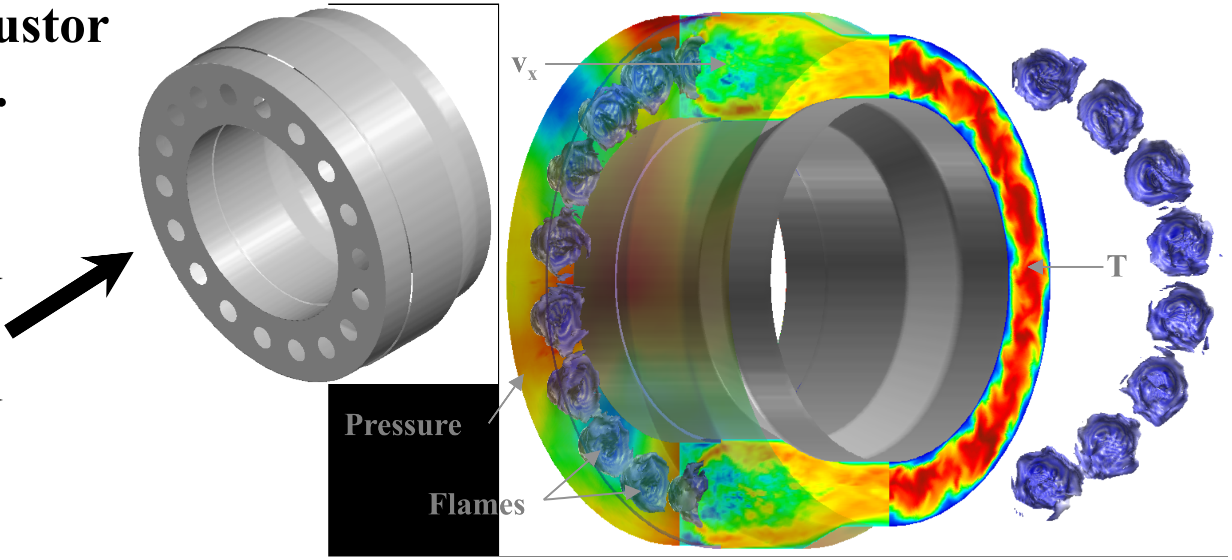
Kim W.-W. & Menon S.; 1999,Comb. Sci.Tech. 143, p 25
Grinstein F.F. & Fureby C.; 2004, Proc. 30th Int Symp on Comb, p 1791

Courtesy C. Fureby

The Annular Multi-Burner Combustor

18 burner annular combustor constructed from the lab.
GE LM6000/2500 model





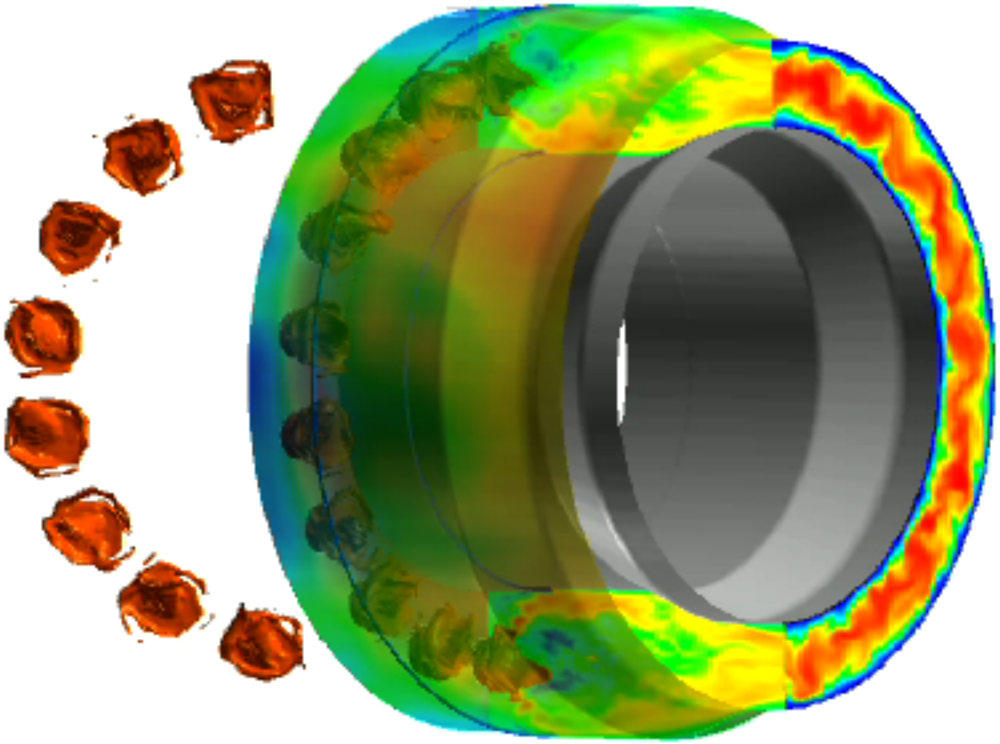
Grids: 10.8, 21.6 Mcells
Re=320,000
CH_4/air, n-$C_{10}H_{22}$/air
S≈0.56 & 0.49 (Swirl #)
R=0.01 & 0.04 (Radial #)
Outlet impedance:s
LRM: $L_1=K(p-p_\infty)$

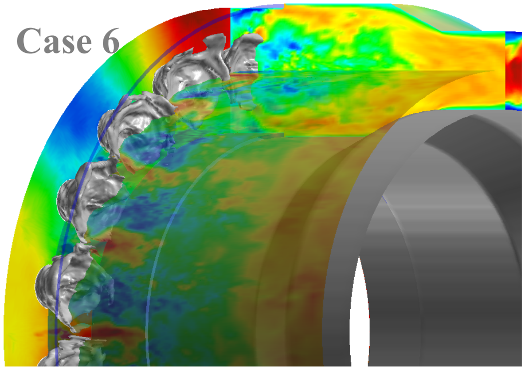
Model	*Case*	*Grids, Mcells*	*Re*	*S*	*R*	*RR model*	*Outflow BC*	*Fuel*	*LES_{IQ}*
Single laboratory combustor	1	0.6	320,000	0.56	0.01	EDC	WT, K=1	CH_4	
	2	1.2	320,000	0.56	0.01	EDC	WT, K=1	CH_4	
	3	1.2	320,000	0.56	0.01	QL	WT, K=1	CH_4	
	4	2.4	320,000	0.56	0.01	EDC	WT, K=1	CH_4	
Single 20° sector combustor	5	0.6	320,000	0.56	0.01	EDC	WT, K=1	CH_4	
Model 18 burner annular combustor	6	10.8	320,000	0.56	0.01	EDC	WT, K=1	CH_4	0.76
	7	10.8	320,000	0.56	0.01	EDC	WT, K=10	CH_4	
	8	10.8	320,000	0.56	0.01	EDC	WT, K=1	n-$C_{10}H_{22}$	
	9	10.8	320,000	0.49	0.01	EDC	WT, K=1	CH_4	
	10	10.8	320,000	0.56	0.04	EDC	WT, K=1	CH_4	
	11	21.6	320,000	0.56	0.01	EDC	WT, K=1	CH_4	0.82
	12	42.2	320,000	0.56	0.01	EDC	WT, K=1	CH_4	0.87

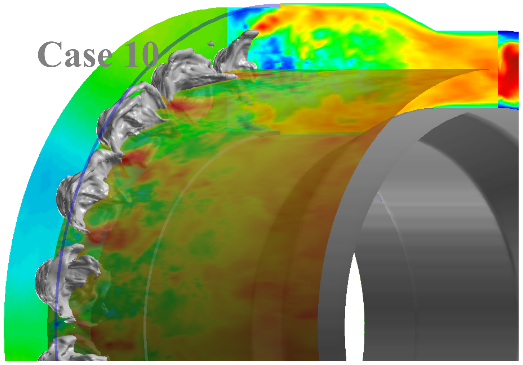
K=1, K=10 (partially reflecting)
K = 1 outflow is non-reflecting

Courtesy C. Fureby

The Annular Multi-Burner Combustor







Case 6: CH_4, K=1, S=0.54, R=0.01
- **Burner-to-to-burner interactions**
- **Pressure oscillations on the ‘liner’ surface**
- **Unsteady wall jets, Inhomogeneous outlet T**
- **Unsteady recirculation region,**
- **Different time scales**

Small modification in key parameters changes the overall flow substantially. E.g. by changing R

Note difference in p

Courtesy C. Fureby

CESAR Engine Models

Single sector single-burner and fully annular multi-burner CESAR engine combustor models.

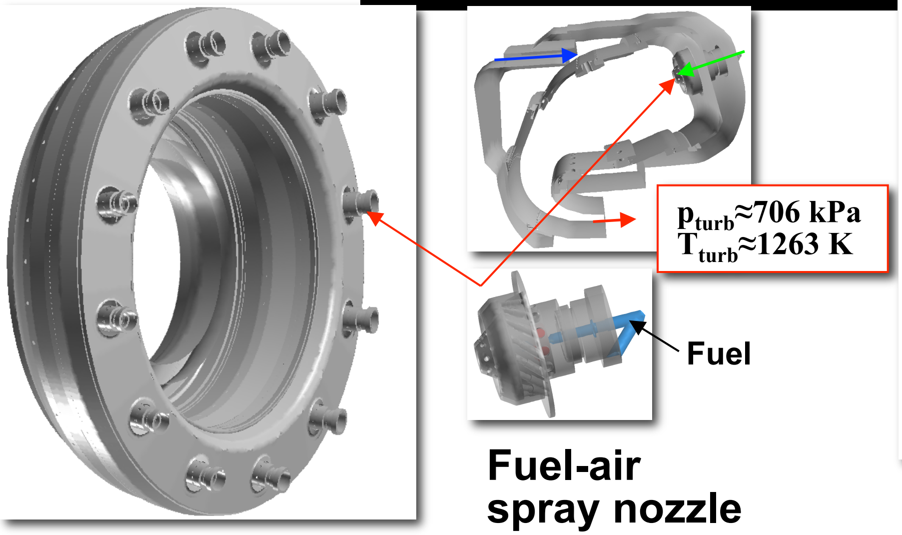
- Only combustor considered.
- All geometrical details included.
- Rich burn, Quick mix & Lean burn (RQL).
- Fuel (Jet A) assumed to be vaporized.

- Unstructured grids (necessary)
- Single-burner: 2.1 Mcells
  4.2 Mcells
  8.3 Mcells
- Multi-burner: 25 Mcells
  50 Mcells
  100 Mcells

Multi-burner model **Single-burner model**

- 12 burners
- BC as for SBM

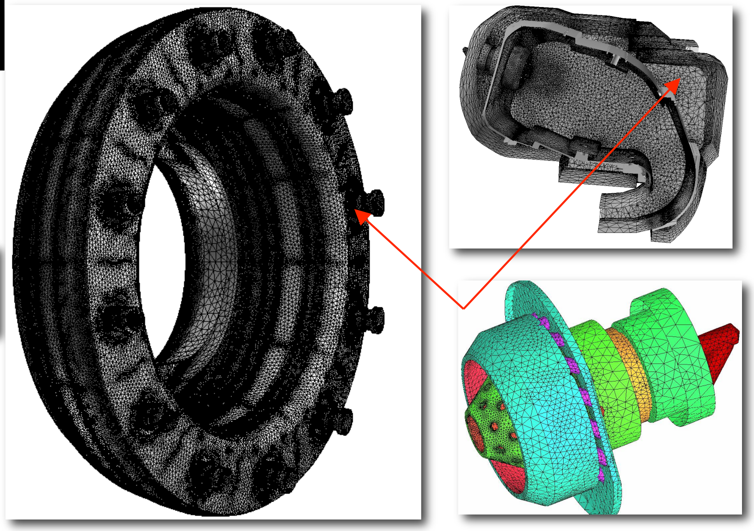
[redacted]



$p_{turb} \approx 706$ kPa
$T_{turb} \approx 1263$ K

Fuel-air
spray nozzle

Multi-burner model **Single-burner model**



BL's poorly resolved ⇒ Wall model.

Jet A – Air Chemical Kinetics

Jet A is a kersone grade fuel with a carbon number distribution between
8 and 16.

Here, Jet A is assumed to consist of C_8H_{18}, $C_{10}H_{22}$, $C_{12}H_{22}$, $C_{12}H_{24}$, $C_{14}H_{26}$ and $C_{16}H_{28}$ with the average molecular formula $C_{12}H_{23}$.

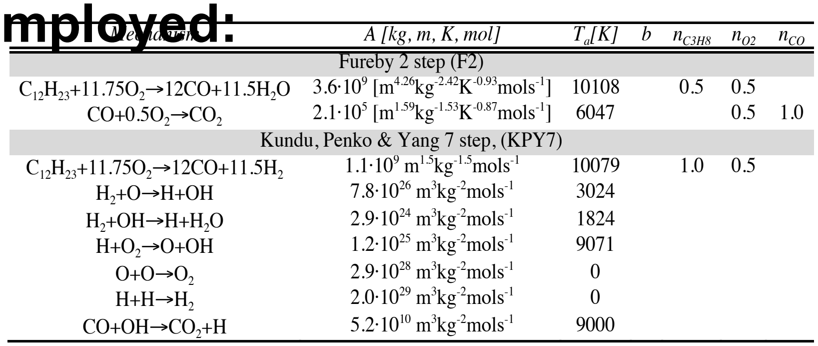
C_7H_{16} (n-heptane); 561 species and 2539 reactions (Lu & Law 2008)

$C_{12}H_{23}$; 18 species and 46 reactions (Yungster & Breisacher 2005)

Two global/reduced mechanisms employed:

2-step mechanism formulated by matching s_u and T_{ad} with exp. data. works OK in $0.4<\phi<1.2$.

7-step obtained from the literature works well in $0.4<\phi<2.0$.



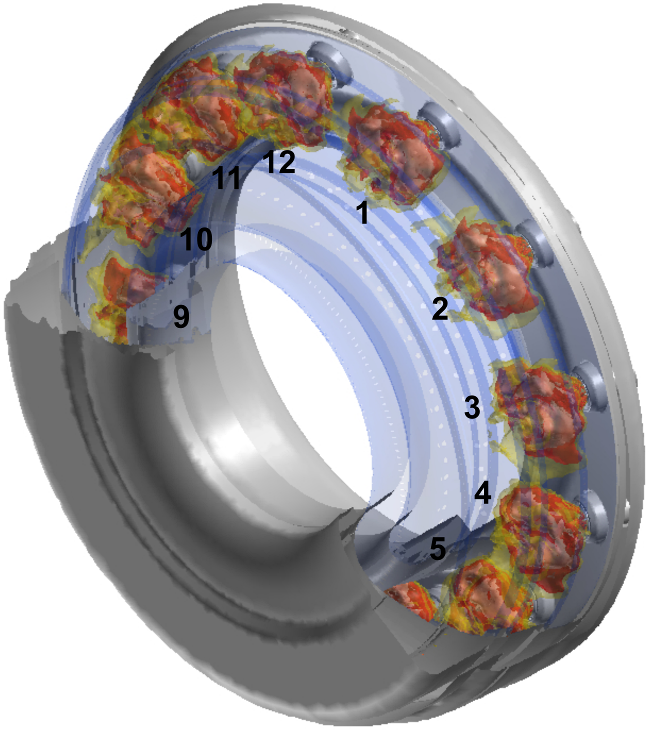
Mechanism	A [kg, m, K, mol]	T_a[K]	b	n_{C3H8}	n_{O2}	n_{CO}
Fureby 2 step (F2)						
$C_{12}H_{23}+11.75O_2 \rightarrow 12CO+11.5H_2O$	$3.6\cdot10^9$ [$m^{4.26}kg^{-2.42}K^{-0.93}mols^{-1}$]	10108		0.5	0.5	
$CO+0.5O_2 \rightarrow CO_2$	$2.1\cdot10^5$ [$m^{1.59}kg^{-1.53}K^{-0.87}mols^{-1}$]	6047			0.5	1.0
Kundu, Penko & Yang 7 step, (KPY7)						
$C_{12}H_{23}+11.75O_2 \rightarrow 12CO+11.5H_2$	$1.1\cdot10^9$ $m^{1.5}kg^{-1.5}mols^{-1}$	10079		1.0	0.5	
$H_2+O \rightarrow H+OH$	$7.8\cdot10^{26}$ $m^3kg^{-2}mols^{-1}$	3024				
$H_2+OH \rightarrow H+H_2O$	$2.9\cdot10^{24}$ $m^3kg^{-2}mols^{-1}$	1824				
$H+O_2 \rightarrow O+OH$	$1.2\cdot10^{25}$ $m^3kg^{-2}mols^{-1}$	9071				
$O+O \rightarrow O_2$	$2.9\cdot10^{28}$ $m^3kg^{-2}mols^{-1}$	0				
$H+H \rightarrow H_2$	$2.0\cdot10^{29}$ $m^3kg^{-2}mols^{-1}$	0				
$CO+OH \rightarrow CO_2+H$	$5.2\cdot10^{10}$ $m^3kg^{-2}mols^{-1}$	9000				

Diffusivities modeled by matching Sc_i numbers.

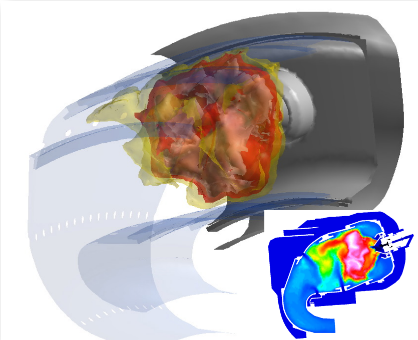
Ajmaini et al AIAA 2006-4791
Yungster & Breisacher AIAA 2005-4210
Meredith & Black AIAA 2006-1168
Mawid & Sekar ASME Turbo Expo 2006

Results: CESAR Combustor

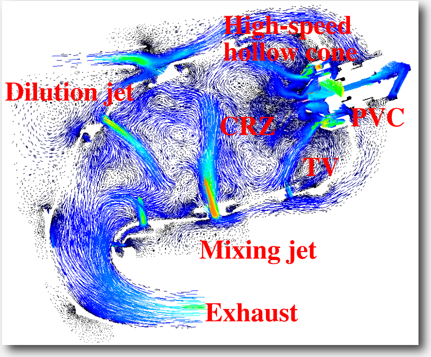
Overview **of the key features at low power engine operating conditions**



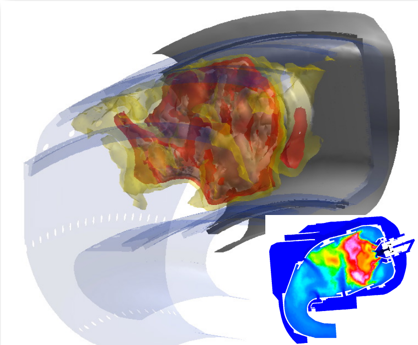
Iso-surfaces of T at 2000, 1800 & 1600 K



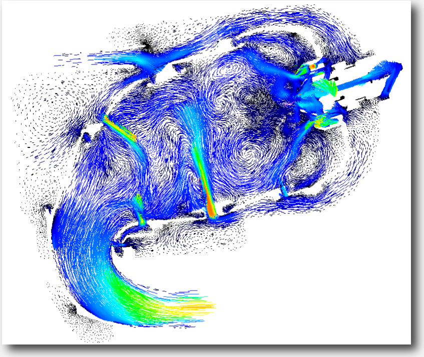
Single sector



Single Sector



Burner 12

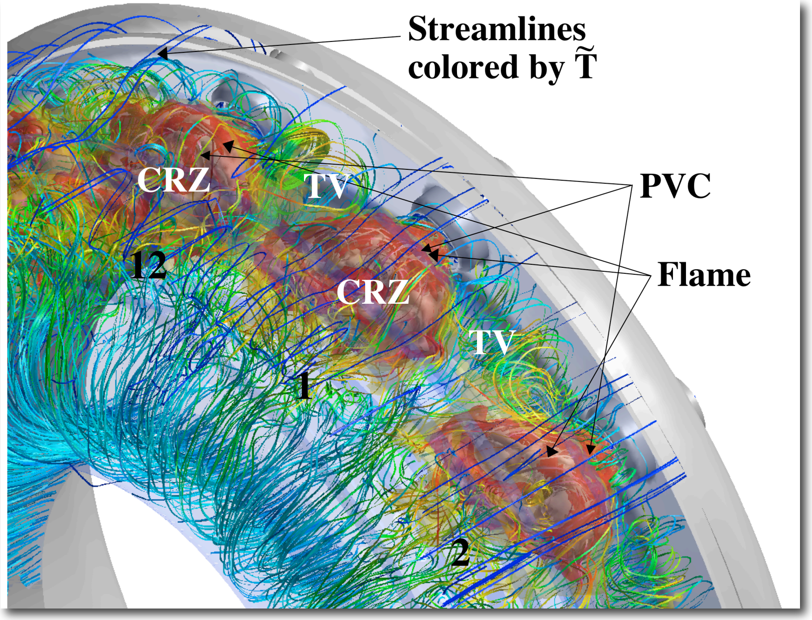


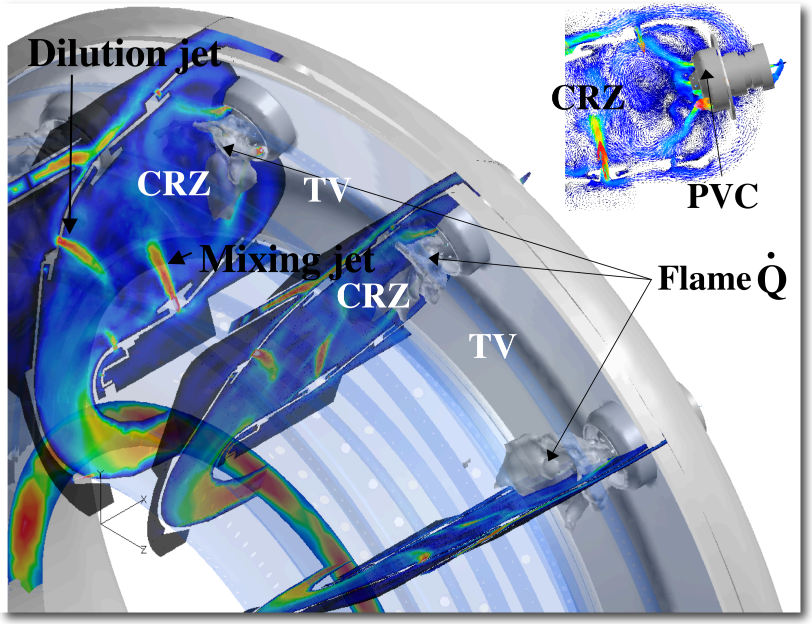
Burner 12

- Single sector and multi-sector configurations globally similar but with differences
- Flames (Q) lifted from fuel-air spray nozzle
- CRZ, TV, PVC, mixing jet, diffusion jet, hollow flame cone etc. identified
- Rich burn, Quick mix, Lean burn (RQL) concept visualized

Results: CESAR Combustor cont’d

Overview of the key features at low power engine operating conditions

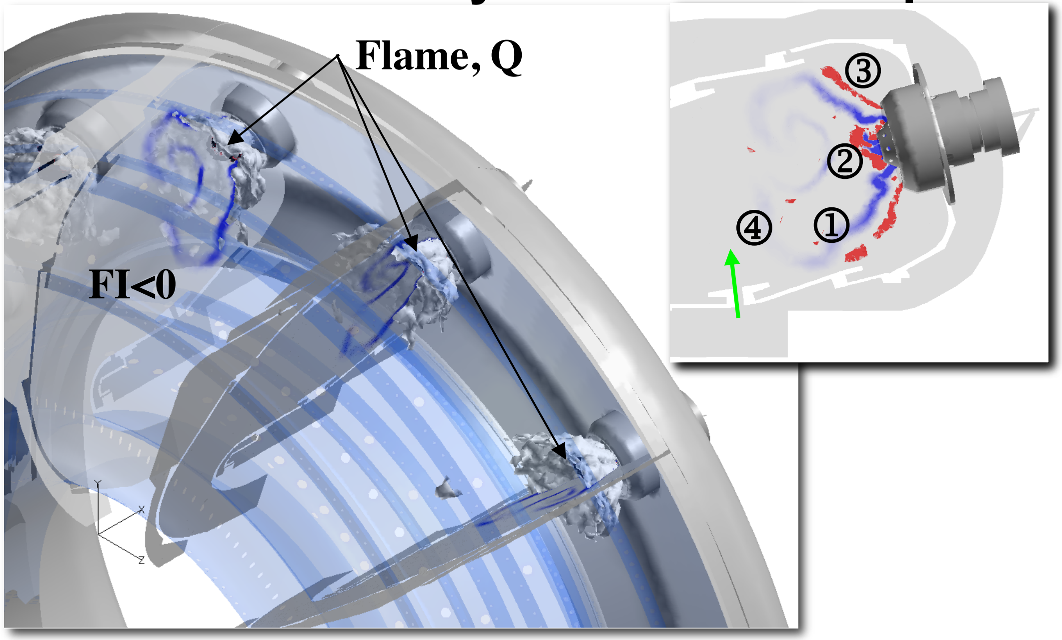




- Semi-connected TV structures exists between the air-fuel nozzles, flames & dump plane
- TV and CRZ stabilize and distributing hot combustion products
- Complex partially lifted flames that interact at their edges
- Most fuel rapidly fan out in a hollow cone surrounding the CRZ
- Cold air through mixing and dilution holes divide the combustor into three regions
  - ① Rich burn region – Rich swirling diffusion flame
  - ② Quick mixing region – Mixing hot combustion products with cold air
  - ③ Lean burn and acceleration region – Post combustion and acceleration

Results: CESAR Combustor cont’d

Overview of the key features at low power engine operating conditions



Flame Characteristics I

– Takeno’s flame index FI=$\nabla Y_{fuel} \cdot \nabla Y_{ox}$

– Premixed FI>0 Diffusion FI<0

① Main flame: Rich swirling diffusion flame

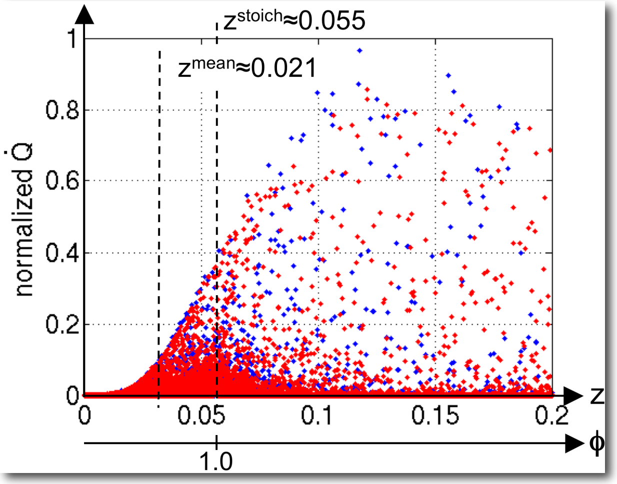
② Central pilot: Premixed flame coupled to the PVC

③ Outer premixed flame:Related to the TV

④ Lean burn flame: Due to mixing jet

Flame Characteristics II

– Consider scatter plots of $\dot{Q}$ vs z for SBC and MBC.



Considerable scatter

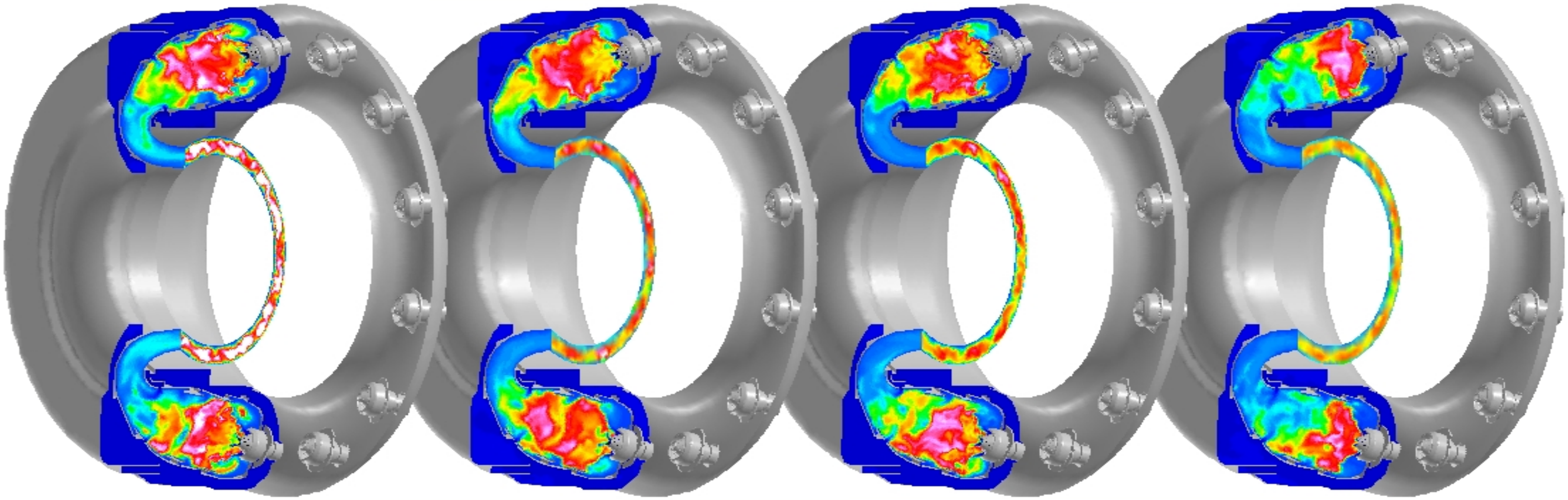
– Points above z^{mean} Main flame

– Points below z^{mean} Central pilot, outer premixed

– 2-step mech. acceptable *but*

Influence of Kinetics and Grid Resolution

**Of key importance to examine the sensitivity to combustion kinetics an
to grid resolution.
Not previously done!**



7 step chemistry
100 Mcells

2 step chemistry
100 Mcells

7 step chemistry
50 Mcells

2 step chemistry
50 Mcells

**Large differences observed at combustor outlet
Both kinetics and grid resolution affects the results**

Summary Comments

- Other GT LES studies are underway using various codes and not fully covered here
  - E.g., Moin, Pitsch, Yang, Oefelin
- 3D LES of realistic combustors are feasible on PC cluster and can be used to get insight into physics
  - Still no guarantee that the results are correct!
  - Many unresolved issues (see Lecture 1 comments)
- However, availability of commodity clusters offers new opportunities if the methodology and strategy are carefully chosen and implemented