Lecture 4
CFD for Bluff-Body Stabilized Flames

- Bluff Body Stabilized flames with or without swirl are in many laboratory combustors
- Applications to ramjets, laboratory burners, afterburners
- premixed and non-premixed gaseous combustion systems studied much detail*
- Spray in cross-flow for afterburners
  - Vitiated air flow
- Stability, blowoff, combustion dynamics

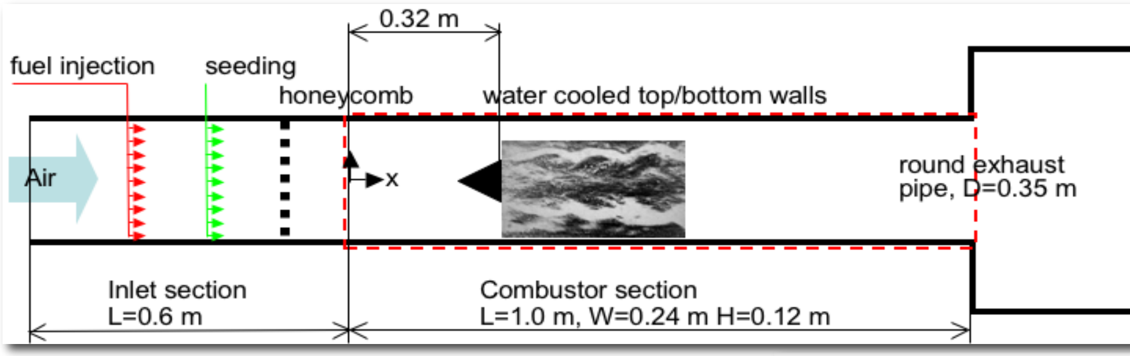
* Shanbhoque, Husain, Lieuwen: "Lean Blowoff of bluff body stabilized flames: Scaling and Dynamics," Prog. Energy & Comb. Sci, Vol. 35, 98-120, 2008

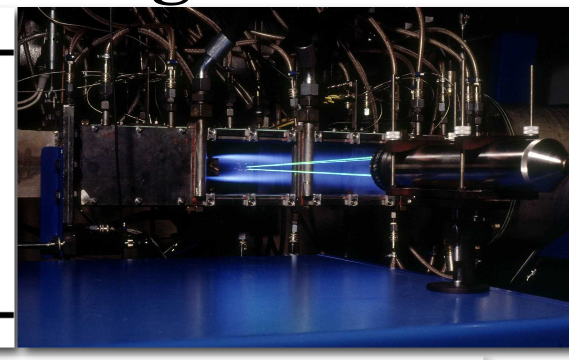
Day 2, Lecture 4, Suresh Menon, Georgia Tech

Issues to Consider

- Premixed flames – flame structure and coupling with heat release and vortex motion
  - Potential for combustion instability and LBO
  - Proper grid resolution to resolve flame wrinkling
  - Wall boundary conditions – isothermal/adiabatic
- Non-premixed flames
  - Fuel injection conditions
  - Resolution of the fuel jet shear layer
  - Mixing occurs downstream so grid resolution is needed in the injection region and downstream
  - Potential for liftoff, blowout
- Inflow and outflow conditions are important for dynamics

The Volvo Validation Rig

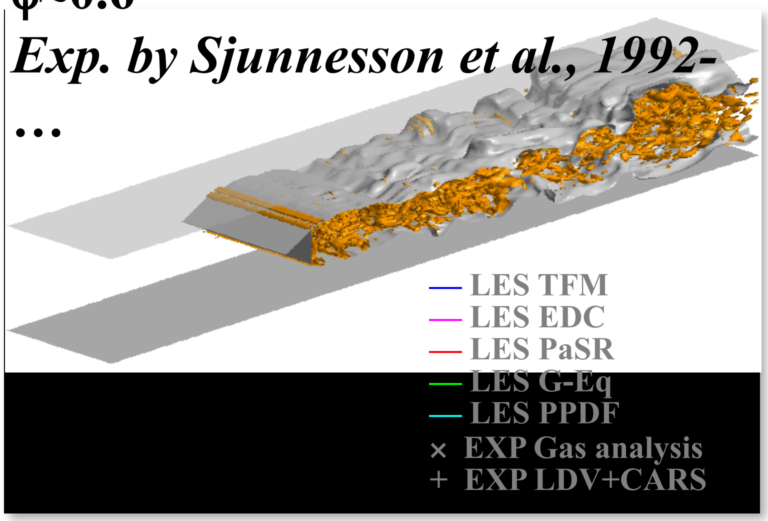


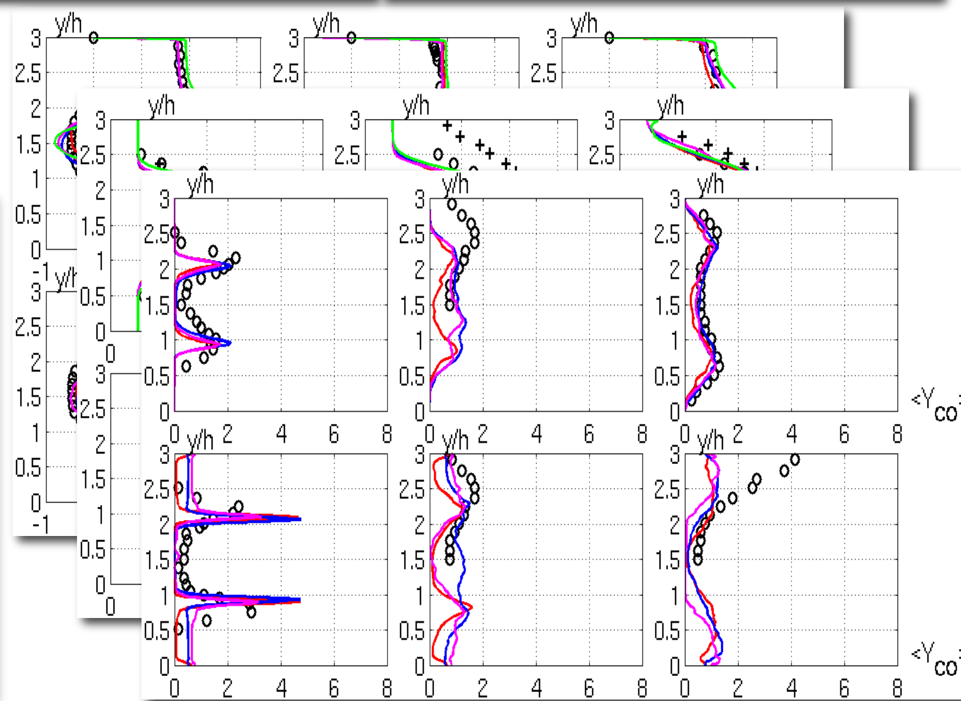


TARS S304545

Re≈30,000-45,000, C_3H_8-air, ϕ≈0.6

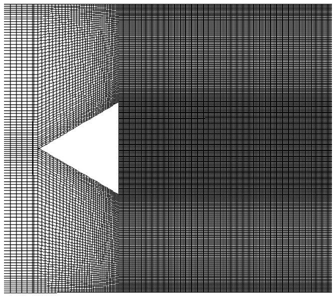
Exp. by Sjunnesson et al., 1992- …

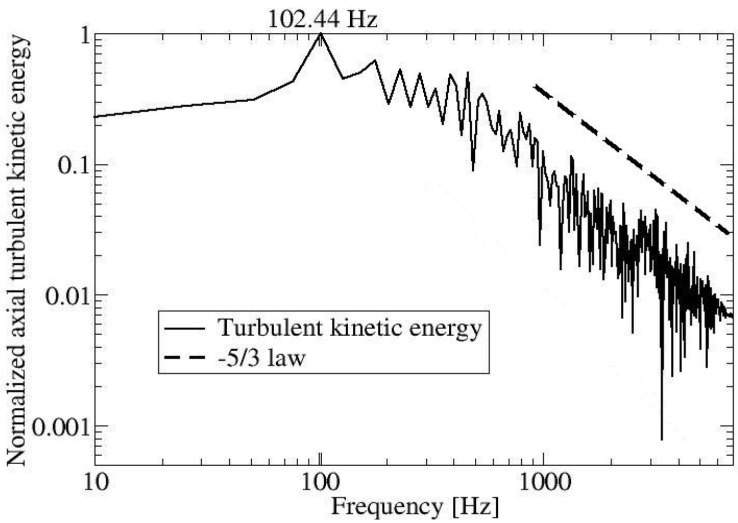




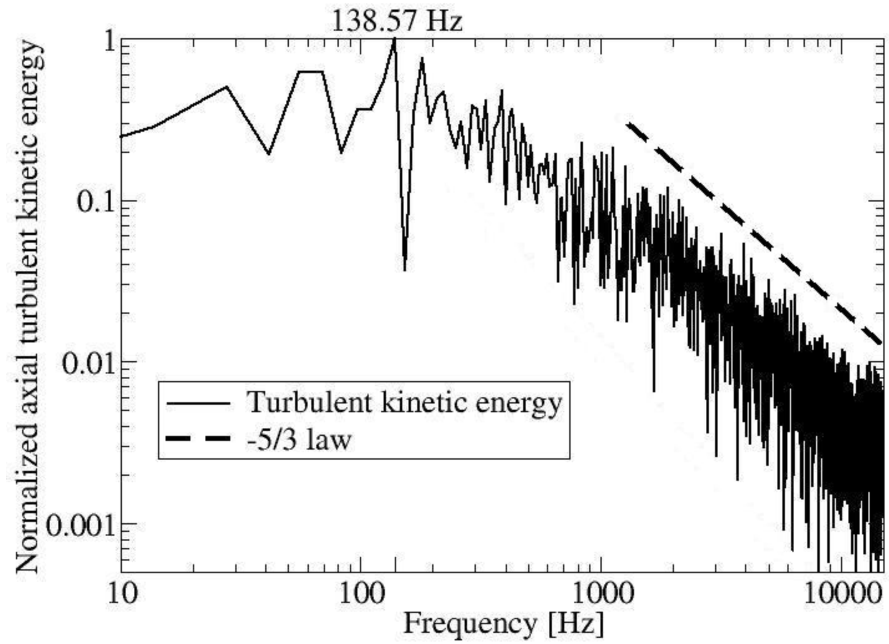
Fureby C.; 2006, AIAA 2006-0155
Fureby C.; 2007, AIAA 2007-0713
Fureby C.; 2009, AIAA 2008-1178

The VOLVO Afterburner





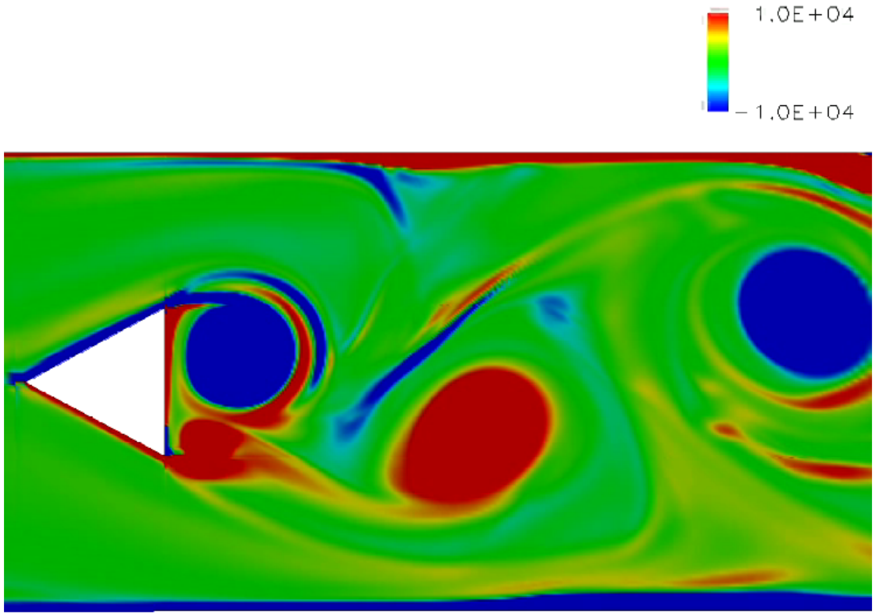
Non-Reacting Flow



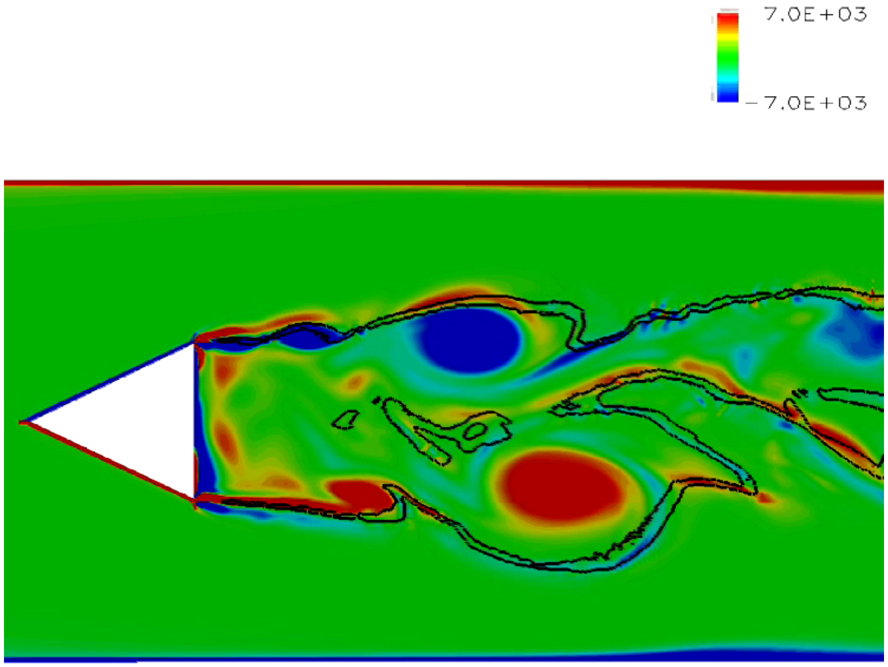
Reacting Flow

LEMLES approach determined the LES grid resolution for the Reacting case based on the Non-Reacting case result

Vortex Shedding in the VOLVO Afterburner

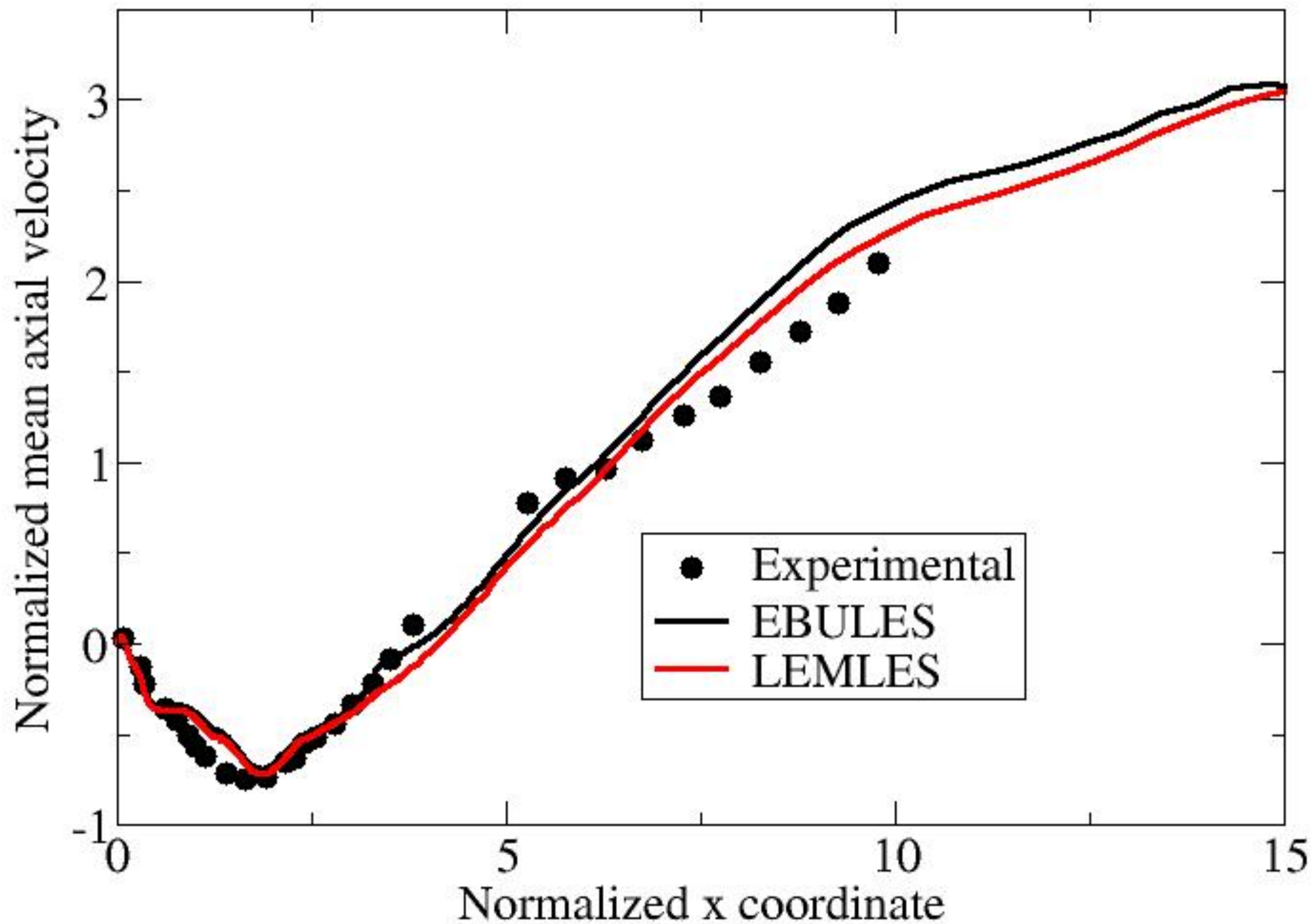


Non-Reacting Flow



Reacting Flow

Results – Reactive Flow



Axial profile of normalized axial velocity

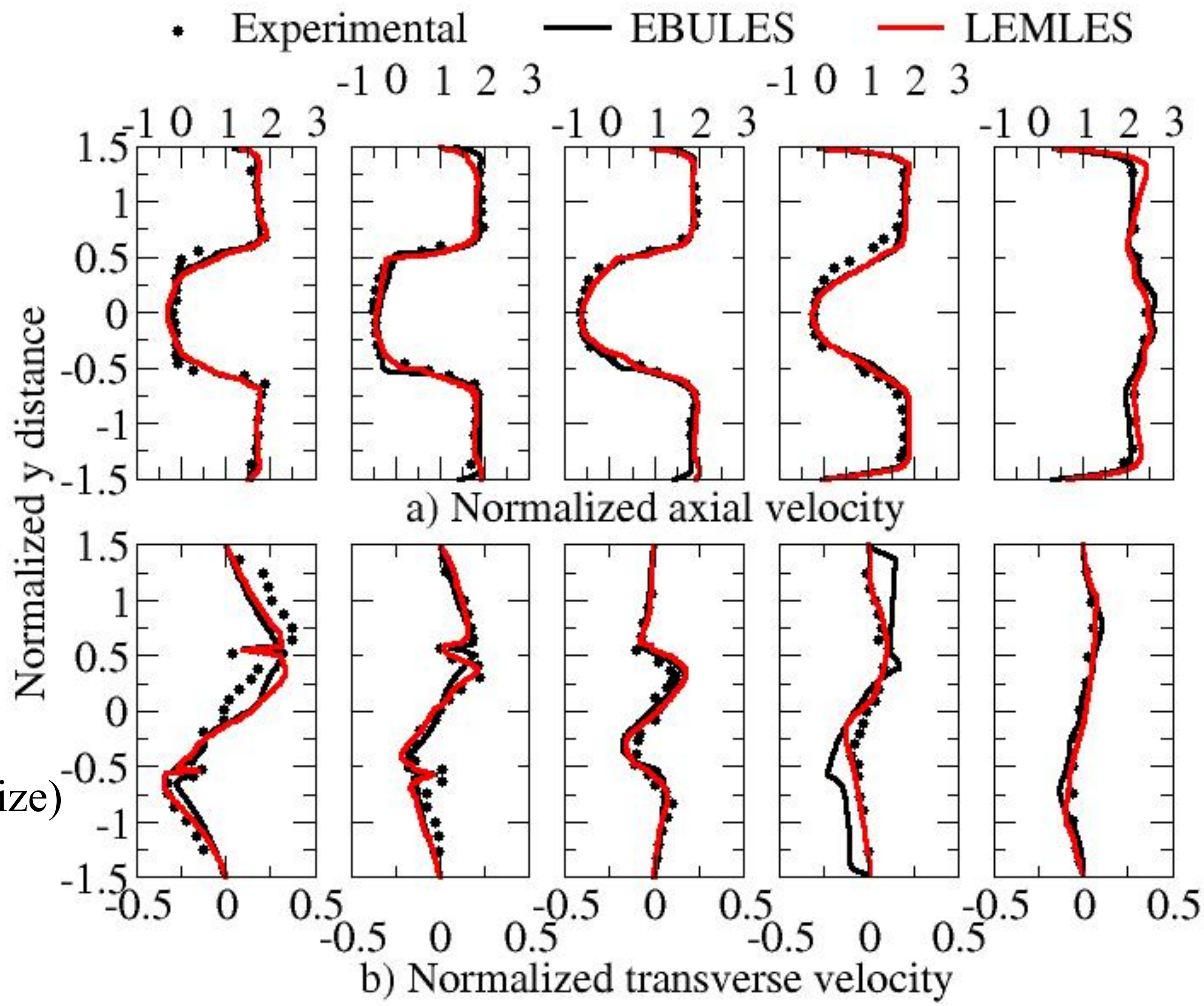
Results – Reactive Flow

Axial locations

(left to right):

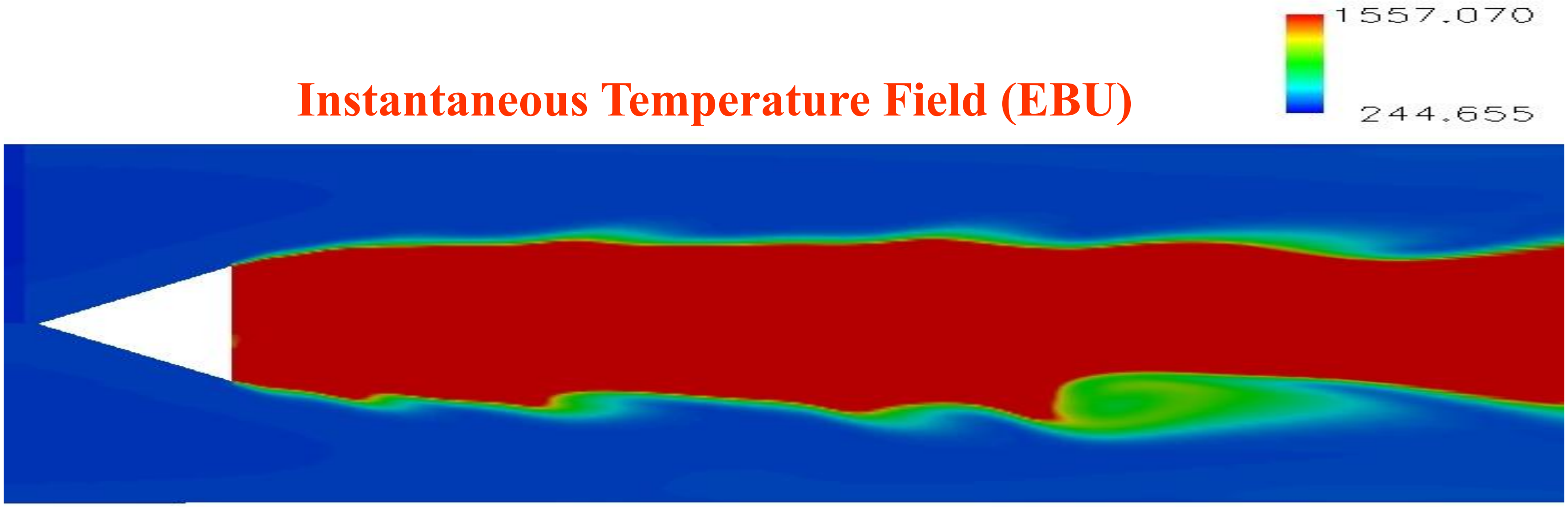
- 0.375 a
- 0.950 a
- 1.530 a
- 3.750 a
- 9.400 a

(a = bluff body size)

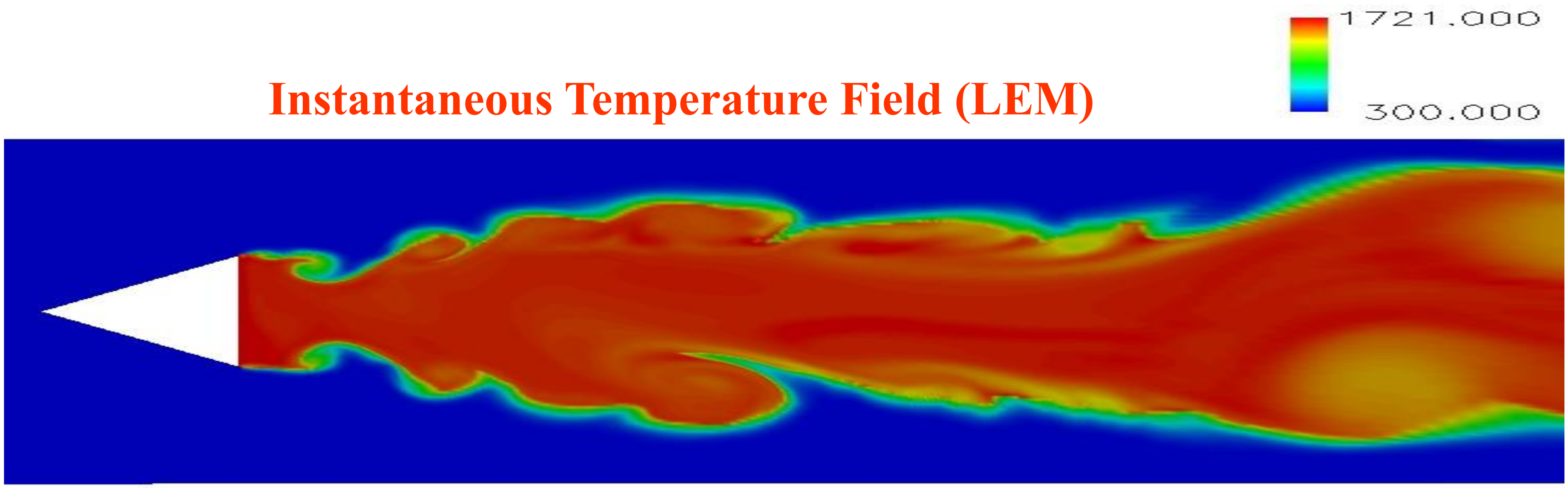


Transverse profiles of time - averaged velocities

Instantaneous Temperature Field (EBU)

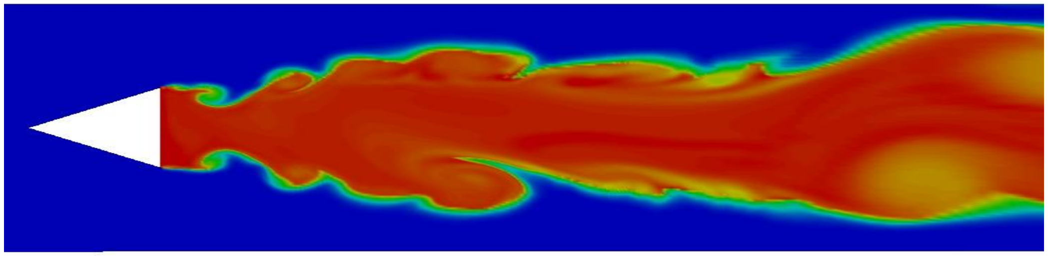


Instantaneous Temperature Field (LEM)

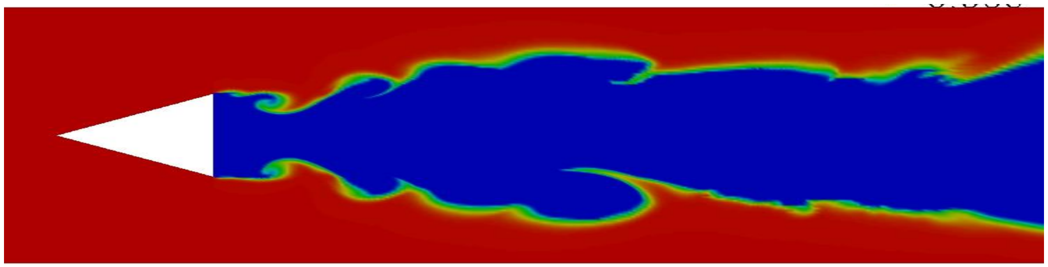


VOLVO Afterburner

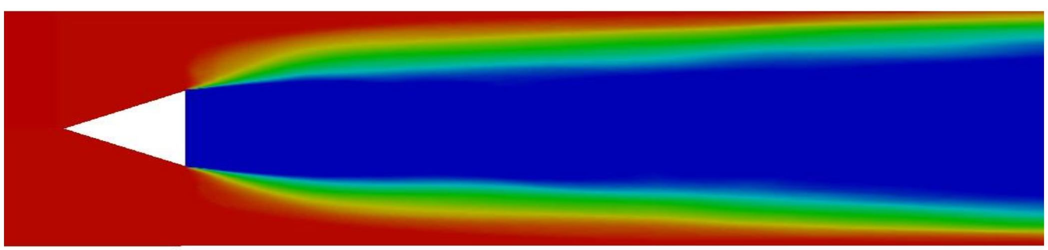
LEMLES Results



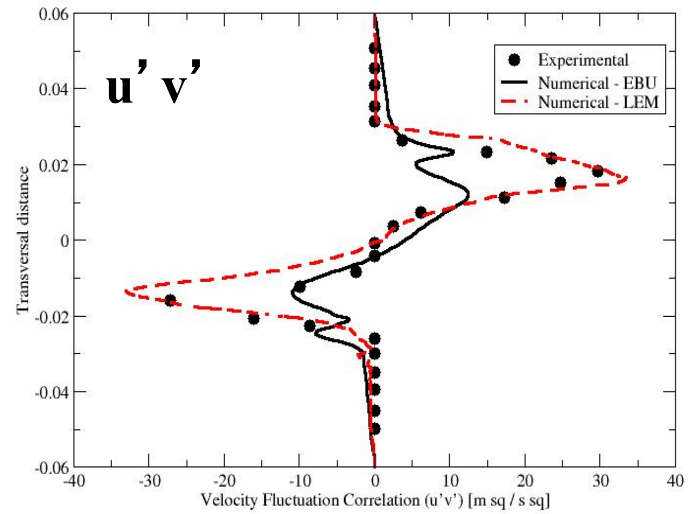
Instantaneous Temperature

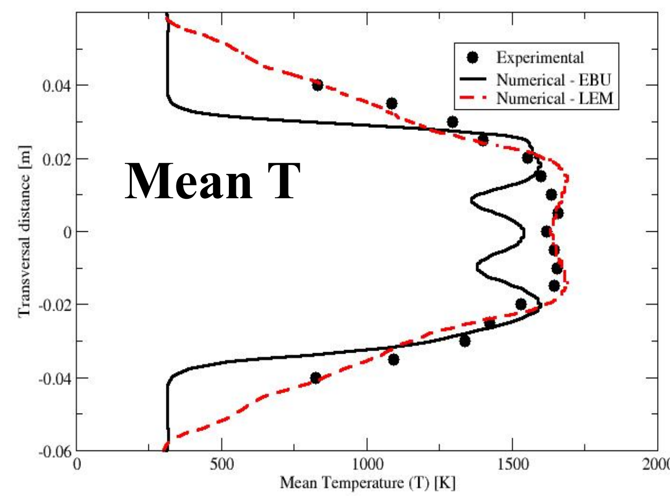


Instantaneous Fuel Mass Fraction



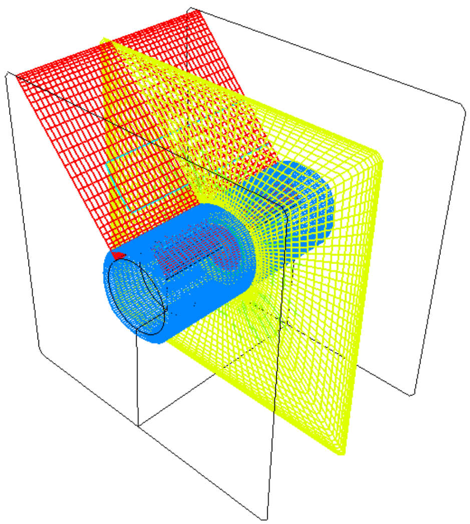
Time-averaged Fuel Mass Fraction

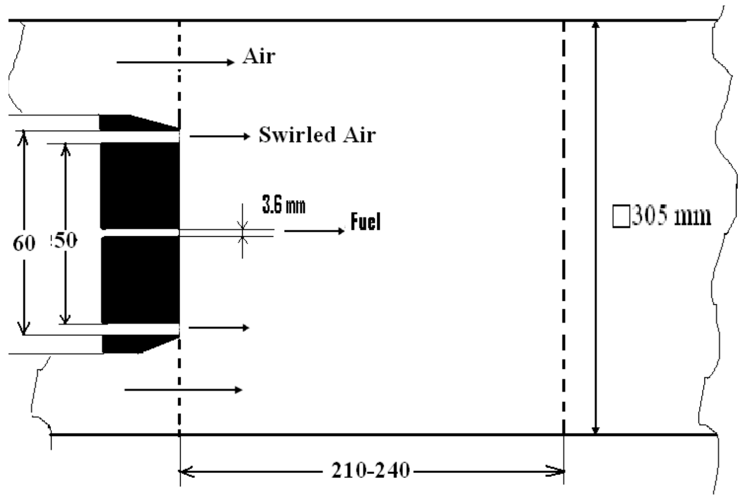




EBULES **LES@GT**

Non-premixed Bluff Body Swirl Flame Sydney/Sandia (Symp. 2006)





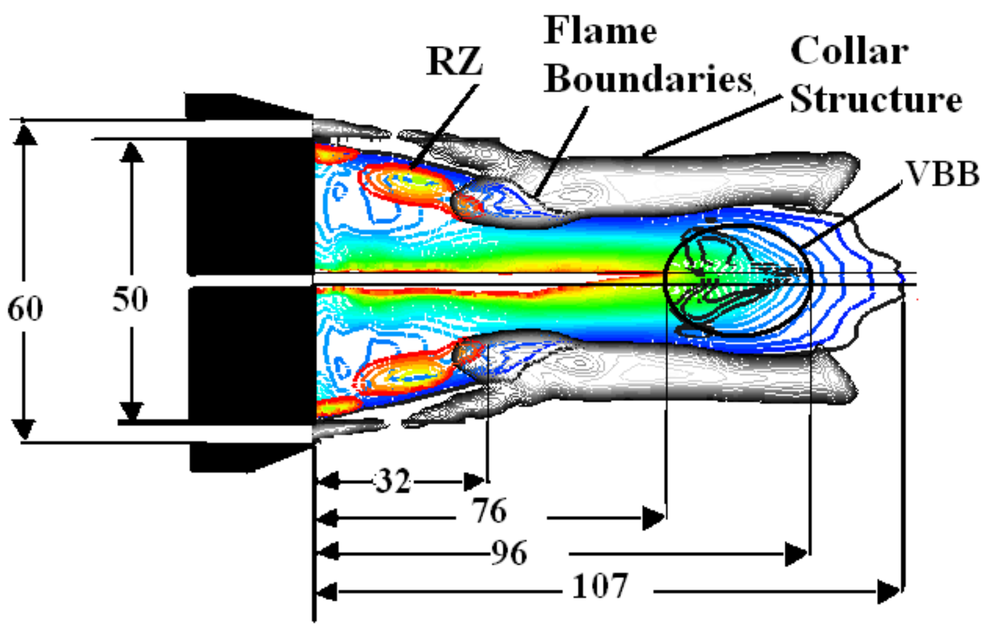
- 3.5 million LES cells
- 9 LEM cells / LES
- 12 LEM cell / LES
- 5-species, 1 step

Flame Type	Jet	S_g	U_j	U_s	U_e	R_s
N29S054	Air	0.55	66	29.74	20.	76,000
SMA2	CH_4/Air	1.59	66.3	16.26	20	32,400
SM1	CH_4	0.5	32.7	38.2	20.	54,000

El Asrag and Menon, 2005, 2006

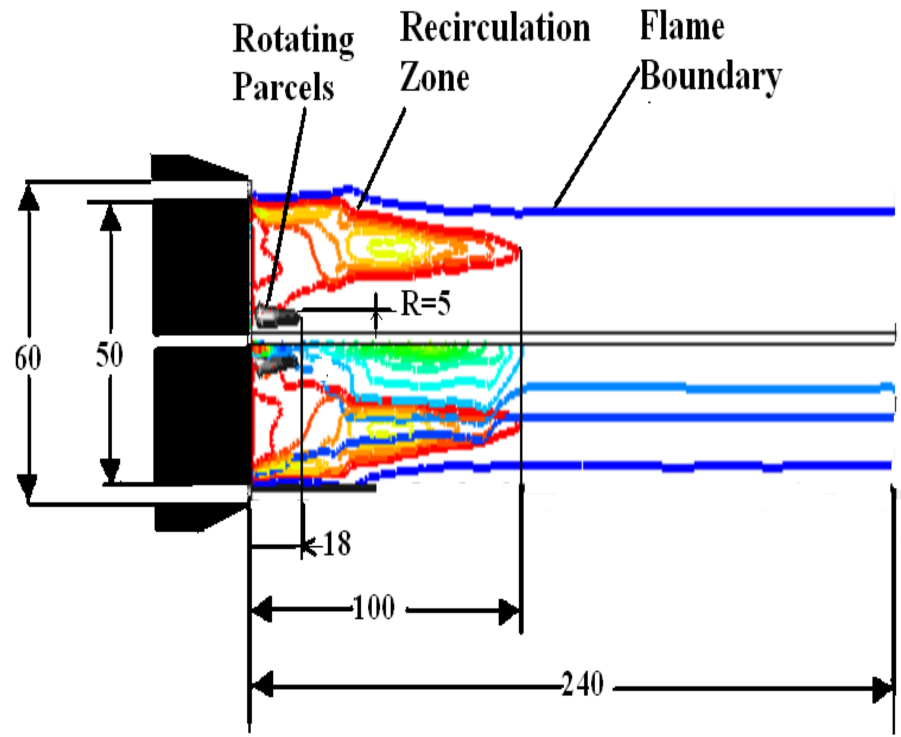
Mean Flow Features

ξ_{SM}=0.054



SM1 flame (S_g=0.5)

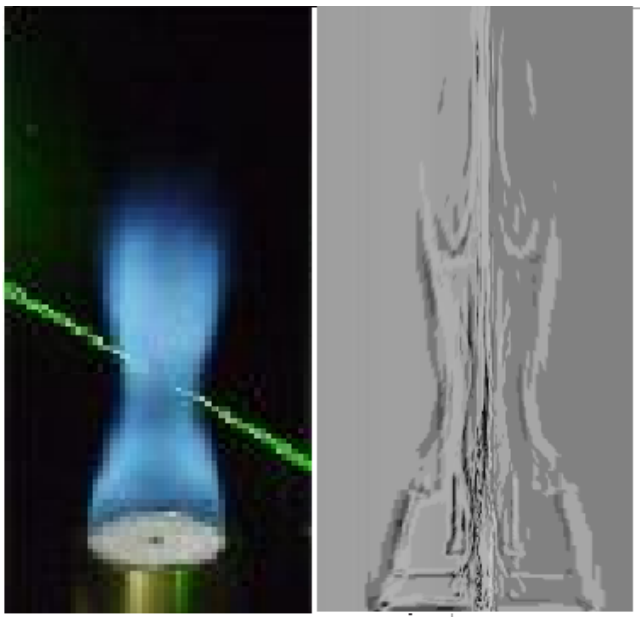
ξ_{SMA}=0.25



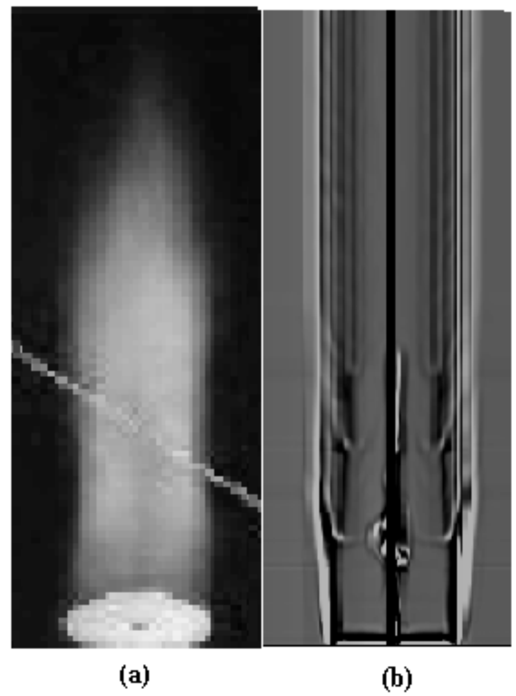
SMA2 flame (S_g=1.59)

El Asrag and Menon, 2005, 2006

SM1 – SMA2 Flame Structure



SM1

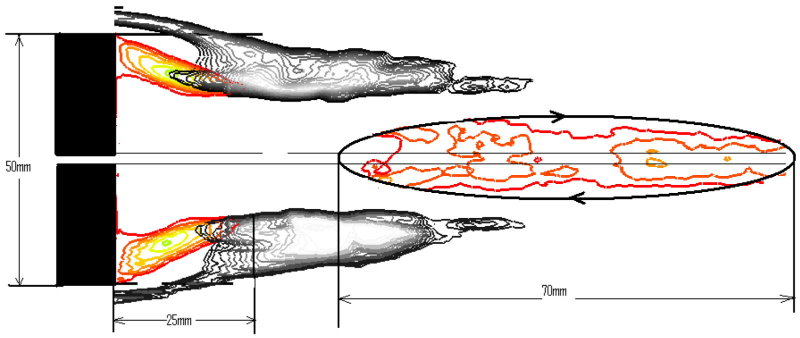


SMA2

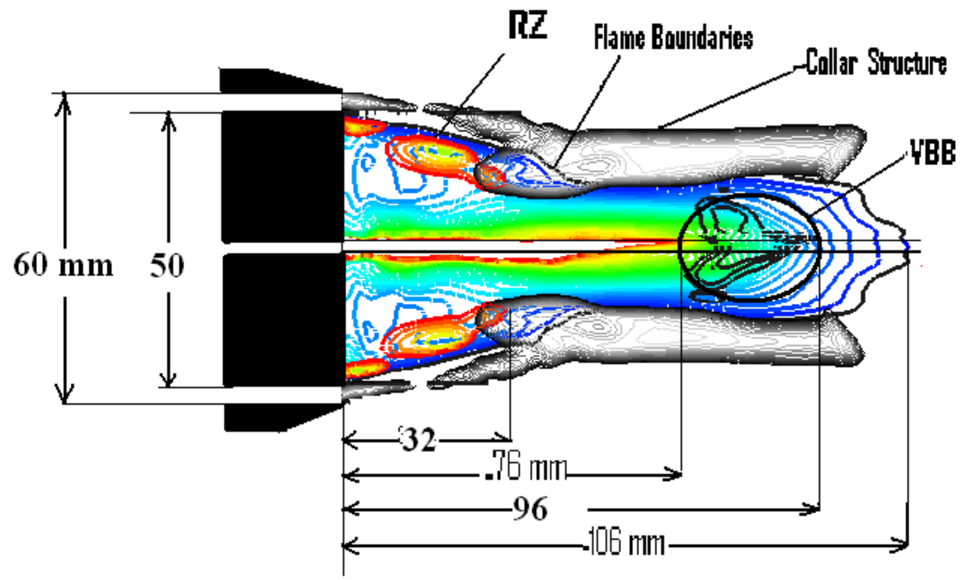
Experimental (left) – LESLEM (right), SM1 flame is an H-type flame, while SMA2 is a C-Type flame with no necking

El Asrag and Menon, 2005, 2006

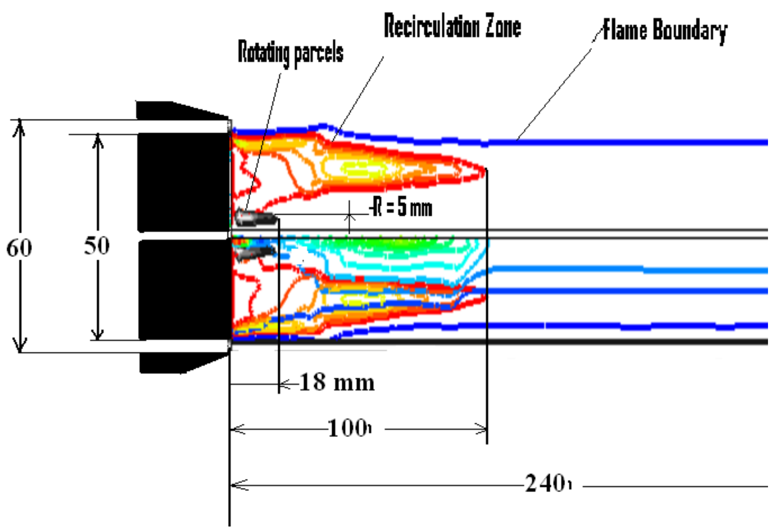
Cold Flow



Bluff body RZ + a centerline VBB + rotational collar structure (grey)



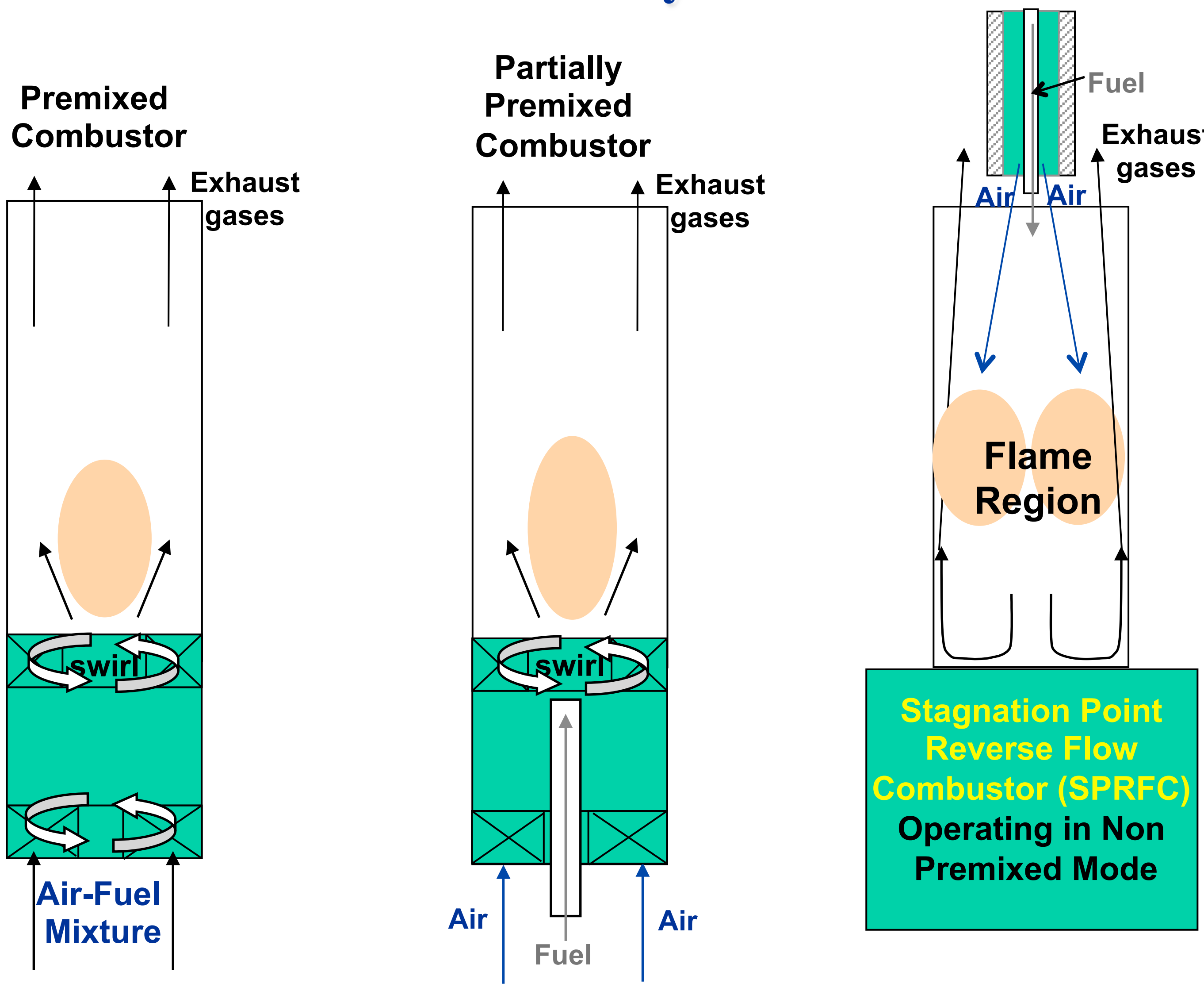
SM1 Flame, BB RZ, VBB



SMA2 Flame, very small BB RZ, no VBB due to high momentum Fuel jet

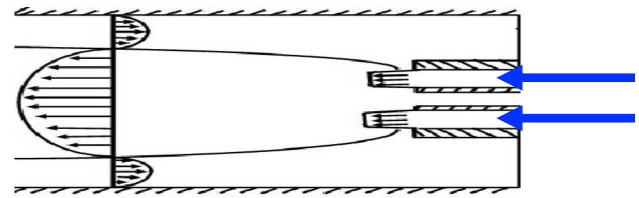
El Asrag and Menon, 2005, 2006

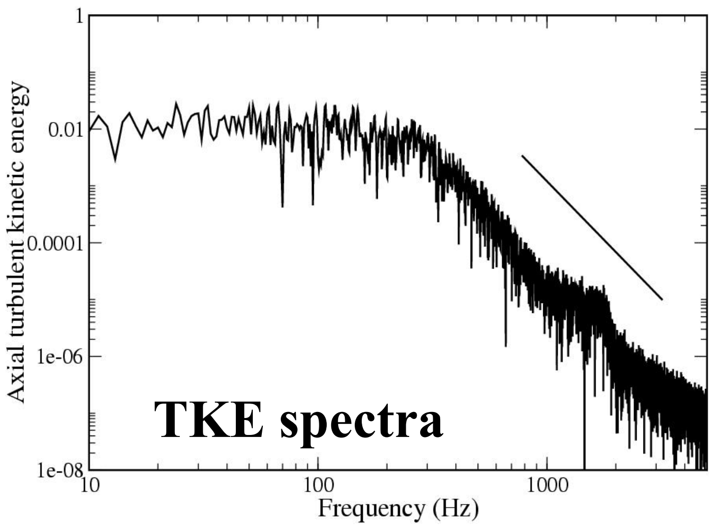
Premixed and Partially Premixed Burners

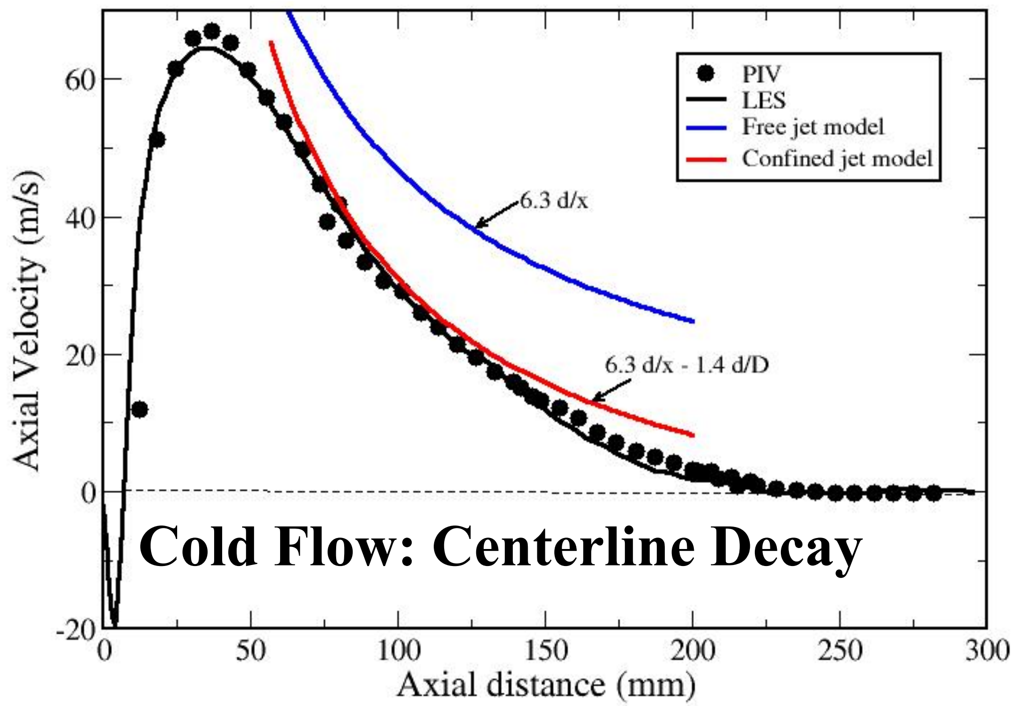


LES of the SPRF Combustor (Symp 08)

- Grid: 1.2 million cells
- Same grid for all LES
- -5/3 in the shear layer







- **Initial decay similar (but not exact) to <u>confined</u> jet**
- **Behaves like a <u>stagnation point flow</u> further downstream**

Undapalli et al., 2008

Simulation Conditions

Premixed

Inlet Velocity : 137 m/s

Equiv ratio : 0.58

T@inlet : 500 K

Pressure : 1 atm

Adiabatic outer walls

Isothermal injector walls

Non-Premixed

Inlet Velocity : 112 m/s

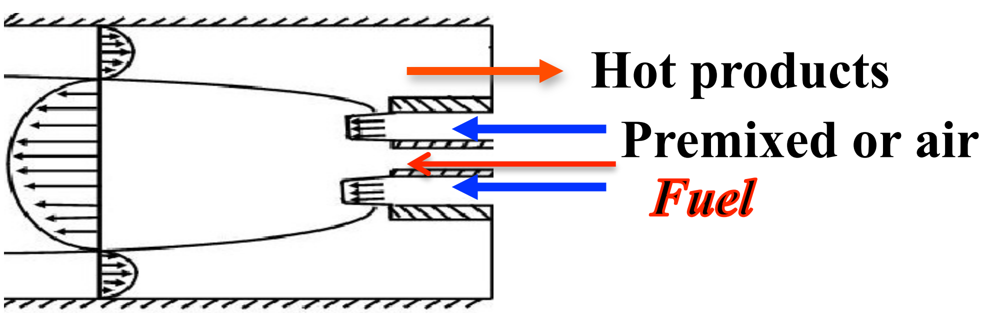
Overall Equiv ratio : 0.58

T@inlet : 450 K

Pressure : 1 atm

Adiabatic outer walls

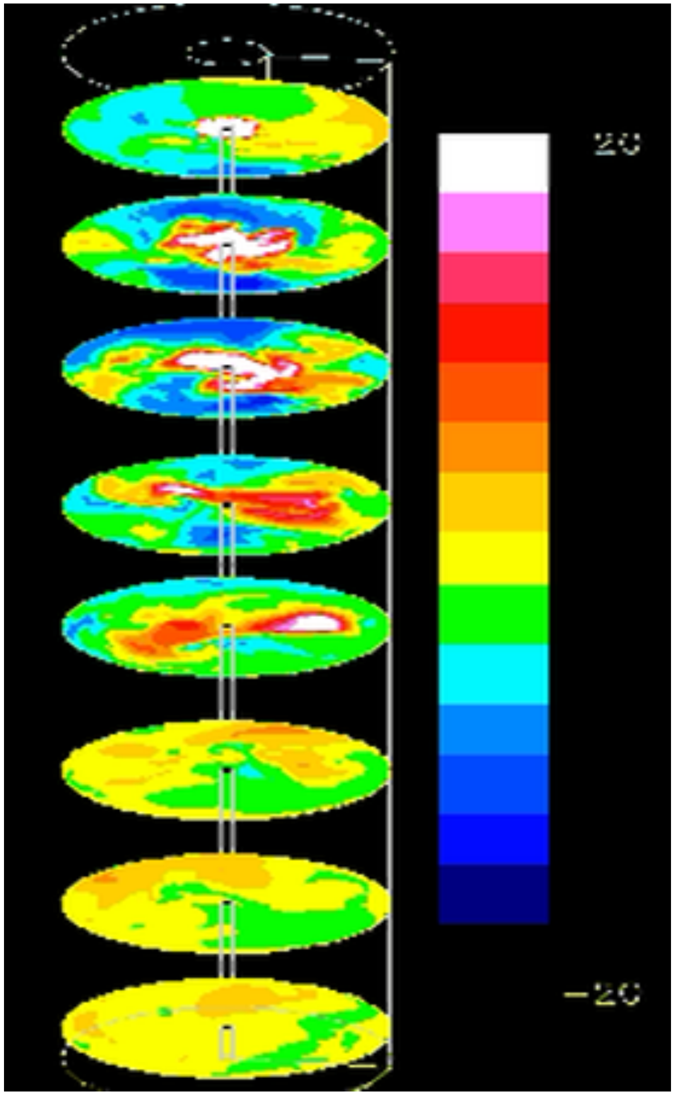
Isothermal injector walls

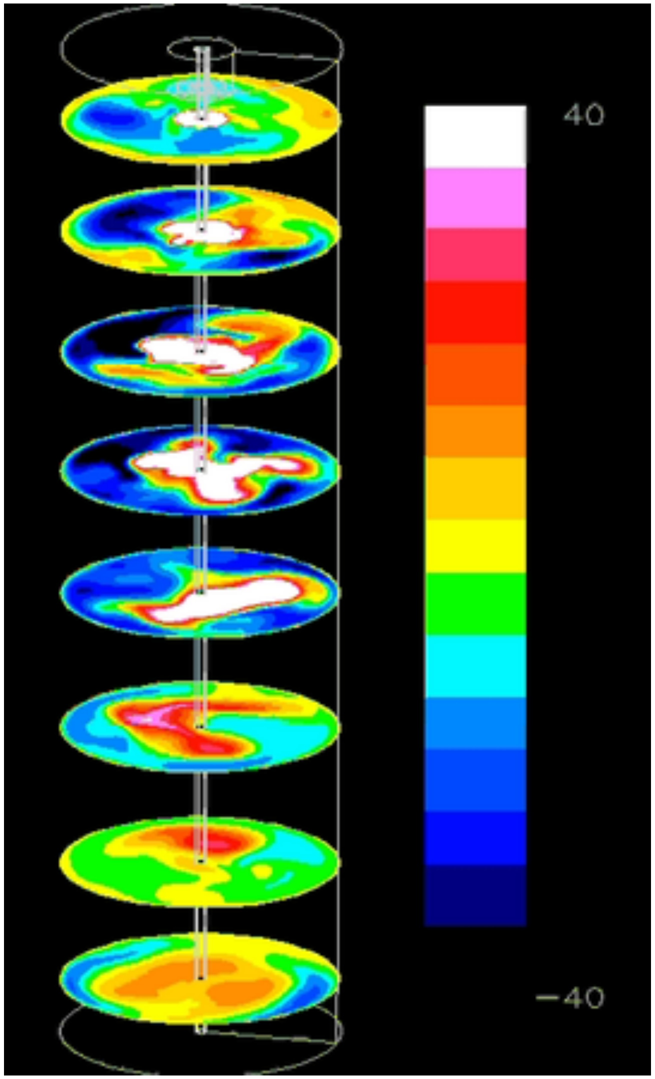


- 2-step Methane-air (Westbrook & Dryer 81)
- 2-step NO (Nicol et al. 99)
    - prompt, thermal
- 7-species
- 12 LEM cells/LES cell

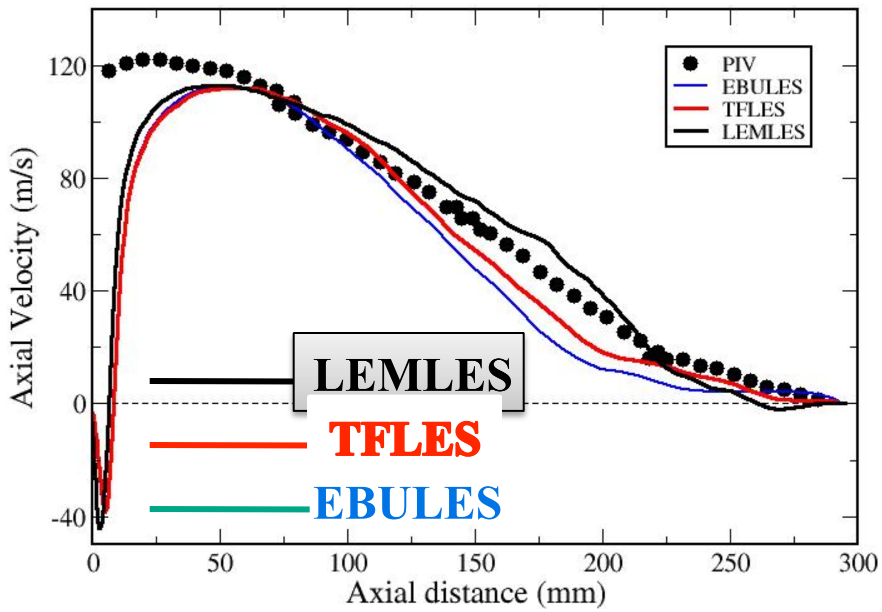
Undapalli et al., 2008

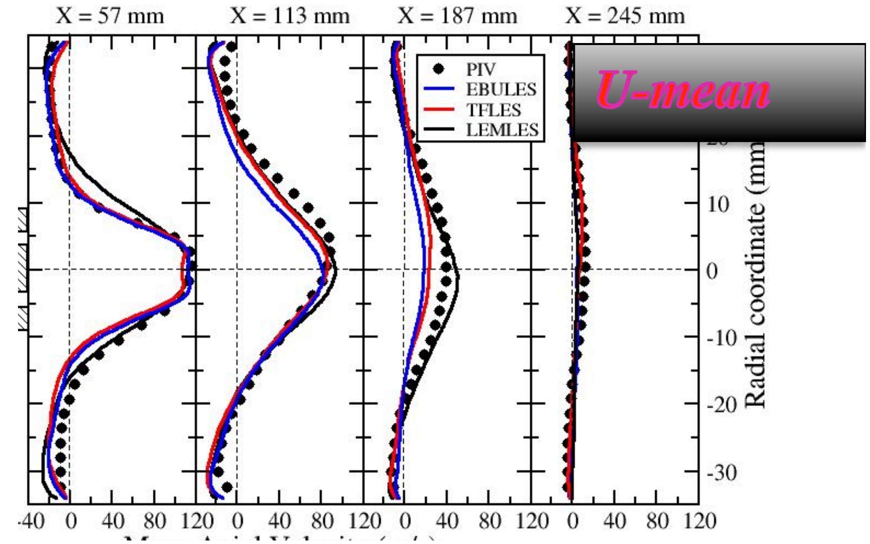
Cold Flow Axial Velocity Premixed

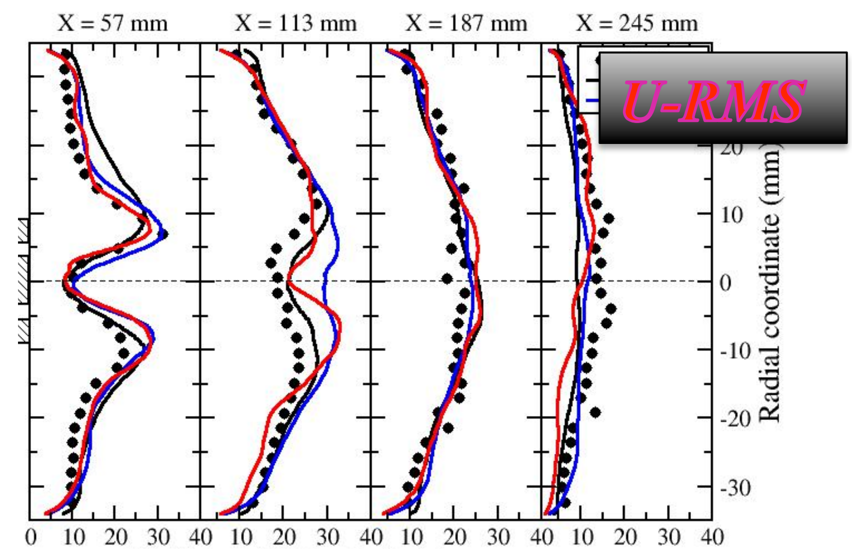




Premixed Mode: Comparisons

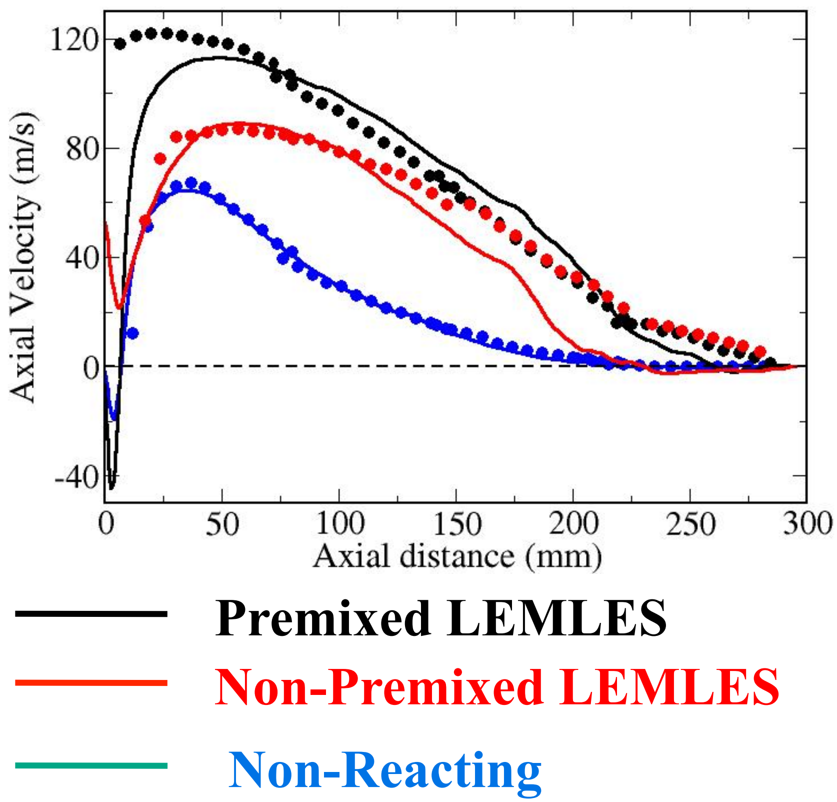


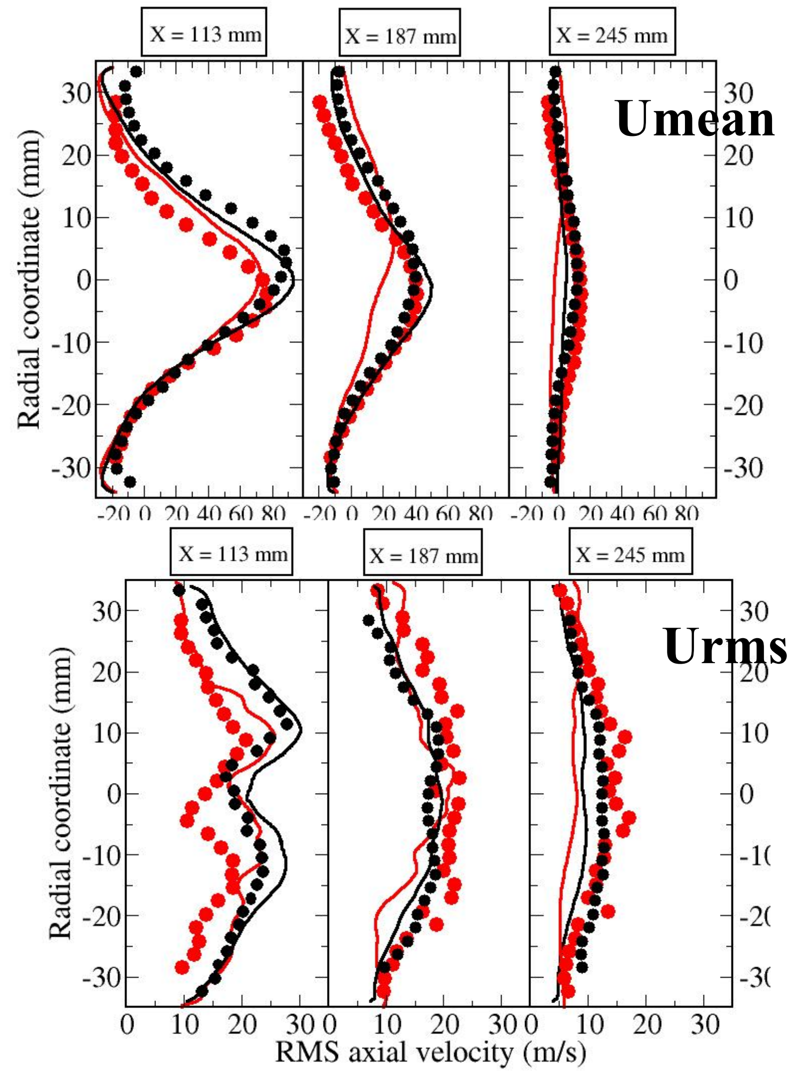




- Near injector discrepancies due to difference in expt and model
- Does not show classical stagnation point type flow
- Similar trend for mean velocity
- TFLES and LEMLES show similar rms peak

Non-Premixed and Premixed Comparison

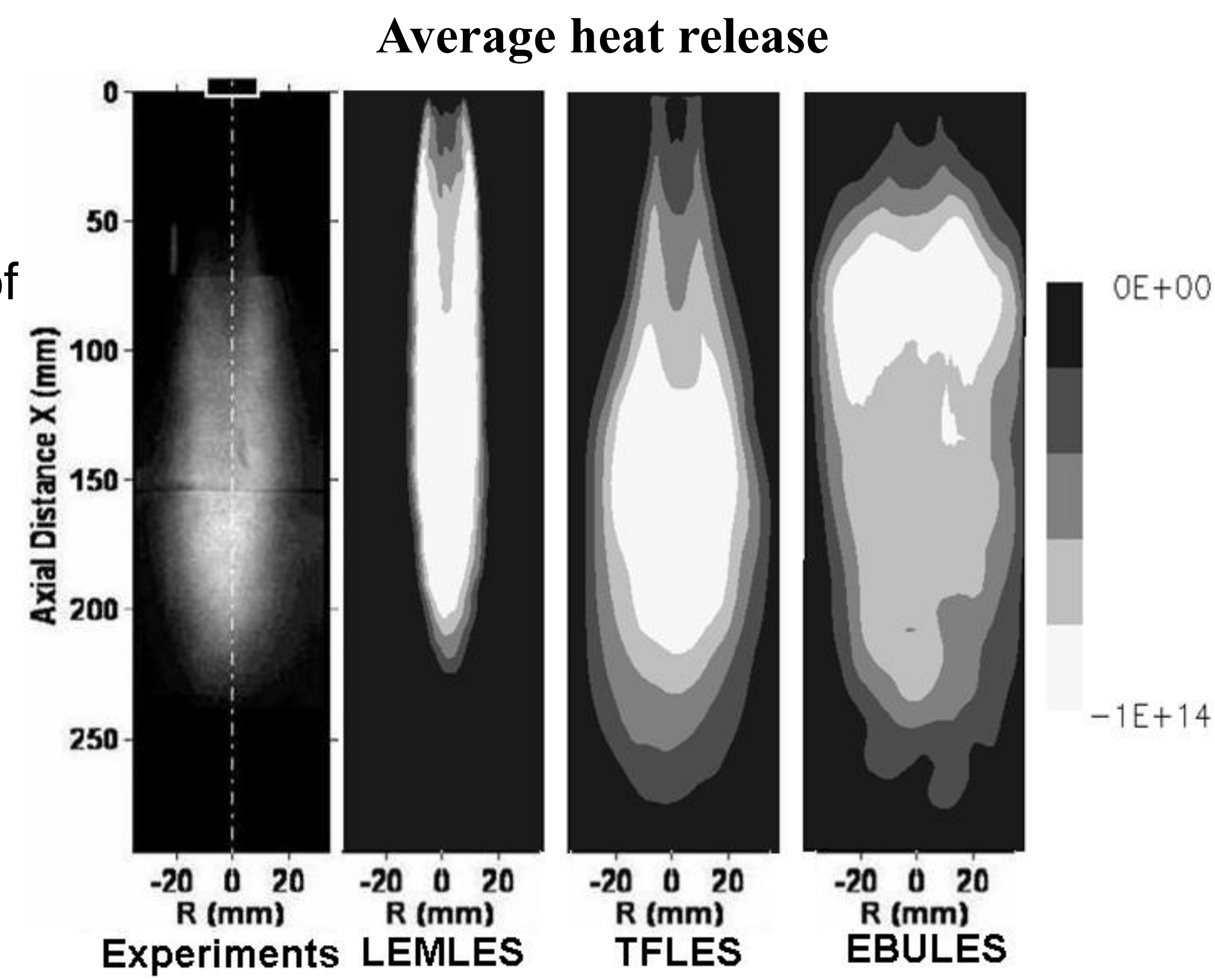




- **Both modes show similar trends**
- **Agreement relatively poorer for non-premixed near the stagnation region – slow convergence**

Premixed Mode: Flame Comparisons

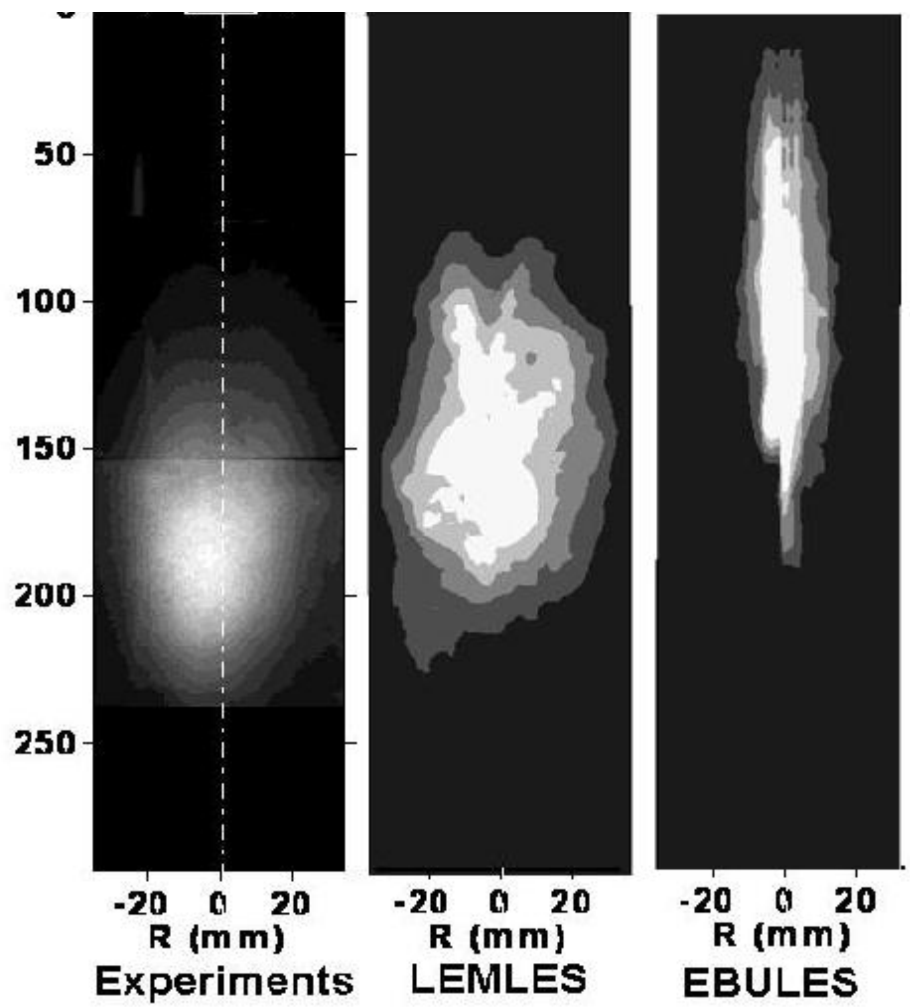
- Note: Exptal flame is attached!
- EBULES: location of peak incorrect
- TFLES: correct location but diffused (could be improved)
- LEMES: correct location and shape
- Cost is x5 for LEMLES!



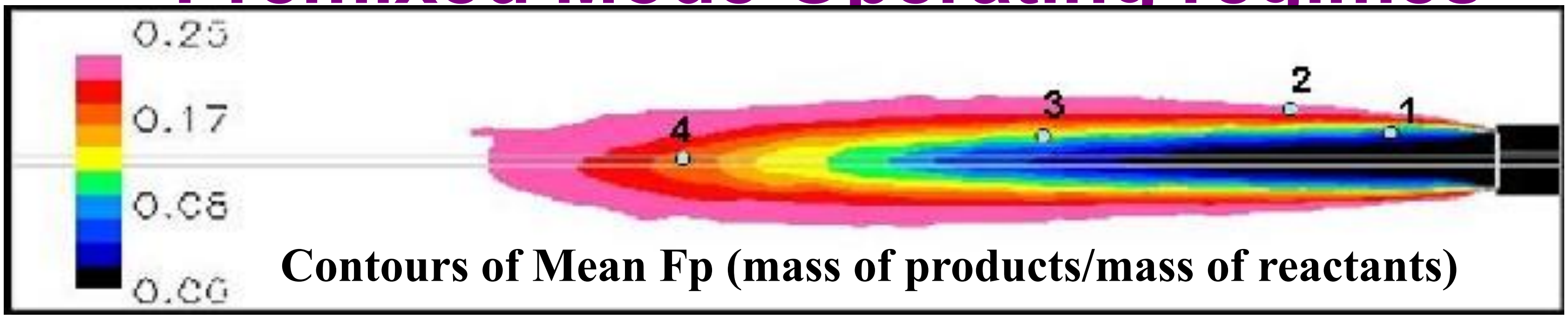
Non-Premixed Mode: Flame Comparisons

- Lifted flame seen in expt.
  - Predicted by LEMLES
  - Under-predicted 20%
    - 2-step kinetics
- SFLES shows attached flame
- Unsteady flamelet may work but will be very expensive

Average heat release

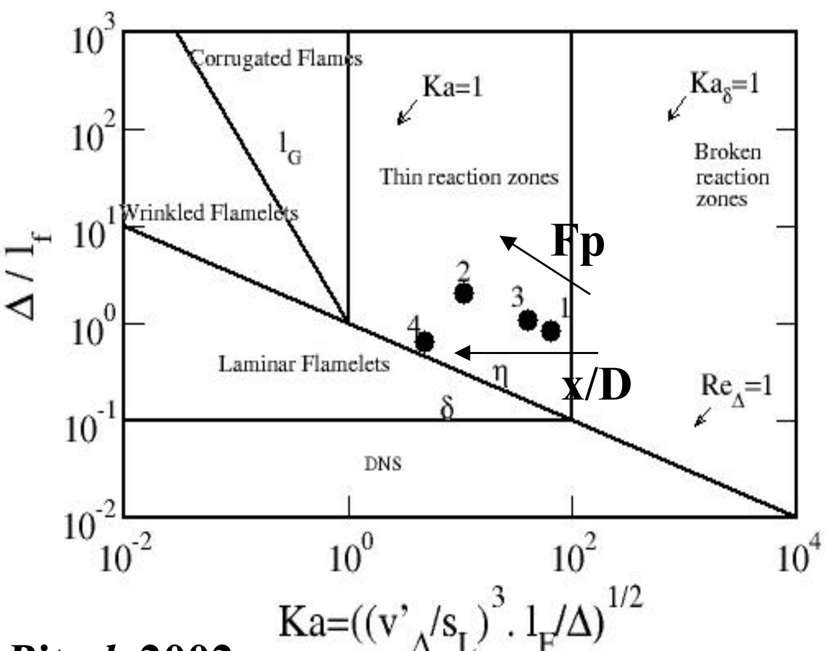


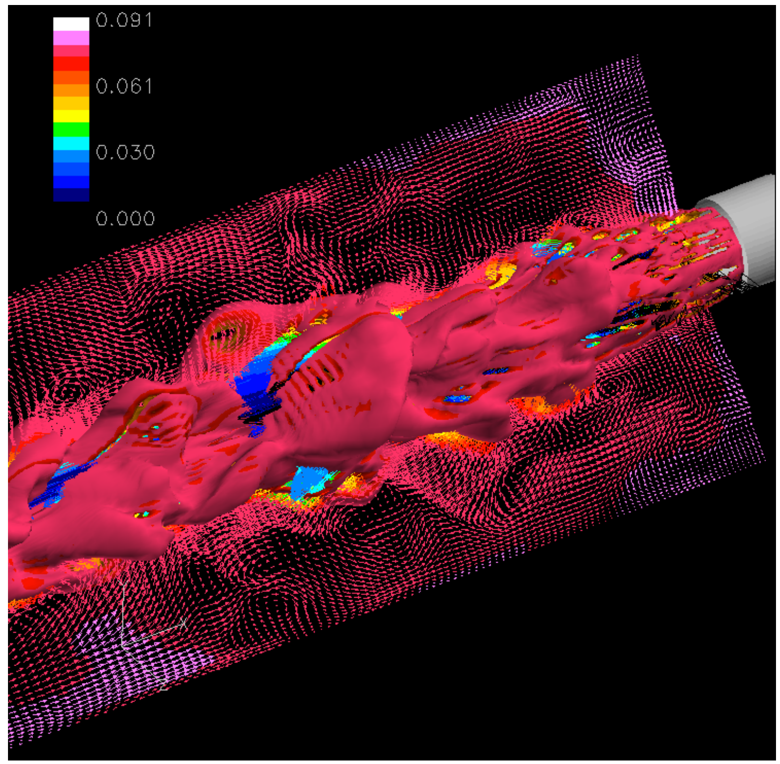
Premixed Mode Operating regimes



Contours of Mean Fp (mass of products/mass of reactants)

Regime diagram



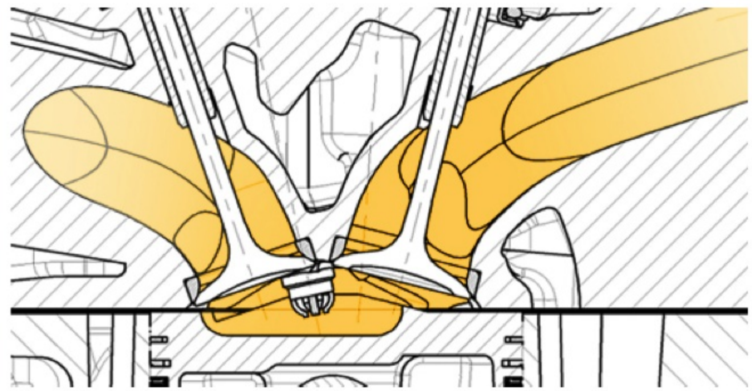


Pitsch 2002

BMW AG
Powertrain
Development
Hasse/Linse

CFD in Engine Combustion

Christian Hasse
Dirk Linse
Powertrain Development



BMW Group

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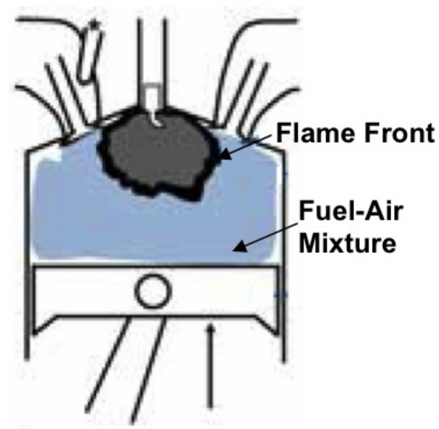
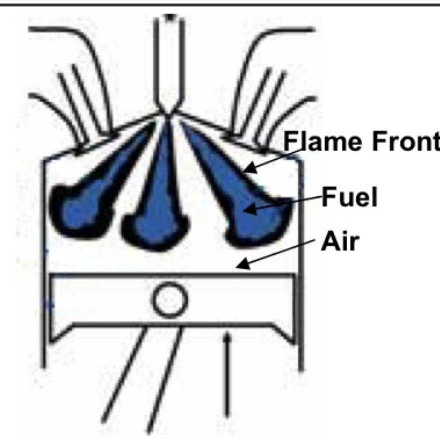
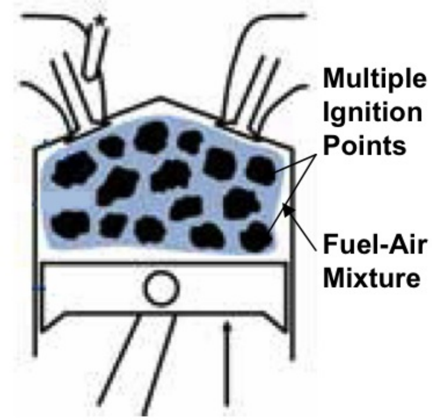
CFD in Engine Combustion

Overview of Engine Types

Gasoline SI	Diesel	Gasoline HCCI
		
• Premixed / Partially Premixed Combustion. • Flame front moves relatively to the flow field with a turbulent burning velocity s_T. • The wrinkling of the flame front is the main mechanism controlling turbulent flames.	• Non-premixed Combustion. • Non-premixed flames do not propagate. They are located at stoichiometric mixture fraction. • Non-premixed flames are dominated by mixing processes.	• Mixture with significant composition and temperature stratification. • Simultaneous multi-point ignition with no flame propagation. • HCCI is mainly controlled by chemical kinetics.

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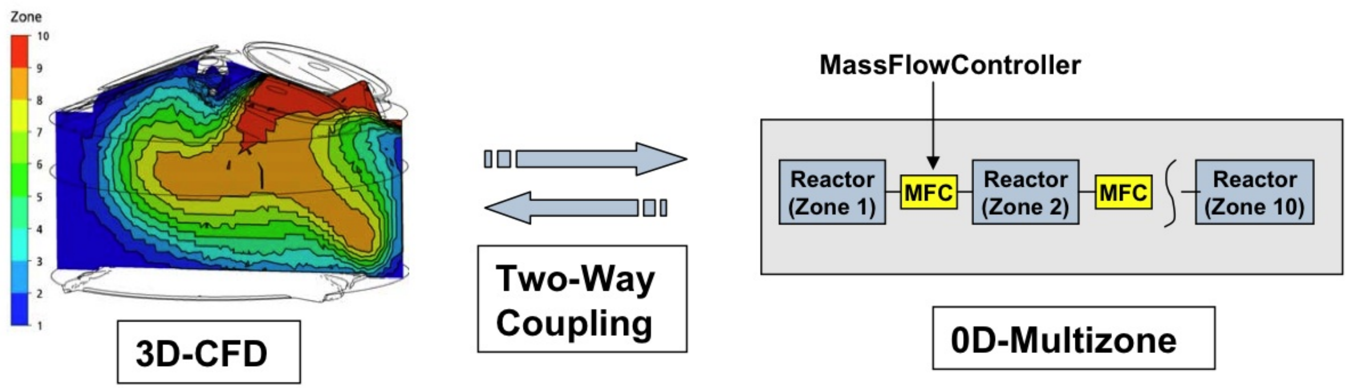
Powertrain
Development
Hasse/Linse

Modeling HCCI
Multizone Model



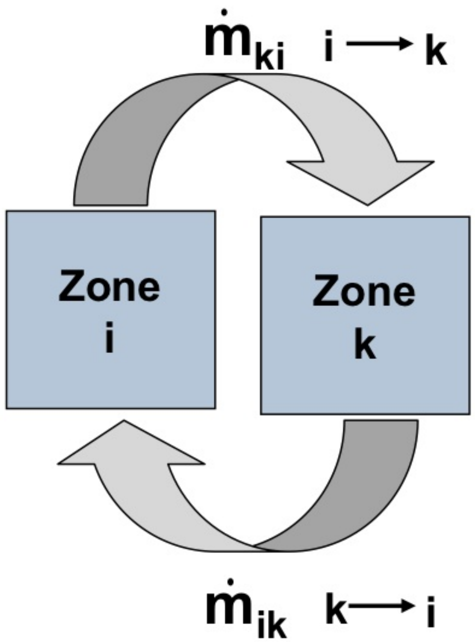
HCCI Modeling

Knock Modeling

Cyclic Variations

- Representation of the combustion chamber by a small number of reactors (zones).
- Computational cells with similar temperature and composition histories are grouped into zones.
- Detailed chemistry (~100 species and ~400 reactions) is solved in the 0D-multizone model and not in every computational cell.
- Zones are coupled due to pressure work and mixing between zones.

Modeling HCCI
Governing Equations



Mass

$$\frac{dm_i}{dt} = \underbrace{\sum_{k=1}^{nz} \dot{m}_{ik}}_{inflow} - \underbrace{\sum_{k=1}^{nz} \dot{m}_{ki}}_{outflow} = \sum_{k=1}^{nz} (\dot{m}_{ik} - \dot{m}_{ki})$$

Species

$$\frac{d(m_i Y_{ij})}{dt} = \dot{m}_{ij,chem} + \underbrace{\sum_{k=1}^{nz} \dot{m}_{ik} Y_{kj}}_{inflow} - \underbrace{\sum_{k=1}^{nz} \dot{m}_{ki} Y_{ij}}_{outflow}$$

Energy

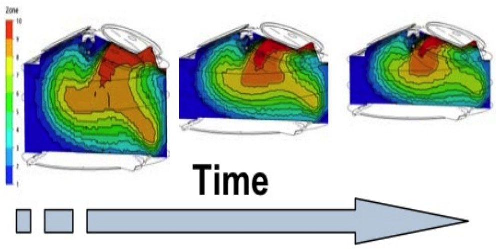
$$\frac{d(m_i h_i)}{dt} = V_i \frac{dp}{dt} + \sum_{k=1}^{nz} (\dot{m}_{ik} h_k - \dot{m}_{ki} h_i) + \dot{Q}_{i,w}$$

Equation of State

$$\frac{dp}{dt} = \frac{p}{V} \sum_{i=1}^{nz} V_i \left(\frac{1}{m_i} \frac{dm_i}{dt} + \frac{1}{T_i} \frac{dT_i}{dt} + \bar{M}_i \sum_{j=1}^{nspec} \frac{1}{M_j} \frac{dY_{ij}}{dt} \right) - \frac{p}{V} \frac{dV}{dt}$$

Modeling HCCI

Mixing Model



- The mixture fraction distribution changes in physical and phase space due to mixing processes.
- A mixing model for the 0D-multizone model is required to account for changes in phase space.

- Mixing is modeled in phase space.

- Calculating mass flow between zones such that $Z^n_{i,0D} = Z^n_{i,3D}$

$$m_i \frac{Z^n_{i,3D} - Z^{n-1}_{i,0D}}{\Delta t} = \sum_{k=1}^{nb} \dot{m}_{ik} (Z^{n-1}_{k,0D} - Z^{n-1}_{i,0D})$$

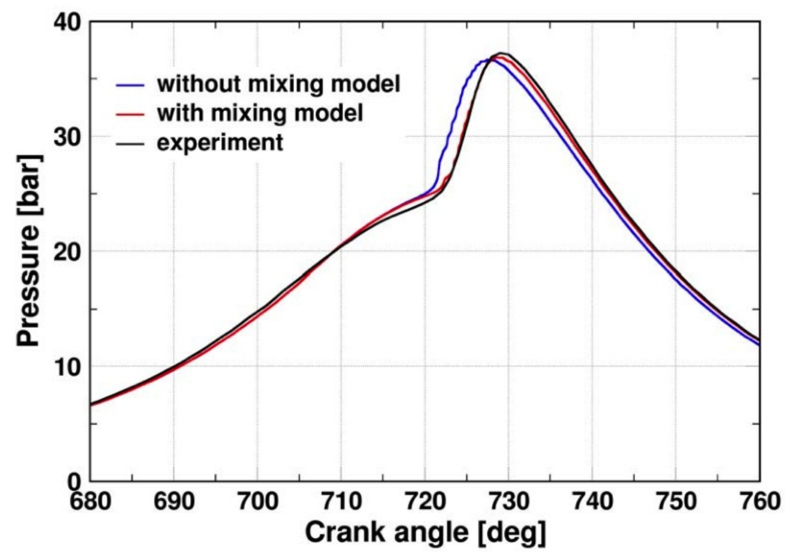
Number of neighbors of zone i in phase space

Mass in zone i

Mass flow from zone k to zone i

Mixture fraction of zone i/k from last time step

- The mass flows $\dot{m}_{ik}$ can now be determined by solving the linear equation system given above.



Cyclic Variations
CFD Methodologies for Engines

URANS

- Time or ensemble-average
- Moderate numerical requirements
- High modelling effort
- Moderate computation effort

Cyclic Variations cannot be resolved

LES

- Spatial filter
- High numerical requirements
- Moderate modeling effort
- High computation effort

Cyclic Variations can be resolved

Hybrid URANS/LES

- Spatial filter of at least the integral length scale
- Numerical requirements and modeling effort depends on the location: LES / URANS region
- Moderate modeling effort
- Reasonable computation effort (CPU-time)

Cyclic variations can be resolved in LES region

Summary Comments

- Bluff body stabilized flames are building block problems
- Configuration has been used to study both stable and unstable combustion and active control
- Laboratory burners provide access for data acquisition and therefore, offers avenue for code validation
  - however, test conditions in the lab may not match actual operational rigs so care must be taken to scale up from lab scale validation studies
- Regardless, there are practical applications as well
- Many of the issues relevant to gas turbine combustors are equally relevant for this type of combustor