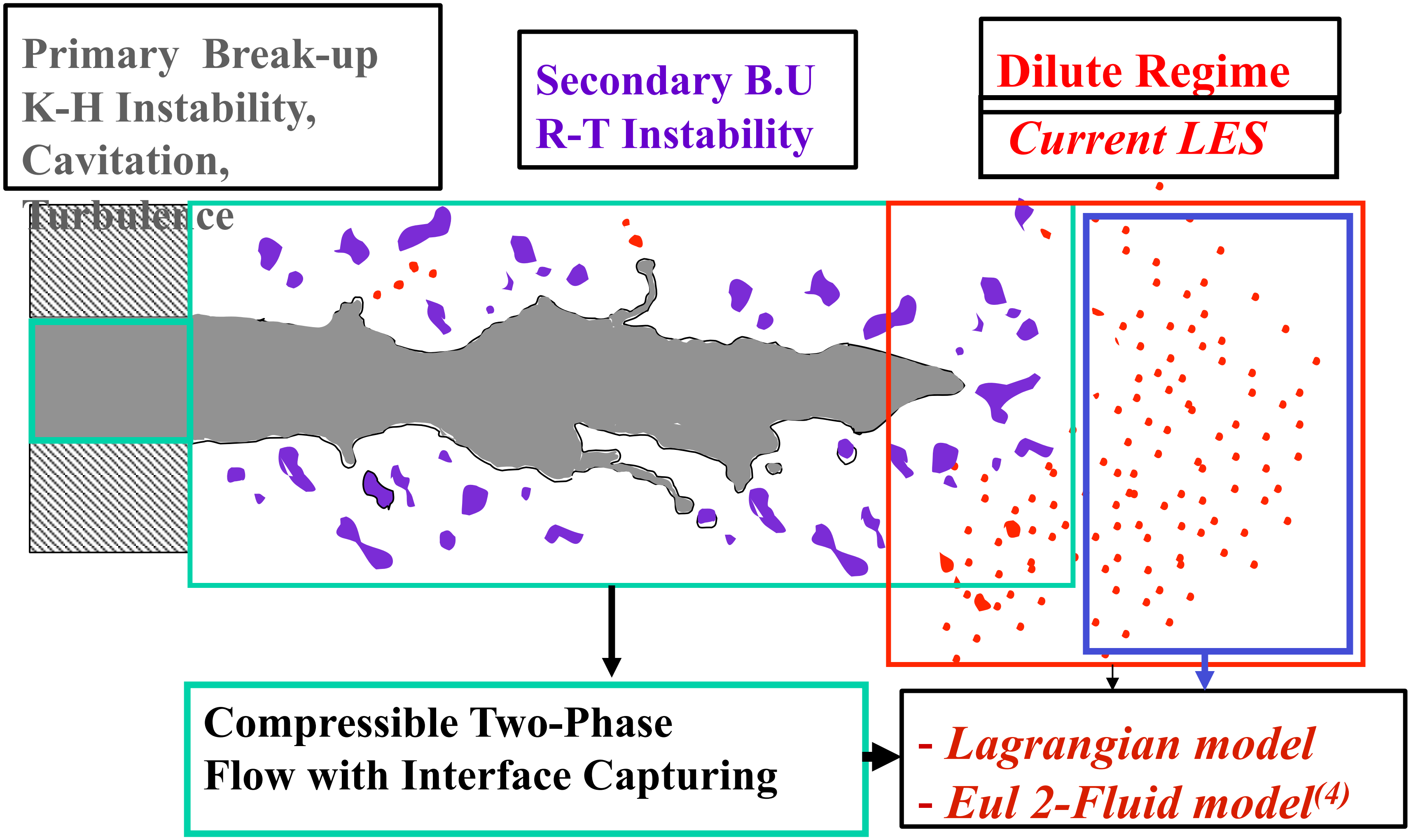
Lecture 7
CFD of Spray Combustion in Gas Turbines

- Spray formulation and implementation issues
- 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
  - Thierry Poinsot, IMF Toulouse, CNRS, France
  - Peter Flohr, ALSTOM, Switzerland
  - Joe Oefelein, Sandia National Laboratory, CA

Suresh Menon, Georgia Tech



Primary Break-up
K-H Instability,
Cavitation,
Turbulence

Secondary B.U
R-T Instability

Dilute Regime

Current LES

Compressible Two-Phase
Flow with Interface Capturing

- Lagrangian model
- Eul 2-Fluid model[(4)]

Spray Modeling Strategies

- Eulerian two-fluid approach (e.g. AVBP)
  - Volume fraction is known but droplet size distribution is not explictly available
  - More cost effective
- Lagrangian droplet tracking approach (e.g., SNL, GT)
  - Each particle or "parcel" is tracked in the Eulerian gas phase with two-way coupling
  - Droplet size distribution can be prescribed
  - Drag laws for different size particles can be included
  - More expensive but perhaps more accurate

Dilute Spray: Modelling Assumptions

- Spherical droplet
  - Droplets deform due to motion
  - Drag correlations are based on spheres of equivalent volume, which "takes" this effect into account.
- Dilute approximation
  - Valid if $v_f/v_g < 0.001$.
  - Not usually valid in the near field of injectors where a breakup model becomes necessary.
  - Drag correlations can be justified under this approximation
  - Particle collision effects areneglected
- Pressure at drop location is constant
- Coriolis, Basset, Gravity forces etc. are ignored.
  - $\rho_l / \rho_g >> 1$

Dilute Sprays: Modelling Assumptions

- Droplet radius smaller than Kolmogorov scale
  - Interaction between droplet and gas is dominated by laminar fluid dynamics
  - Heat conduction can be ignored if Bi<0.1
  - Radiation between drop and surroundings is neglected
- Oxidation process neglected in the flow field around drop
  - Droplet Damkohler number too small for envelope flames, wake flames, etc.

Gas Phase Equations

- Liquid-gas phase coupling through source terms.

$$\frac{\partial\bar{\rho}}{\partial t} + \frac{\partial\bar{\rho}\tilde{u}_i}{\partial x_i} = \widetilde{\dot{\rho}_s}$$

$$\frac{\partial\bar{\rho}\tilde{u}_i}{\partial t} + \frac{\partial}{\partial x_j}[\bar{\rho}\tilde{u}_i\tilde{u}_j + \bar{p}\delta_{ij} - \bar{\tau}_{ij} + \tau_{ij}^{sgs}] = \widetilde{\dot{F}_{s,i}}$$

$$\frac{\partial\bar{\rho}\tilde{E}}{\partial t} + \frac{\partial}{\partial x_i}[(\bar{\rho}\tilde{E} + \bar{p})\tilde{u}_i + \bar{q}_i - \tilde{u}_j\bar{\tau}_{ji} + H_i^{sgs} + \sigma_i^{sgs}] = \widetilde{\dot{Q}_s}$$

$$\frac{\partial\bar{\rho}\tilde{Y}_k}{\partial t} + \frac{\partial}{\partial x_i}[\bar{\rho}\tilde{Y}_k\tilde{u}_i - \bar{\rho}\tilde{Y}_k\widetilde{V_{i,k}} + Y_{i,k}^{sgs} + \theta_{i,k}^{sgs}] = \bar{\dot{w}}_k + \widetilde{\dot{S}_{s,k}} \qquad k = 1, N_s$$

$$\begin{pmatrix} \dot{\rho}_s \\ \dot{F}_{s,i} \\ \dot{Q}_s \\ \dot{S}_{s,k} \end{pmatrix} = -\begin{pmatrix} \frac{dm_d}{dt} \\ \frac{dm_d u_i}{dt} \\ \frac{dm_d e_d}{dt} \\ \frac{dm_d Y_m}{dt} \end{pmatrix} = -\begin{pmatrix} \rho_d\frac{dV_d}{dt} + V_d\frac{d\rho_d}{dt} \\ m_d\frac{du_{i,d}}{dt} + u_{i,d}\frac{dm_d}{dt} \\ m_d\frac{de_d}{dt} + e_d\frac{dm_d}{dt} \\ m_d\frac{dY_{m,d}}{dt} + Y_{m,d}\frac{dm_d}{dt} \end{pmatrix}$$

Filtered Conservation Equations

- Mass:

$$\frac{\partial}{\partial t}(\theta\bar{\rho}) + \nabla\cdot(\theta\bar{\rho}\tilde{\mathbf{u}}) = \overline{\dot{\rho}}_s$$

- Momentum:

$$\frac{\partial}{\partial t}(\theta\bar{\rho}\tilde{\mathbf{u}}) + \nabla\cdot\left[\theta\left(\bar{\rho}\tilde{\mathbf{u}}\otimes\tilde{\mathbf{u}} + \frac{\mathcal{P}}{M^2}\mathbf{I}\right)\right] = \nabla\cdot(\theta\vec{\vec{\mathcal{T}}}) + \overline{\dot{\mathbf{F}}}_s$$

- Total Energy:

$$\frac{\partial}{\partial t}(\theta\bar{\rho}\tilde{e}_t) + \nabla\cdot[\theta(\bar{\rho}\tilde{e}_t + \mathcal{P})\tilde{\mathbf{u}}] = \nabla\cdot\left[\theta\left(\vec{\mathcal{Q}}_e + M^2(\vec{\vec{\mathcal{T}}}\cdot\tilde{\mathbf{u}})\right)\right] + \theta\overline{\dot{Q}}_e + \overline{\dot{Q}}_s$$

- Species:

$$\frac{\partial}{\partial t}(\theta\bar{\rho}\tilde{Y}_i) + \nabla\cdot(\theta\bar{\rho}\tilde{Y}_i\tilde{\mathbf{u}}) = \nabla\cdot(\theta\vec{\mathcal{S}}_i) + \theta\overline{\dot{\omega}}_i + \overline{\dot{\omega}}_{s_i}$$

Oefelein, J. C. (2006). Large eddy simulation of turbulent combustion processes in propulsion and power systems. *Progress in Aerospace Sciences*, 42: 2-37.

Subgrid-Scale Model for Particle Dispersion

- Instantaneous particle motion tracked in Lagrangian frame as succession of SGS eddies traversed
  - Decompositions of the form $u_p(x,t) = U_p(x,t) + u_p''(x,t)$ reconstructed
  - Fluctuations generated stochastically assuming isotropic and Gaussian
  - Stochastic intervals coincident with particle-eddy interaction time
- Particles interact with eddies for time taken as smaller of eddy lifetime or transit time

$$\dot{\overline{\mathbf{F}}}_s(\mathbf{x},t) = \underbrace{\int_{-\infty}^{t} \underbrace{\sum_p \mathcal{G}(\mathbf{y}_p-\mathbf{x},\tau-t) \underbrace{\left\{ m_p \frac{d\mathbf{u}_p}{d\tau}\right\}}_{(i)}}_{(ii)} d\tau}_{(iii)}$$

(i) Instantaneous force induced by particles at remote points y_p and times τ

(ii) Spatially filtered effect of remote exchange processes on discrete points x within filter volume of influence

(iii) Filtered effect of sgs temporal disturbances over the integration time-step $\delta\tau$

Two-way coupling by evaluating individual contributions imposed by each particle

Explicit filtering of the particulate phase is performed using a top-hat filter

Oefelein, J. C. (2006). Large eddy simulation of turbulent combustion processes in propulsion and power systems. *Progress in Aerospace Sciences*, 42: 2-37.

Mass Conservation

$$\frac{dm_d}{dt} = -\dot{m}_d$$

$$\frac{\dot{m}_d}{\dot{m}_{Re_d=0}} = 1 + [0.278\sqrt{Re_d}Sc^{1/3}]\left[1 + \frac{1.232}{Re_d Sc^{4/3}}\right]^{1/2}$$

$$Re_d = \sqrt{(u_i - u_{i,d})(u_i - u_i,d)}d_d/\nu$$

$$Sc = \nu/D$$

- Experimental data used for most of these correlations
- Effect of turbulence can be considered in the Reynolds number through a fluctuation term computed from KSGS
- However, other than this there is no difference between LES and RANS spray models

Momentum Conservation

$$\frac{dx_{i,d}}{dt} = u_{i,d}$$

$$\frac{du_{i,d}}{dt} = \frac{f}{\tau_V}\left[(u_i) + u_i" - u_{i,d}\right]$$

- Effect of small scales through subgrid KE and a random number factor to compute u”
- Drag factor $f = \frac{C_D Re_D}{24}$

$$C_D = \begin{cases} \frac{24}{Re_d}\left(1 + \frac{1}{6} Re_d^{2/3}\right) & Re_d \leq 1000 \\ 0.424 & Re_d > 1000 \end{cases}$$

- Particle response time

$$\tau_V = \frac{\rho_d d_d^2}{18\mu_g}$$

Energy Equation

$$m_d C_L \frac{dT_d}{dt} = h_d \pi d_d^2 (\tilde{T} - T_d) - \dot{m}_d L_v \qquad (16)$$

- L_v is the latent heat of vaporization, h_d is the heat transfer coefficient

$$\frac{h_d}{h_{Re_d=0}} = 1 + 0.278 Re_d^{1/2} Pr^{1/3} \Big/ \left[1 + \frac{1.232}{Re_d Pr^{4/3}}\right]^{1/2}$$

$$h_{Re_d=0} = \frac{\kappa Nu_{Re_d=0}}{d_d} \qquad Nu_{Re_d=0} = 2ln\left(\frac{\alpha}{\alpha - 1}\right)$$

Droplet Time Scales

- Modelling physics at the appropriate timescales necessary to accurately capture the transient dynamics of droplet combustion.
- Droplet relaxation time $$\tau_v = \frac{16\rho_d r_d^2 (C_D Re_d)^{-1}}{3\rho_g \nu}$$
  - Time required for droplet to reach 63% of the free stream velocity
- Droplet lifetime $$\tau_{life} = \frac{4\pi r_d^3 \rho_d}{3\dot{m}_d}$$
  - Ensure that droplet size does not become negative within a Lagrangian time step
- Droplet Heating time scale $$\tau_{evap} = \frac{\rho_d C_v d_d}{6 h_d}$$
    - Ensures that local mass loading does not create numerical instability

Droplet Time Scales

- Eddy life and transit time
  - Drop interacts with the eddy for its life time or the time required to traverse the eddy.

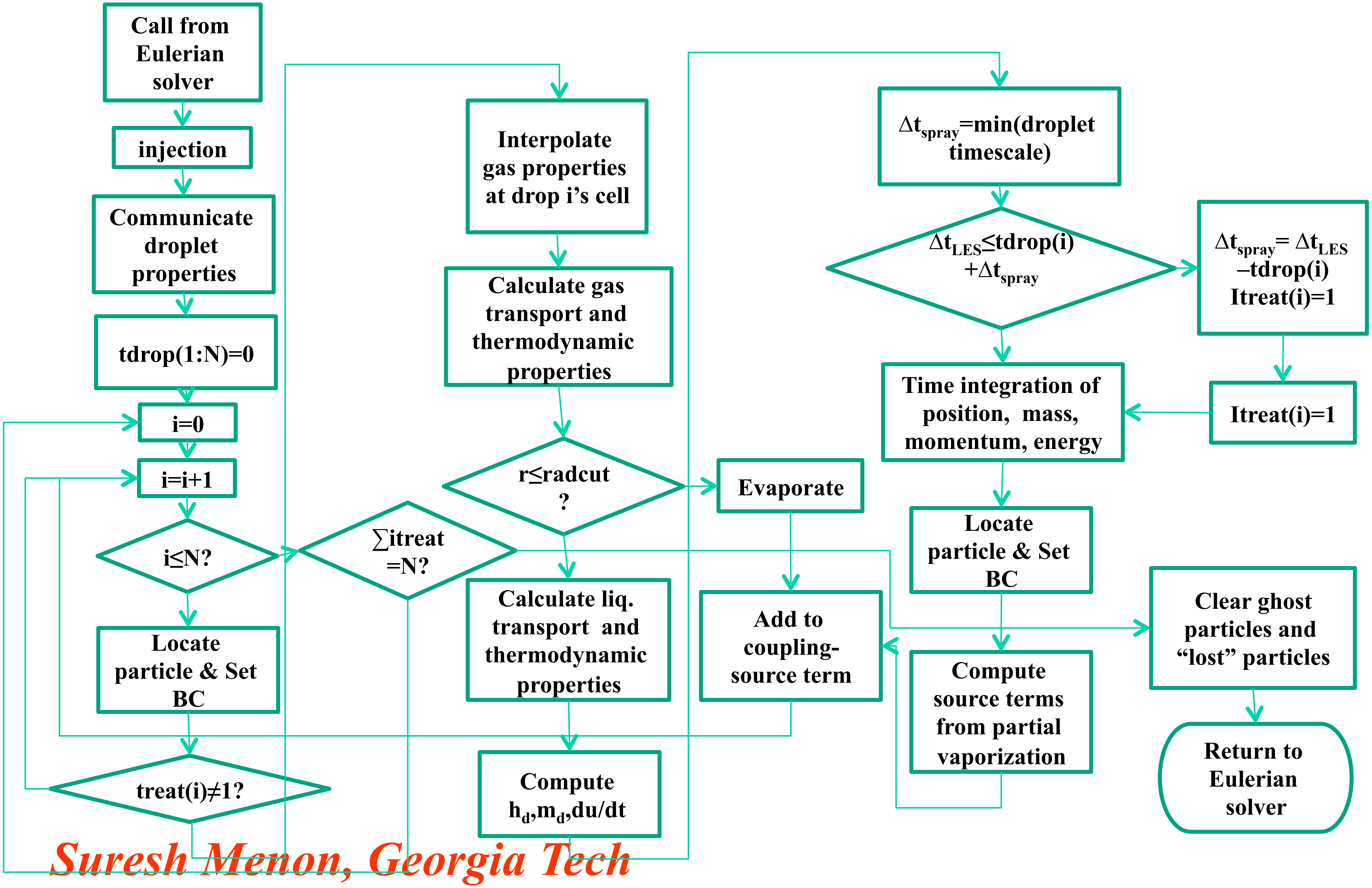
$$\tau_{eddy} = \Delta/\sqrt{(2k^{sgs}/3))}$$

$$\tau_{transit} = \tau_{relax} \ln(1 - \frac{\Delta}{(\tau_{relax}|u_i - u_{i,d}|})$$

$$\tau_{eddy\ int} = \begin{cases} \tau_{eddy} & , \quad \Delta > \tau_{relax}|u_i - u_{i,d}| \\ min(\tau_{eddy}, \tau_{transit}), & \Delta \le \tau_{relax}|u_i - u_{i,d}| \end{cases}$$

$$\Delta t = \min\left(\tau_{\mathrm{evap}}, \tau_{\mathrm{life}}, \tau_{\mathrm{relax}}, \tau_{\mathrm{eddy}}, \tau_{\mathrm{transit}}, \tau_{\mathrm{LES}}\right)$$

Algorithm



Call from Eulerian solver

injection

Communicate droplet properties

tdrop(1:N)=0

i=0

i=i+1

i≤N?

Locate particle & Set BC

treat(i)≠1?

∑itreat =N?

Interpolate gas properties at drop i's cell

Calculate gas transport and thermodynamic properties

r≤radcut ?

Calculate liq. transport and thermodynamic properties

Compute h_d,m_d,du/dt

Evaporate

Add to coupling-source term

Δt_{spray}=min(droplet timescale)

$\Delta t_{LES} \leq$tdrop(i) $+\Delta t_{spray}$

$\Delta t_{spray}= \Delta t_{LES}$ –tdrop(i) Itreat(i)=1

Itreat(i)=1

Time integration of position, mass, momentum, energy

Locate particle & Set BC

Compute source terms from partial vaporization

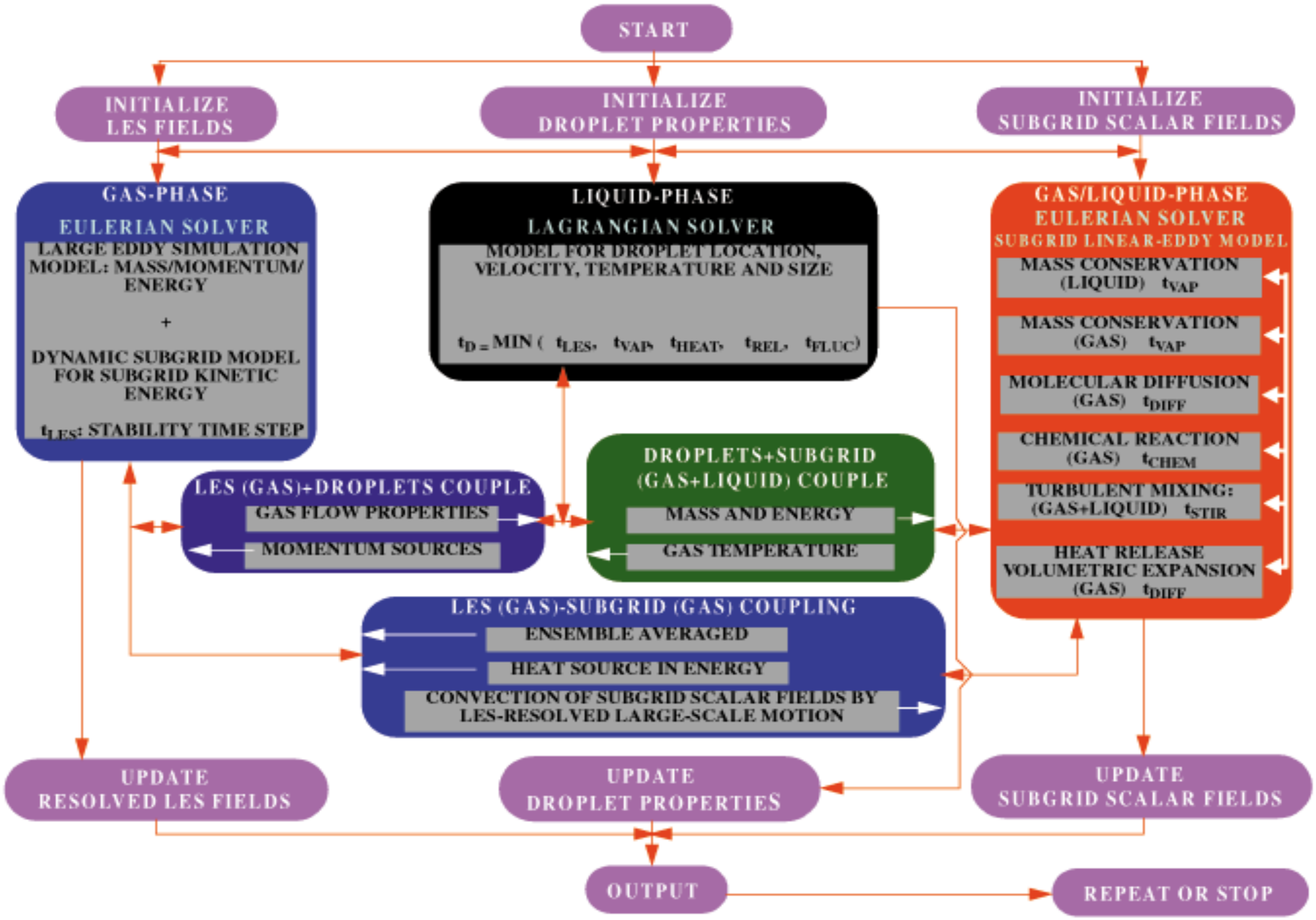
Clear ghost particles and "lost" particles

Return to Eulerian solver

AIAA CFD for Combustion Modeling

Georgia Tech

Aerospace



START

INITIALIZE LES FIELDS

INITIALIZE DROPLET PROPERTIES

INITIALIZE SUBGRID SCALAR FIELDS

GAS-PHASE

EULERIAN SOLVER

LARGE EDDY SIMULATION MODEL: MASS/MOMENTUM/ ENERGY

+

DYNAMIC SUBGRID MODEL FOR SUBGRID KINETIC ENERGY

t_{LES}: STABILITY TIME STEP

LIQUID-PHASE

LAGRANGIAN SOLVER

MODEL FOR DROPLET LOCATION, VELOCITY, TEMPERATURE AND SIZE

$t_{D} = \mathrm{MIN}(t_{LES}, t_{VAP}, t_{HEAT}, t_{REL}, t_{FLUC})$

GAS/LIQUID-PHASE

EULERIAN SOLVER

SUBGRID LINEAR-EDDY MODEL

MASS CONSERVATION (LIQUID) t_{VAP}

MASS CONSERVATION (GAS) t_{VAP}

MOLECULAR DIFFUSION (GAS) t_{DIFF}

CHEMICAL REACTION (GAS) t_{CHEM}

TURBULENT MIXING: (GAS+LIQUID) t_{STIR}

HEAT RELEASE VOLUMETRIC EXPANSION (GAS) t_{DIFF}

LES (GAS)+DROPLETS COUPLE

GAS FLOW PROPERTIES

MOMENTUM SOURCES

DROPLETS+SUBGRID (GAS+LIQUID) COUPLE

MASS AND ENERGY

GAS TEMPERATURE

LES (GAS)-SUBGRID (GAS) COUPLING

ENSEMBLE AVERAGED

HEAT SOURCE IN ENERGY

CONVECTION OF SUBGRID SCALAR FIELDS BY LES-RESOLVED LARGE-SCALE MOTION

UPDATE RESOLVED LES FIELDS

UPDATE DROPLET PROPERTIES

UPDATE SUBGRID SCALAR FIELDS

OUTPUT

REPEAT OR STOP

Computational Combustion Laboratory

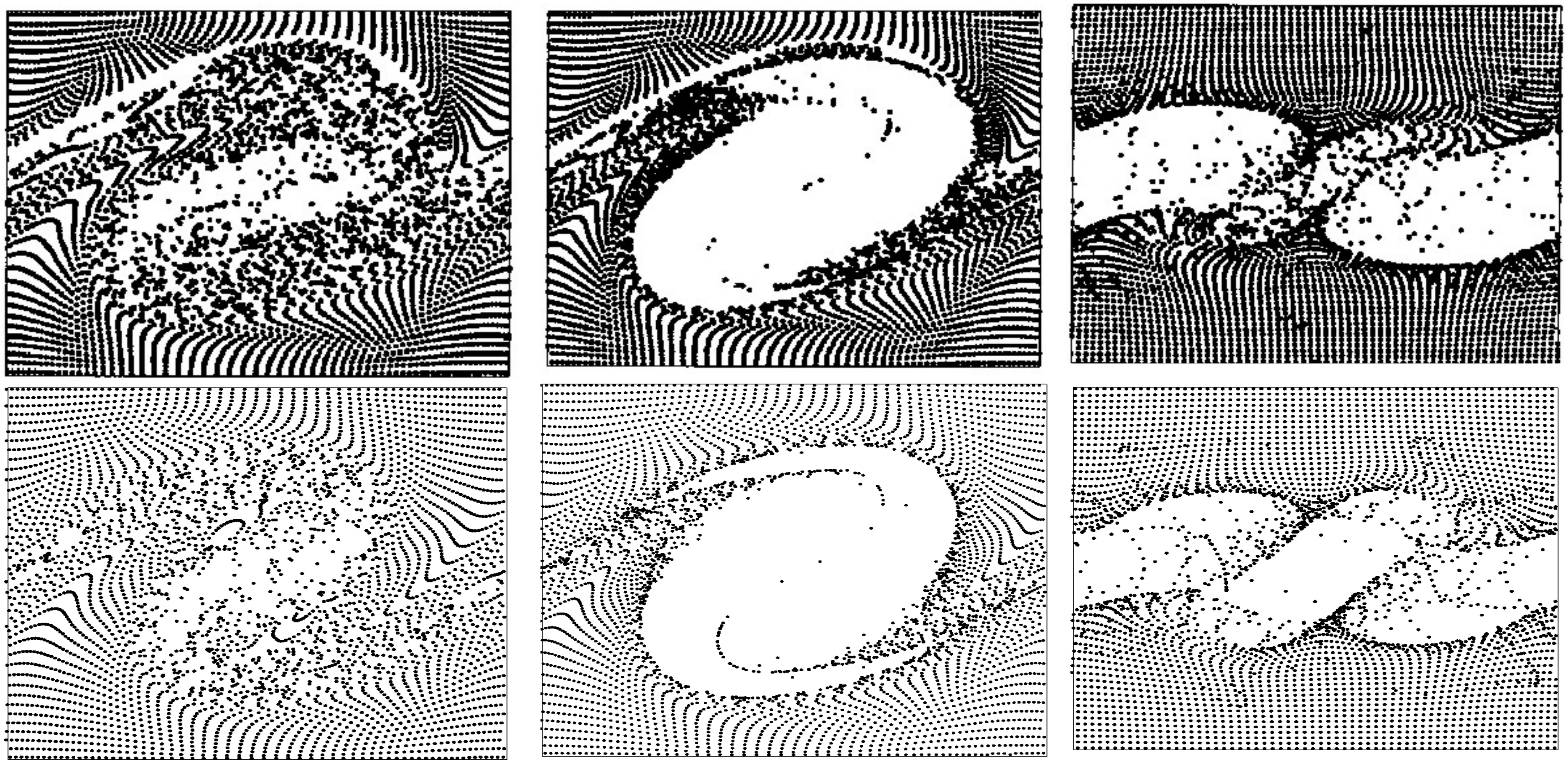
Suresh Menon, Georgia Tech

Implementation and Modeling Issues

- Injector exit flow field (spray distribution, velocities etc) has to be defined for dilute spray modeling
- For breakup – models are needed
  - Still not fully resolved
  - All current models are based on RANS studies
  - K-H instability, TAB model, etc.
- Parallel implementation
  - Gather-scatter
  - Point-to-point
  - Advantages and disadvantages of each approach

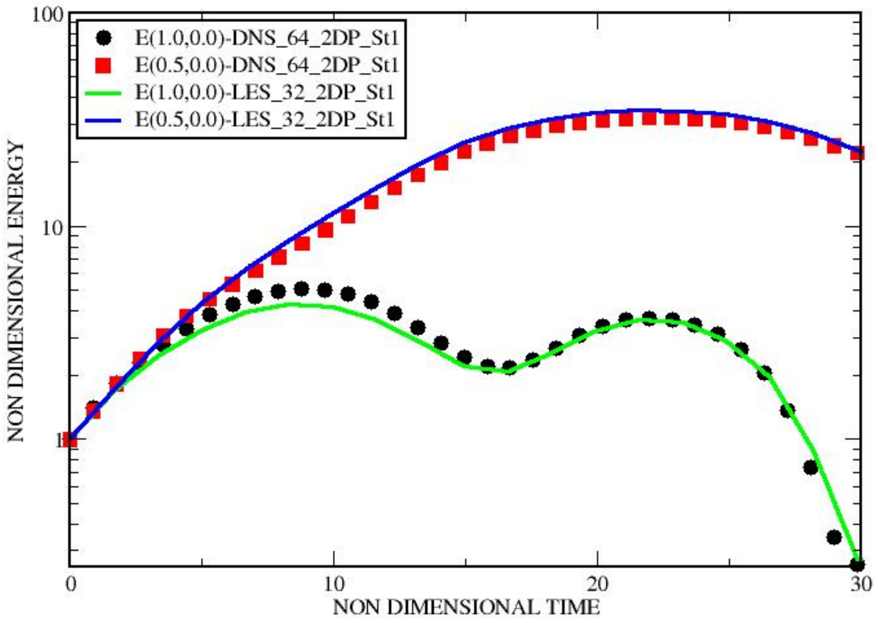
DNS of Particle Laden Mixing Layers

Top row: Ling et al., JFM 98, Bottom row: Menon, 2005

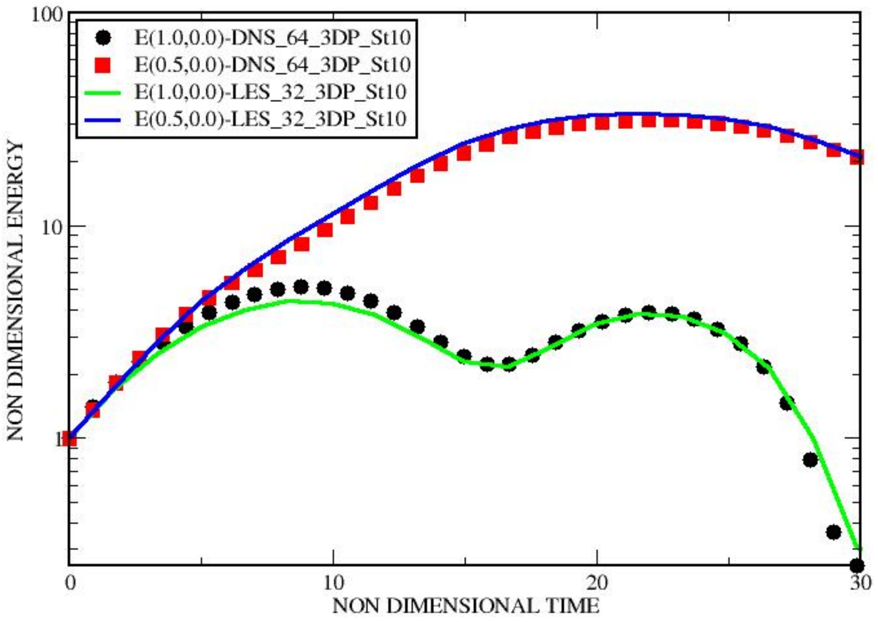


St = 0.1 **St = 1** **St = 100**

Comparison of LES and DNS in Particle Laden Temporal Mixing Layer



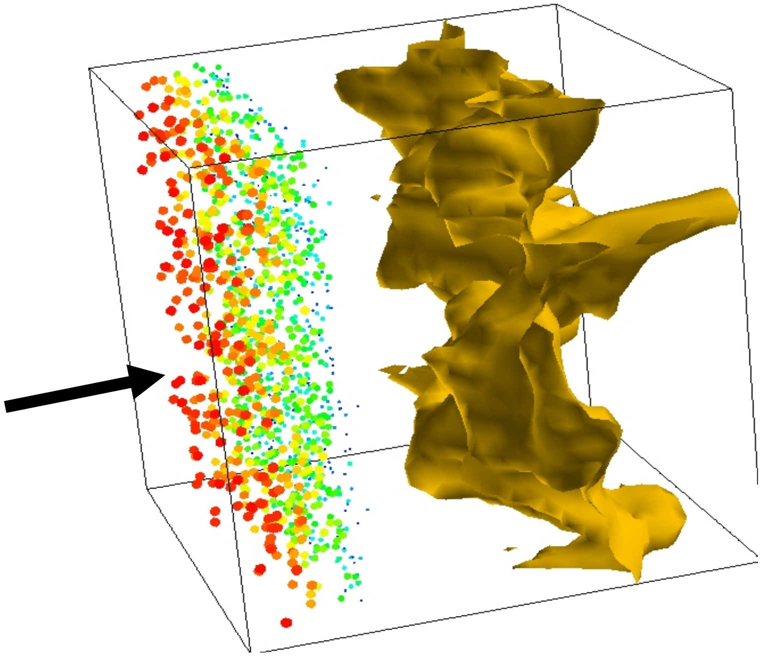
St =1

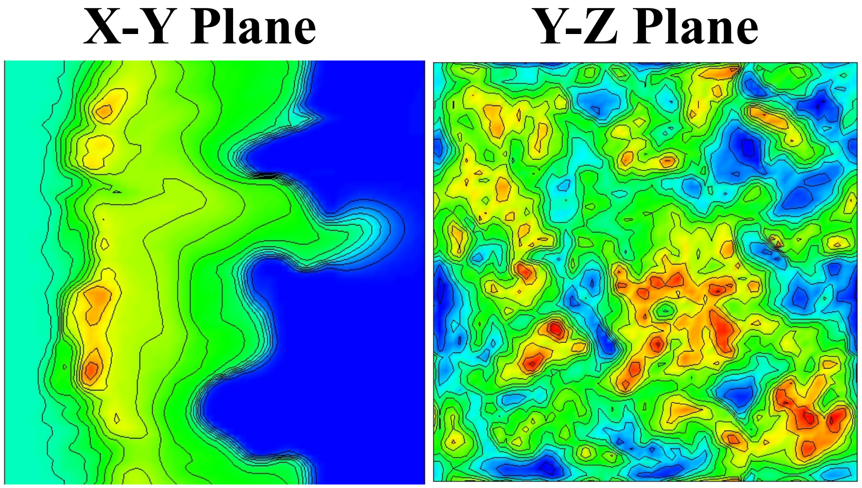


St =10

DNS: 643, O(4), LES: 32**3, O(4), Dynamic k-sgs model**
2 Mode Initialization: Fundamental and Subharmonic

LES of Partially Premixed Combustion in Two-Phase Mixtures





Contours of Methane Mass Fraction just before the flame

Lean Methane-air Premixed Mixture with 5-10 (blue-red) micron Methanol droplets, Overall Equivalence Ratio of 0.8. Grid is 643 with 18 LEM cells per LES cell.**

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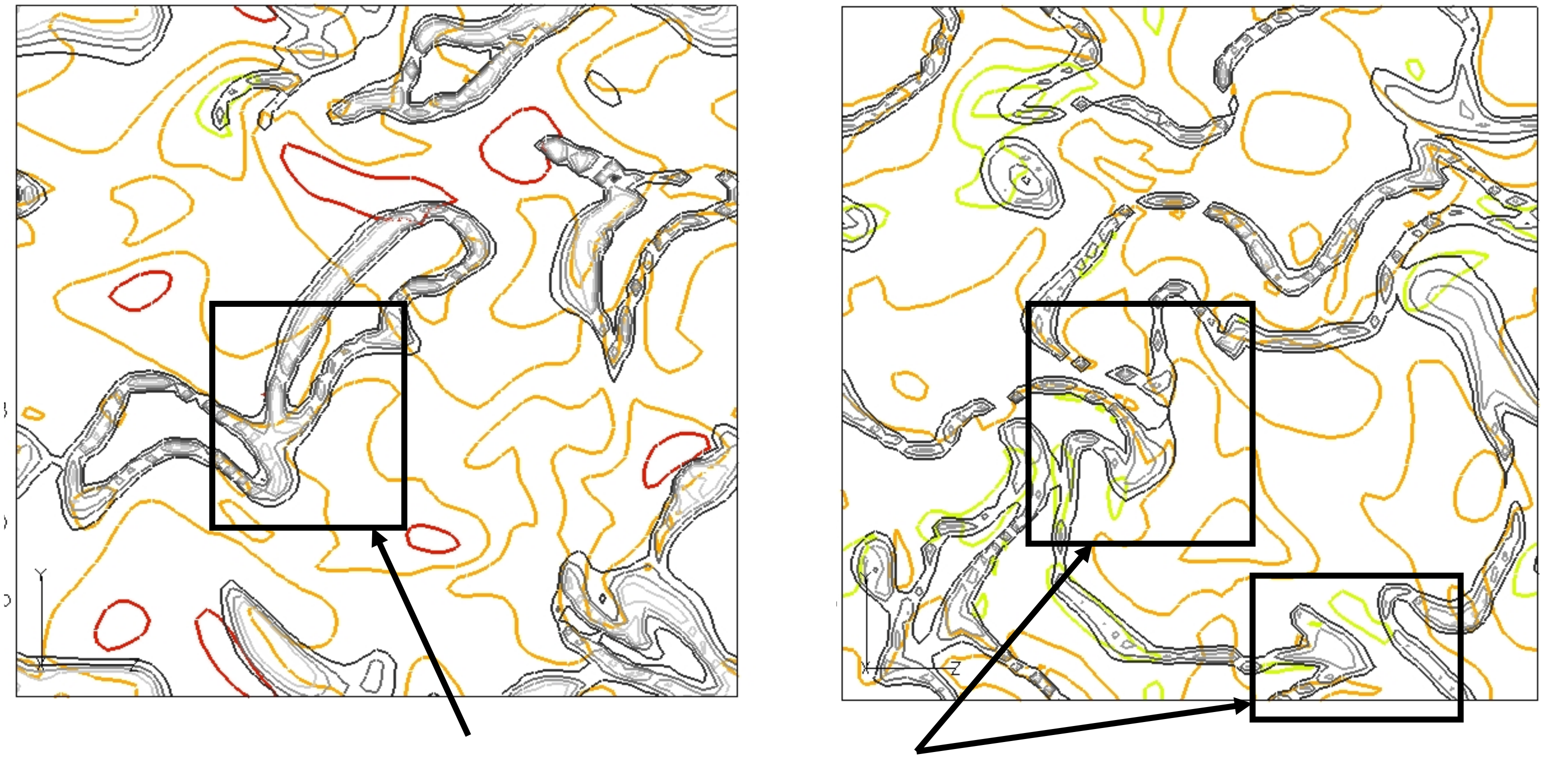
Fine-Scale Flame Structure in Partially Premixed Two-Phase Mixture



Triple-Flame Structure in the Flame Zone

Contours of Reaction Rate (BLACK) and Mixture Fraction (COLOR)

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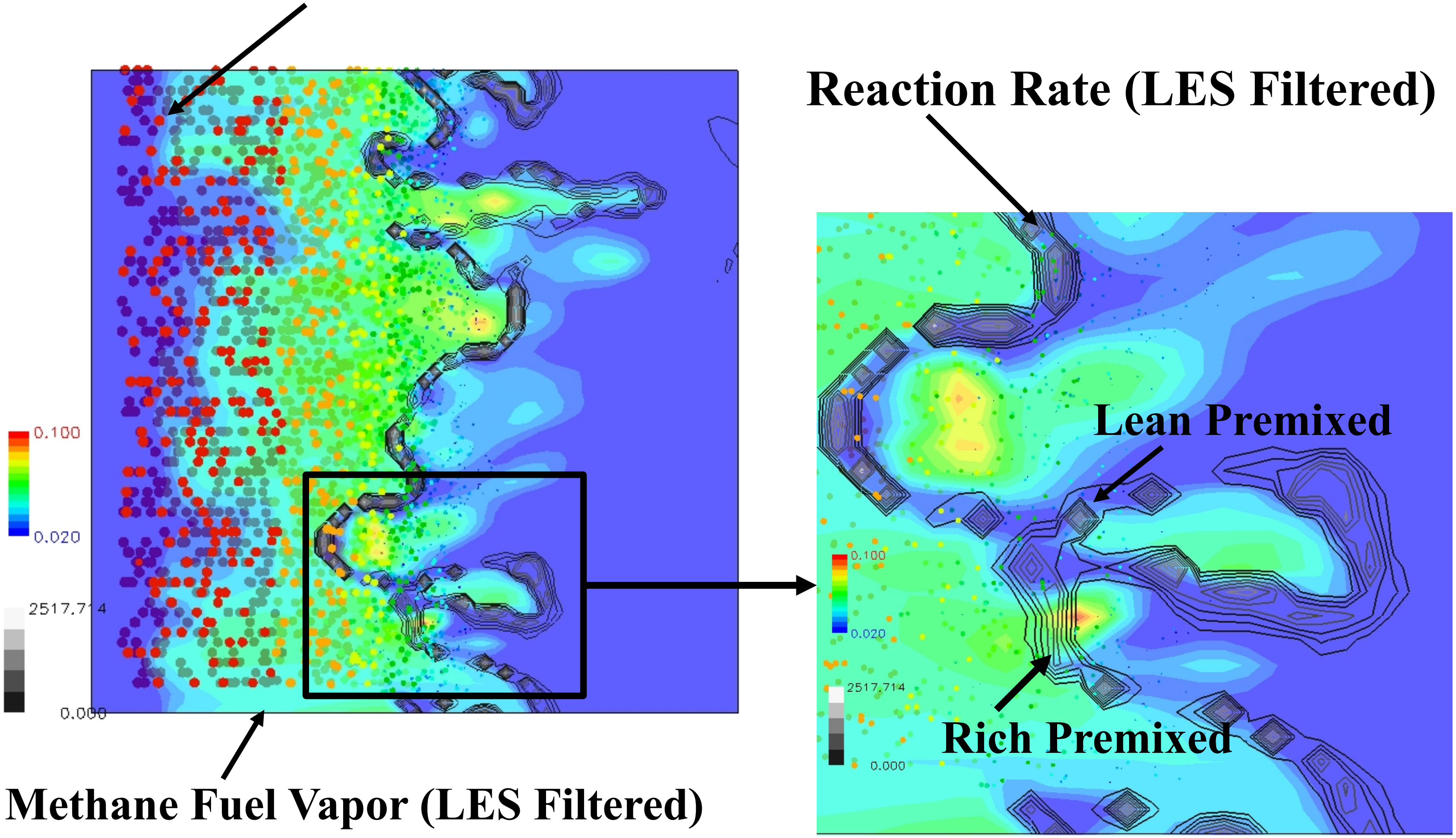
Triple-Flame Structure in Two-Phase Flame Zone



Methanol Droplets (Log Normal, SMD= 40)

Reaction Rate (LES Filtered)

Lean Premixed

Rich Premixed

Methane Fuel Vapor (LES Filtered)

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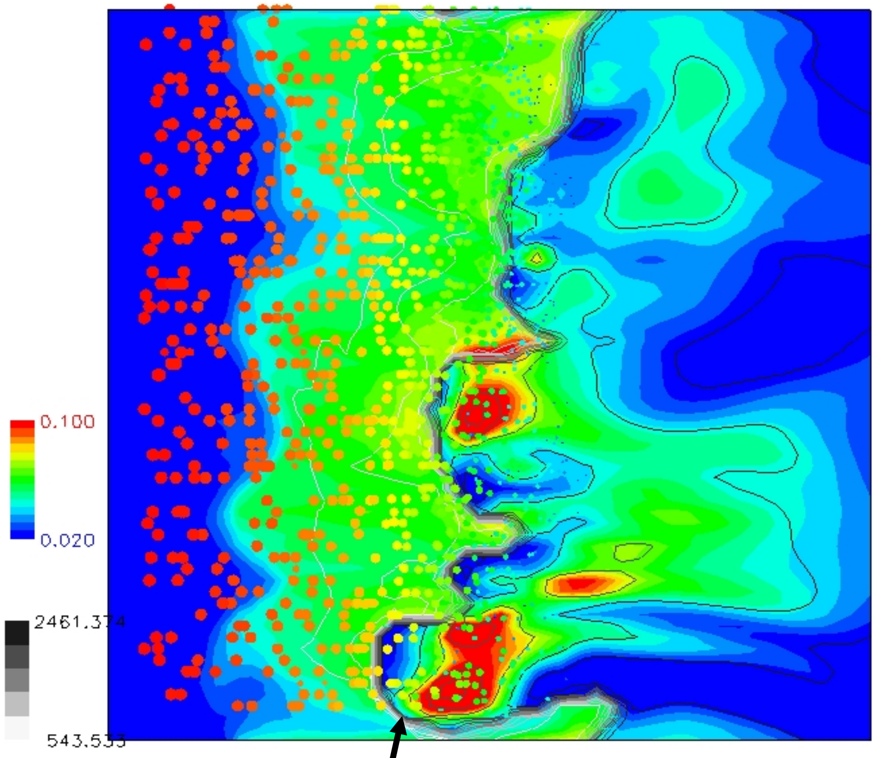
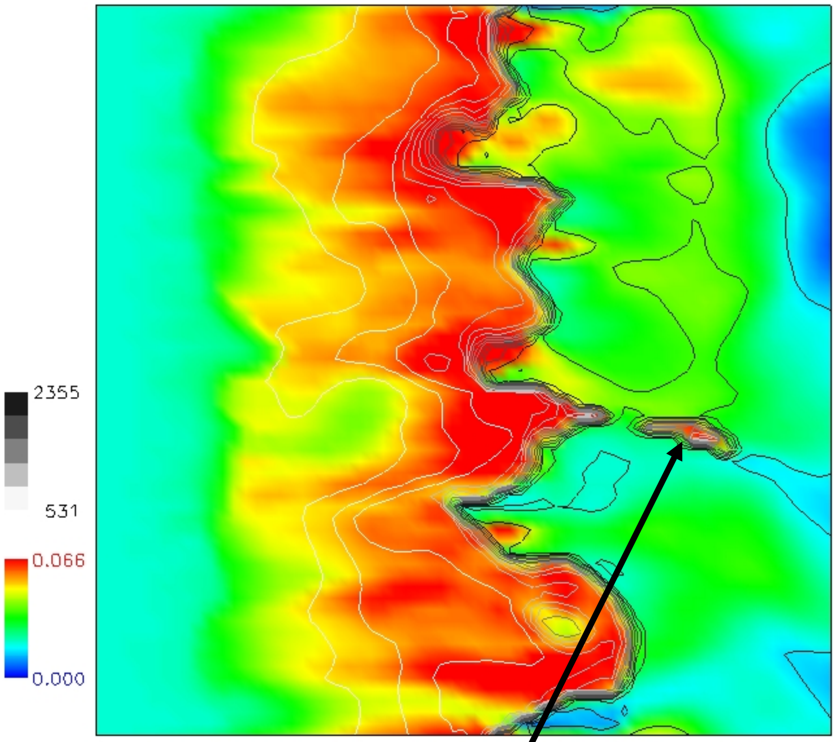
Flame Structure around Droplets



Connected Flame around Droplet Clusters



Disconnected Flame around Droplet Clusters

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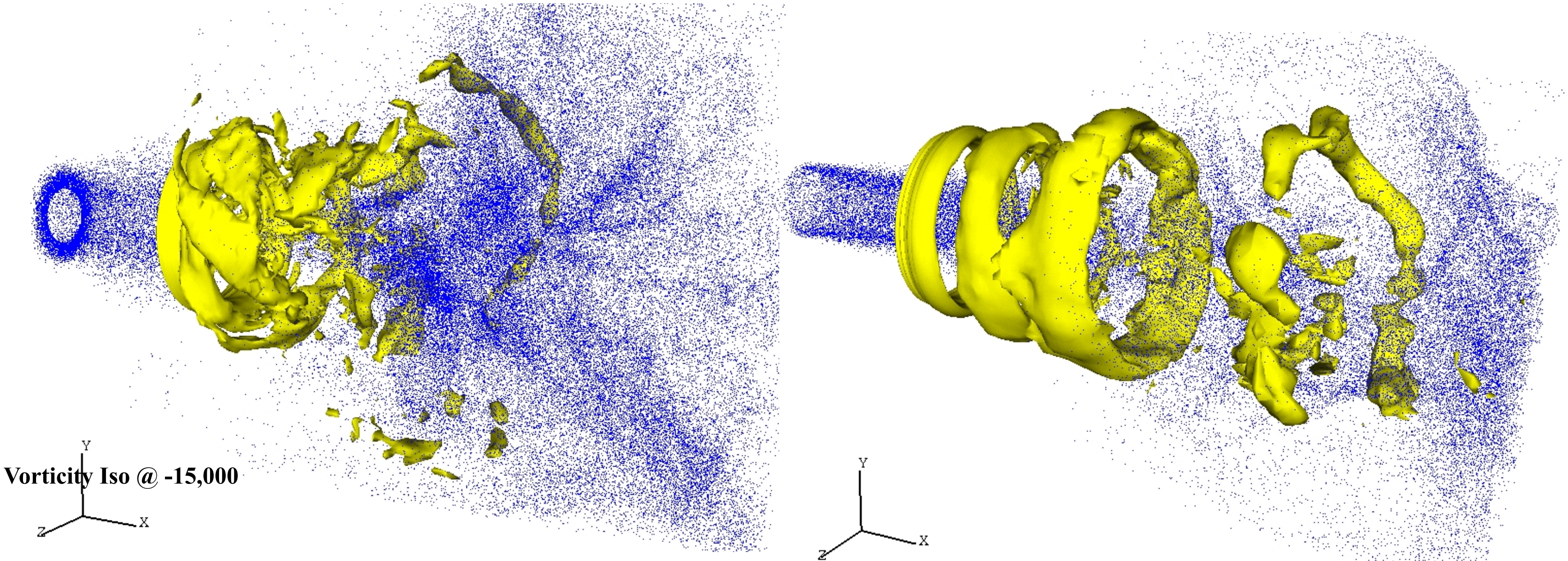
Effect of Swirl on Spray Dispersion in a General Electric DACRS Gas Turbine Combustor

Non-Reacting HIGH Swirl *Non-Reacting LOW Swirl*



Iso-Surface : Azimuthal Vorticity, Dots: Droplets (40 micron).

Vortical structures in low swirl flow are more coherent and they modulate droplets motion resulting in lower dispersion, mixing and hence, inefficient combustion.

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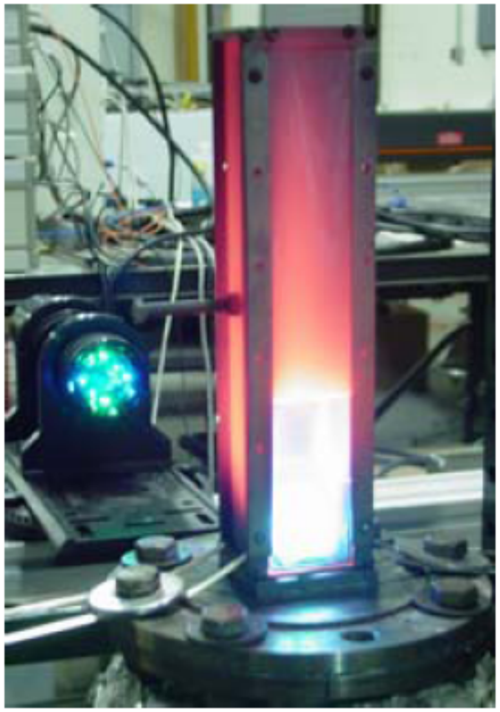
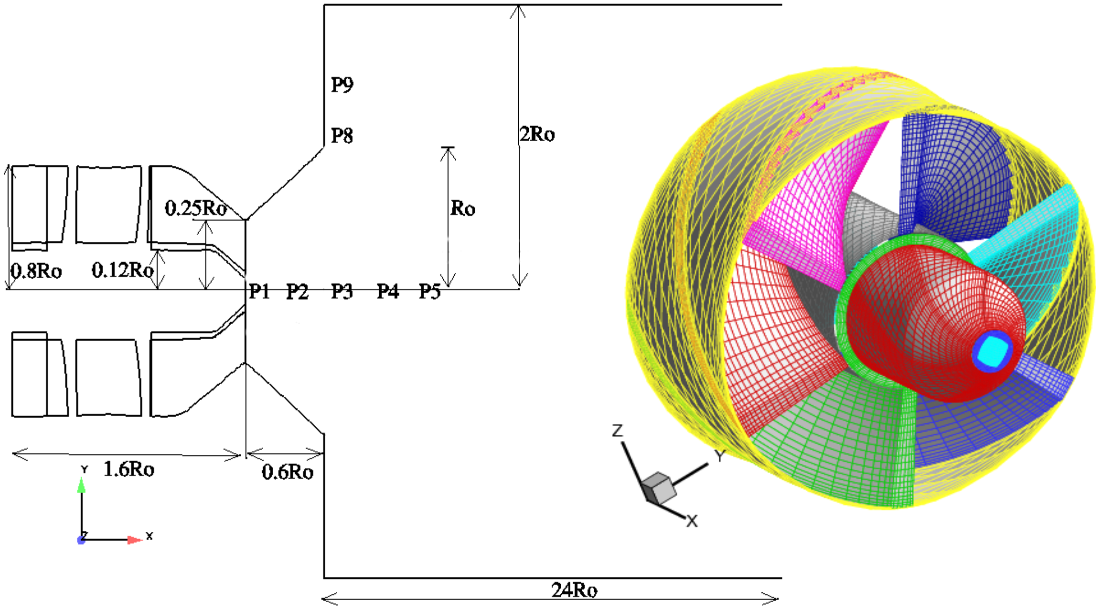
LDI Experimental Setup



Experimental Setup; Cai *et al.*



Computational Domain

- Assembly consists of six 60° helical swirl vaned inlet
- Ensuing Swirl number is 1.0; R_o=12.6 mm; U_{BULK}=20 m/s
- Butterfly domain of 1.5 M nodes; y^+~6 swirler vane walls

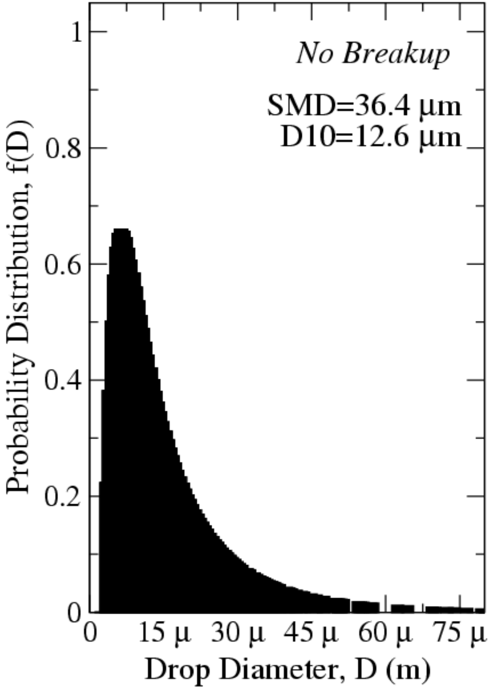
Patel and Menon, 2006, 2008

Gas-Phase Inflow Conditions

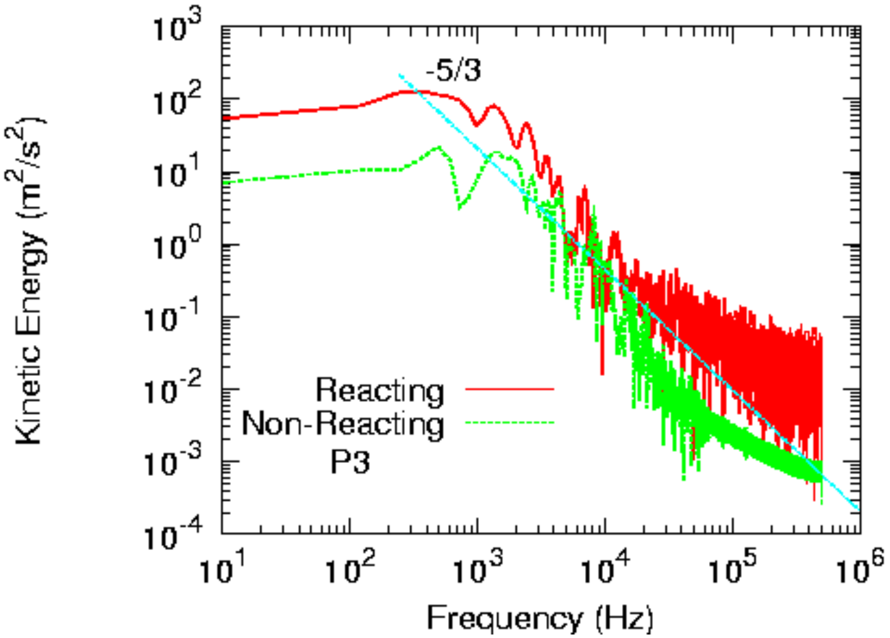
- **Through-The-Vane (TTV) simulation performed**
  - **Eliminates need to prescribe inflow velocity profiles**
  - **Turbulence generation ensues from flow through vanes**
- **Measurements performed at:**
  - **Atmospheric pressure, 300 K air, Overall $\varphi \sim 0.75$**
  - **Experimental Jet-A fuel approx as $C_{12}H_{23}$**
  - **$Re_D \sim 30{,}759$ (based on bulk flow & inlet diameter)**
  - **$Re_\Delta \sim 56$ (based on κ^{sgs} & LES filter width)**
- **Chemistry:**
  - **3-step, 7-species, Global reduced mechanism**
  - **Arrhenius rates adapted from Westbrook & Dryer for first two steps & Malte *et al.* for NO chemistry**

Patel and Menon, 2006, 2008

Liquid-Phase Initial Conditions



Initial Droplet Distribution

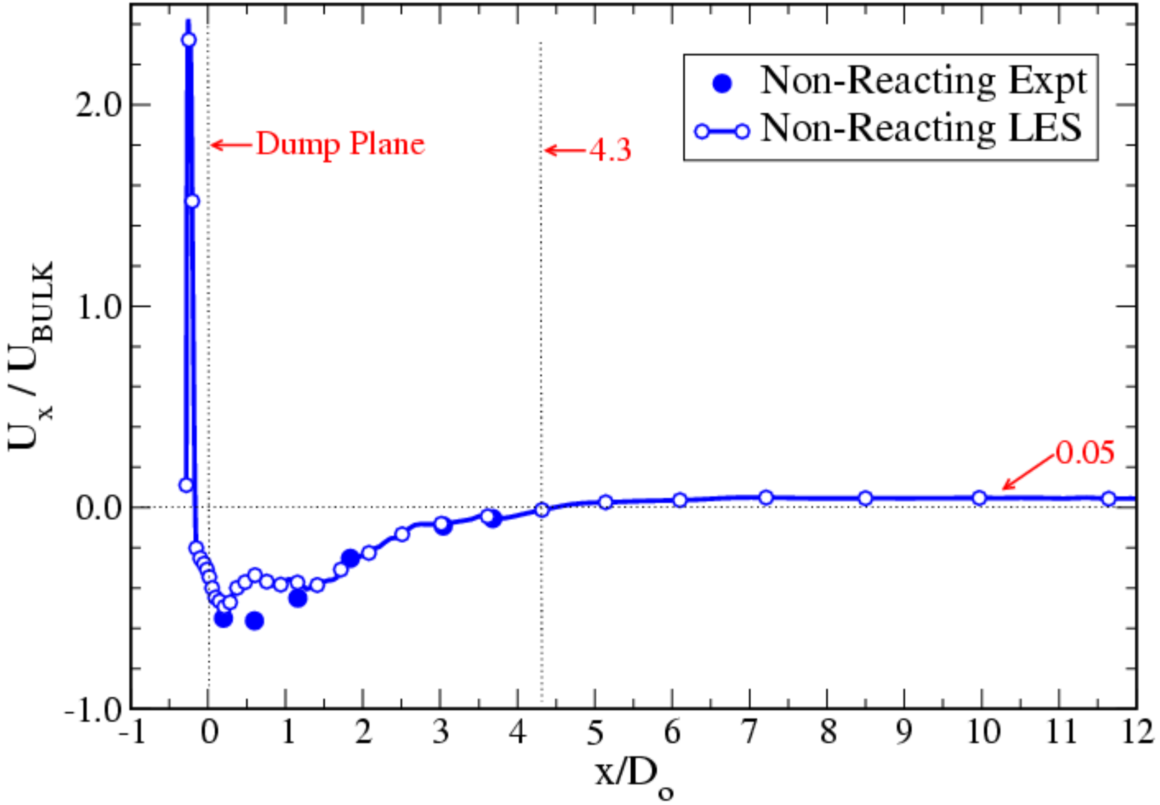


Kinetic Energy Spectra

- Log-normal droplet size distribution w/ 36.4 mm SMD
    - Spray data chosen to match near injector data
- Droplet cut-off radius ~ 1 mm; Approx. 25,000 parcels
- Grid resolution is adequate to recover some inertial range for both non-reacting & reacting cases

Patel and Menon, 2006, 2008

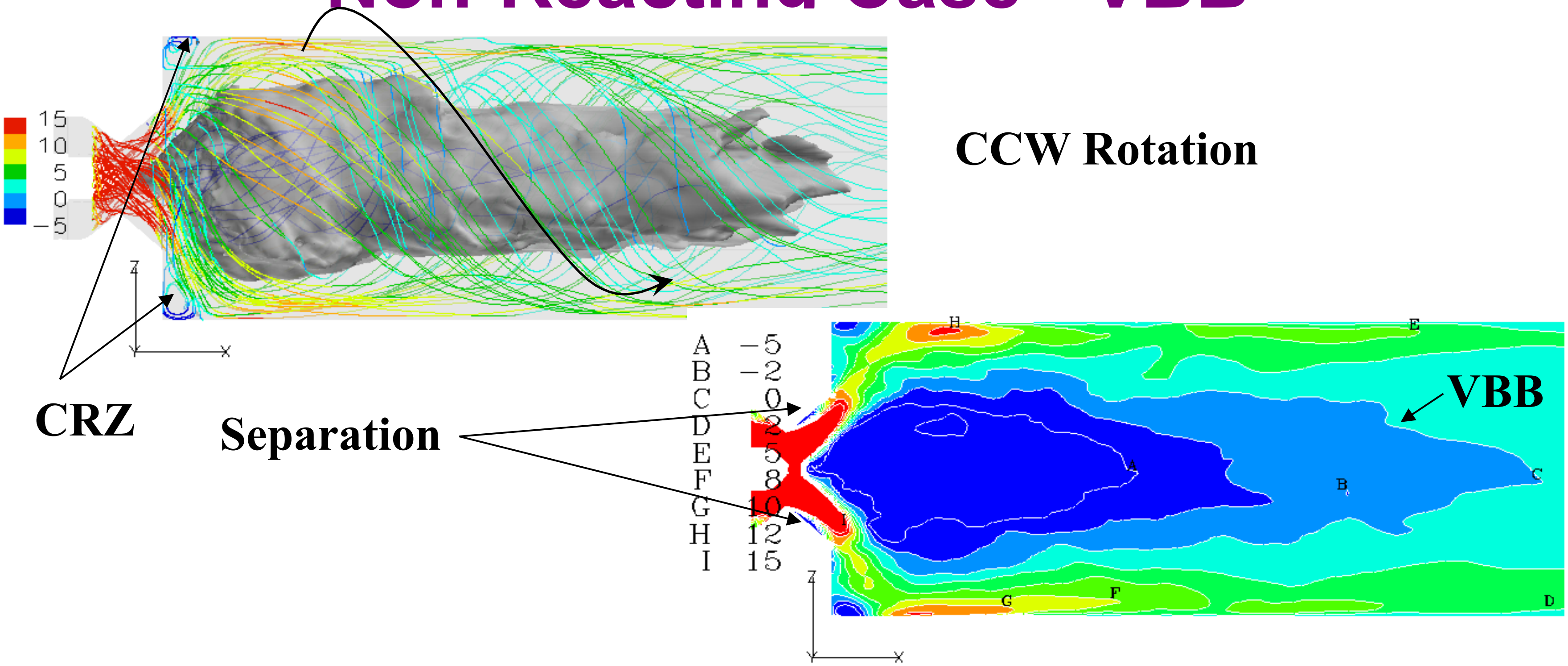
Non-Reacting Centerline Axial Velocity



- VBB length x/D_o ~ 4.3; Recovery velocity ~ 5% of U_{BULK}
- Peak negative ~ 60%; Peak Positive ~ 240% of Bulk
- Strength & Extent of VBB reasonably predicted by LES

Patel and Menon, 2006, 2008

Non-Reacting Case - VBB



CCW Rotation

CRZ

Separation

VBB

- VBB (iso-surface) is a single contiguous region
- Corner re-circulation zone (CRZ) noted
- Leaf-shaped cross-section for VBB in the center-planes
- Strong TKE observed between VBB and venturi walls

Patel and Menon, 2006, 2008

Non-Reacting Case - Axial
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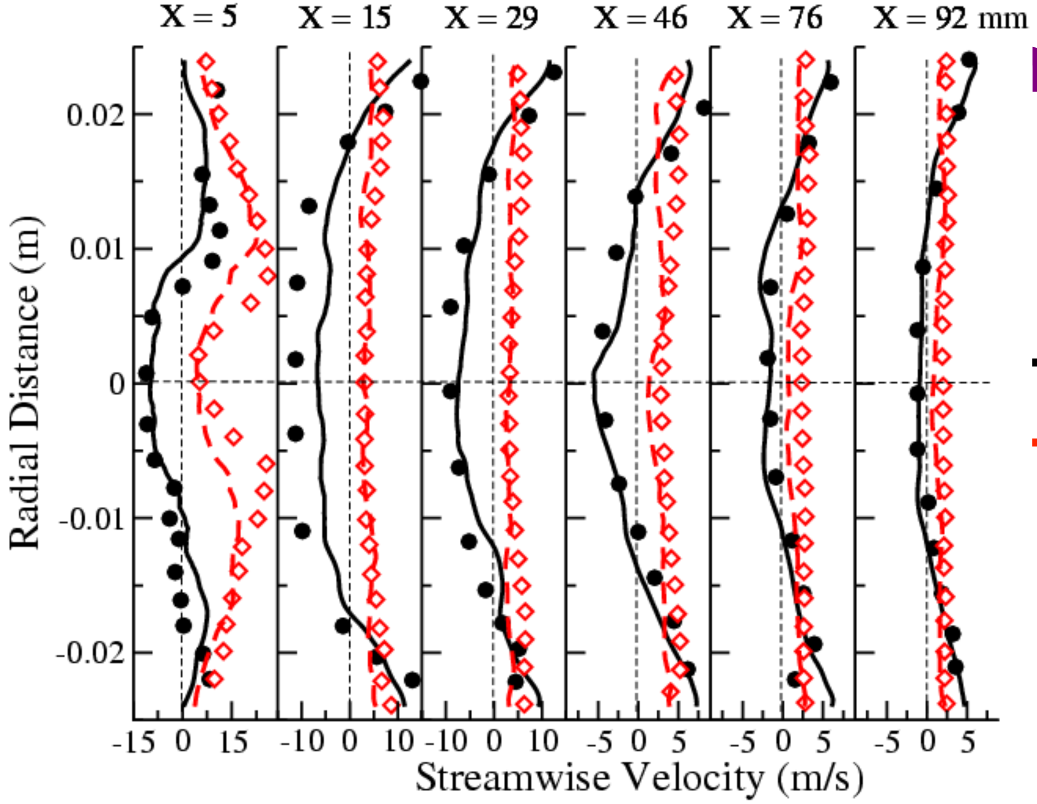


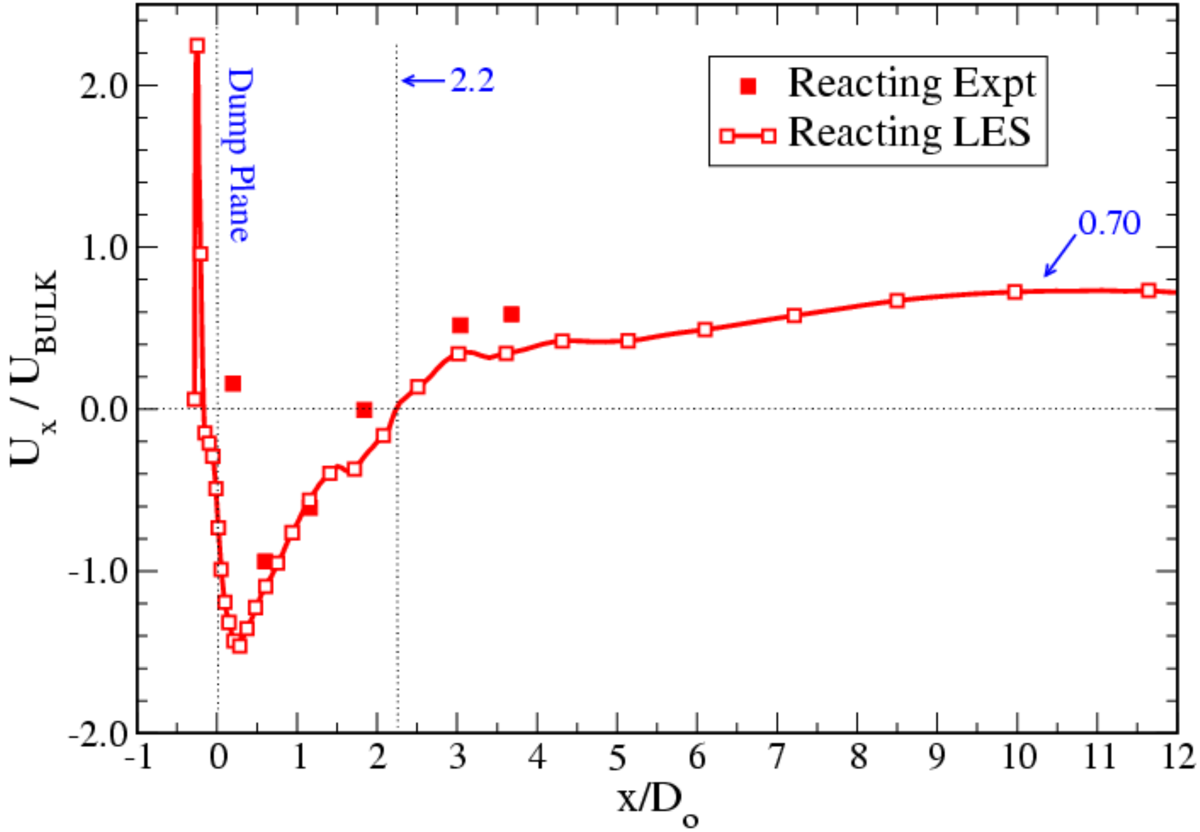
——, Solid Symbols: Mean

– – –, Open Symbols: RMS

- Radial extent of VBB: $r/R_o \sim 1.4$ @ $x/R_o \sim 1.0$
- RMS profile peaks indicates shear-layer regions
- RMS decays and approaches uniform radial profiles

Patel and Menon, 2006, 2008

Centerline Axial Velocity - Reacting



- VBB length x/D_o ~ 2.2; Recovery vel ~ 70% of U_{BULK}
- Peak negative ~ 160%; Peak Positive ~ 240% of Bulk
- Strength & Extent of VBB reasonably predicted by LES

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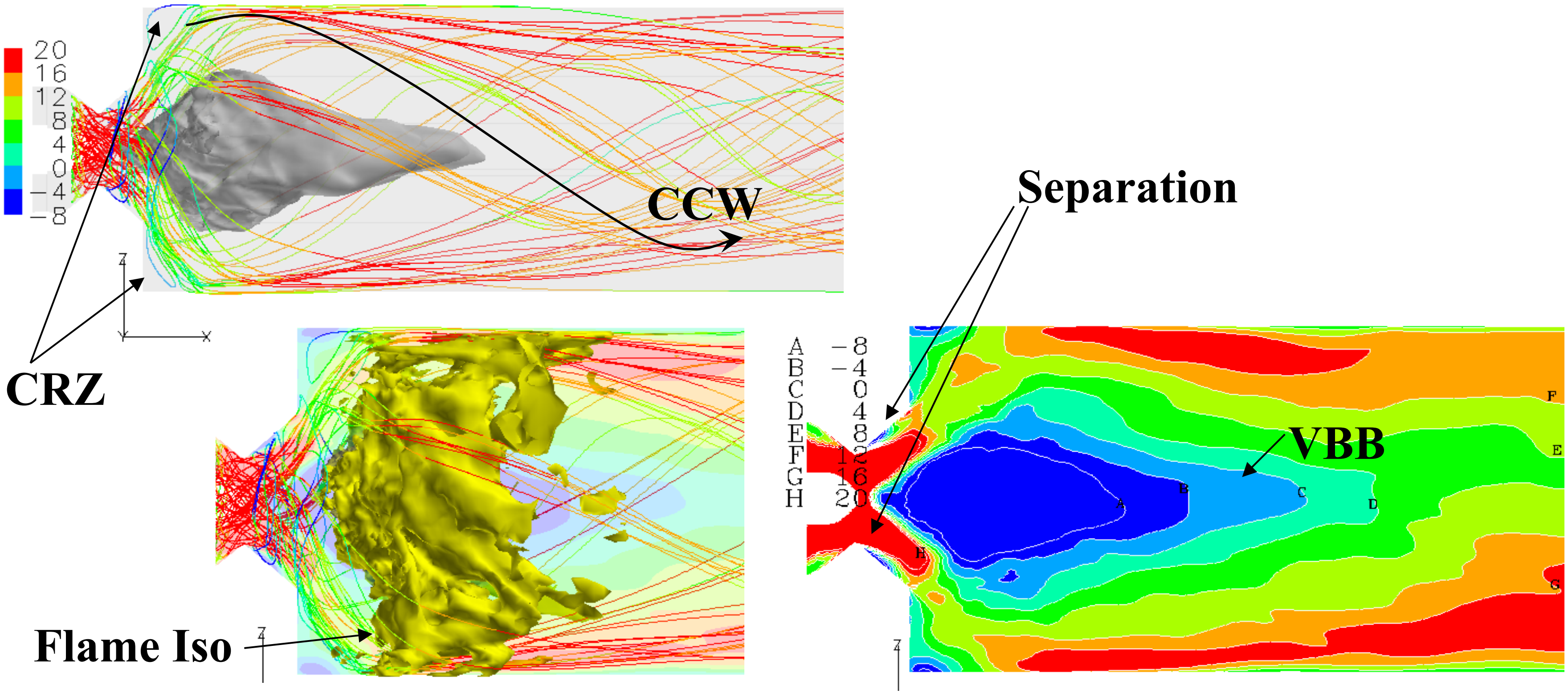
Reacting Case - VBB



- VBB is a single contiguous region albeit <u>smaller</u>
- Separation seen at 45^o expansion angle, CRZ noted as well
- Mean flame surface stabilized by the VBB

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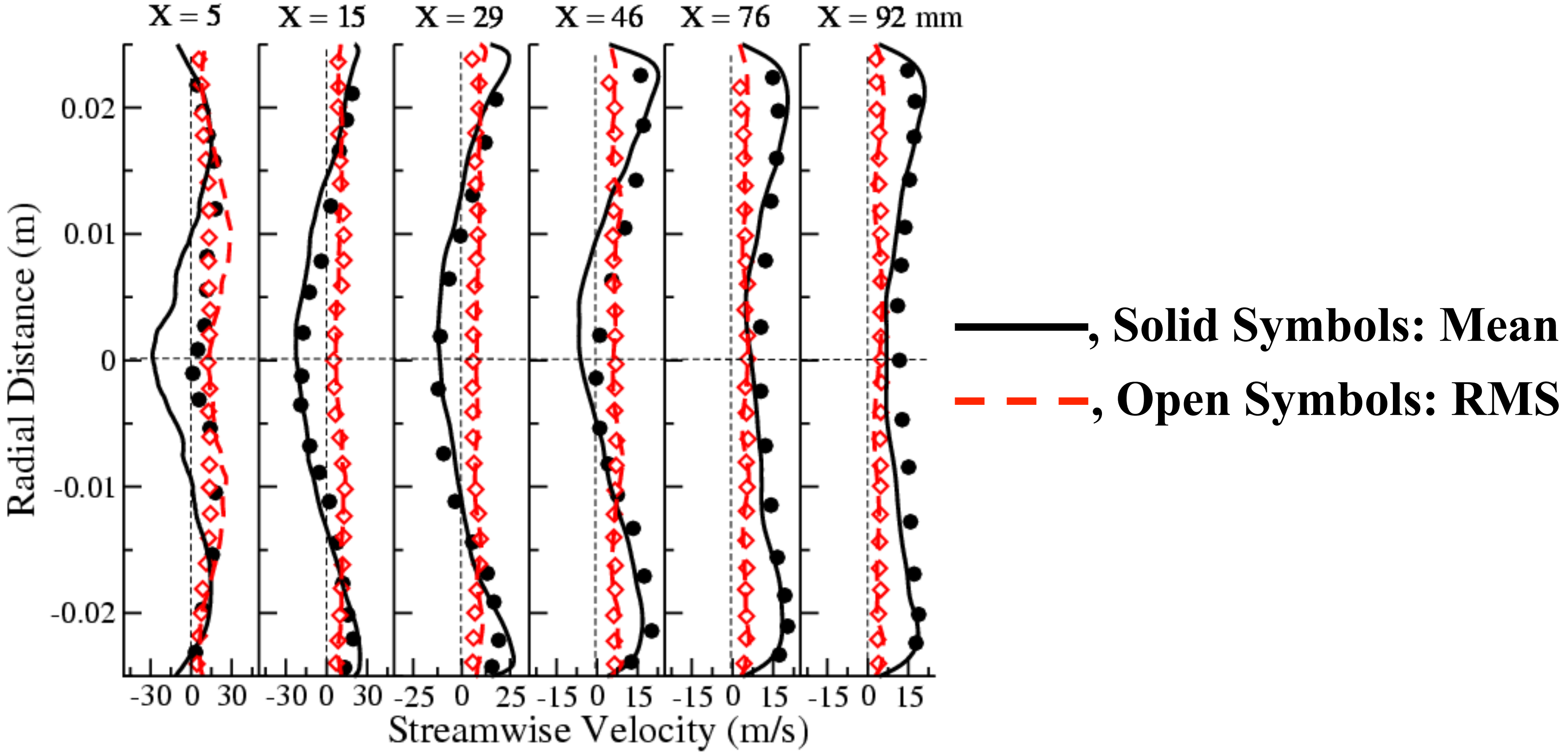
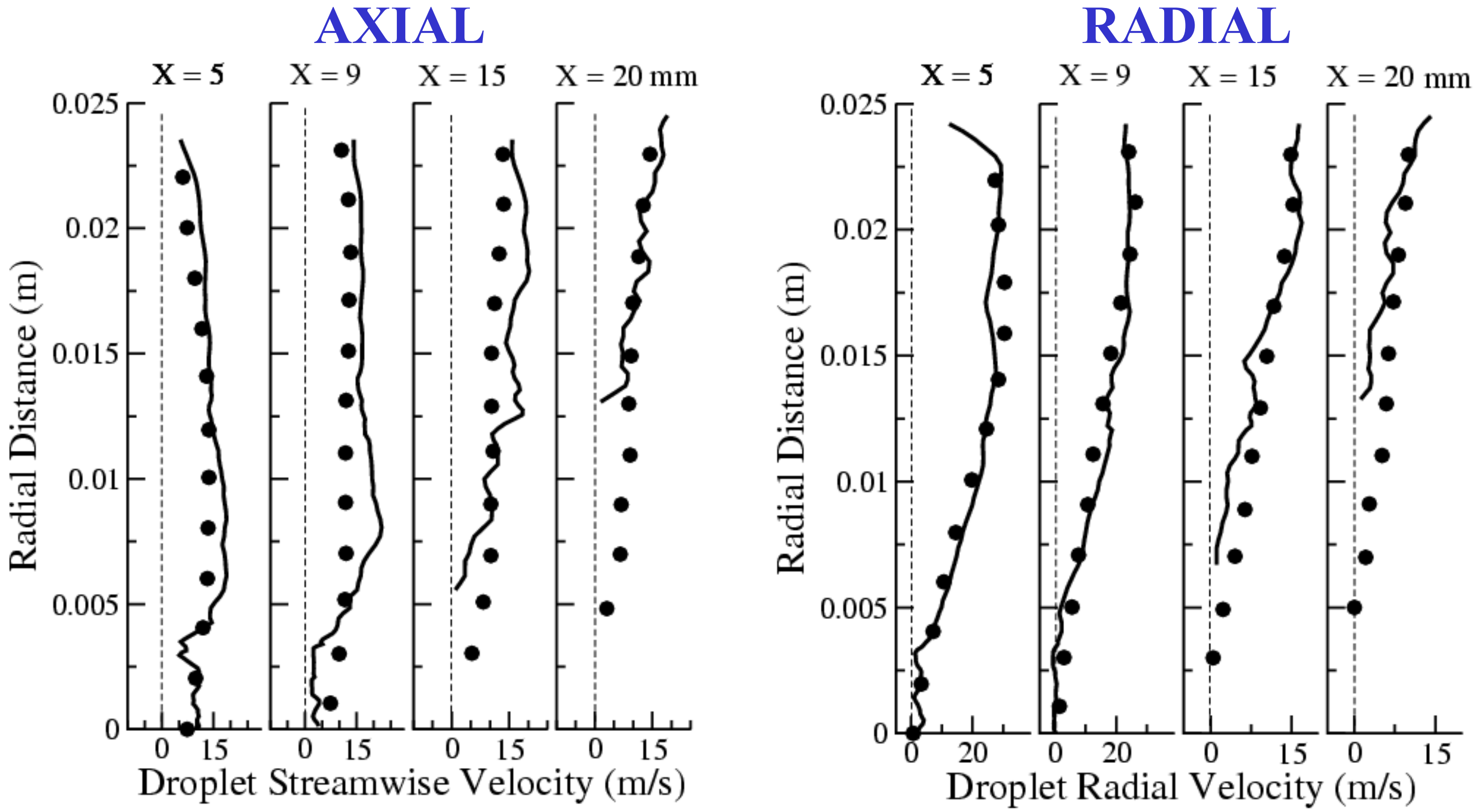
Reacting Case - Axial Comparisons



- Radial extent of VBB: $r/R_o \sim 1.0$ @ $x/R_o \sim 1.0$
- Peak in axial velocity found on outer edges, Wall-jet effect
- RMS decays, uniform profile downstream; 30% intensity

Patel and Menon, 2006, 2008

Reacting - Particle Velocity



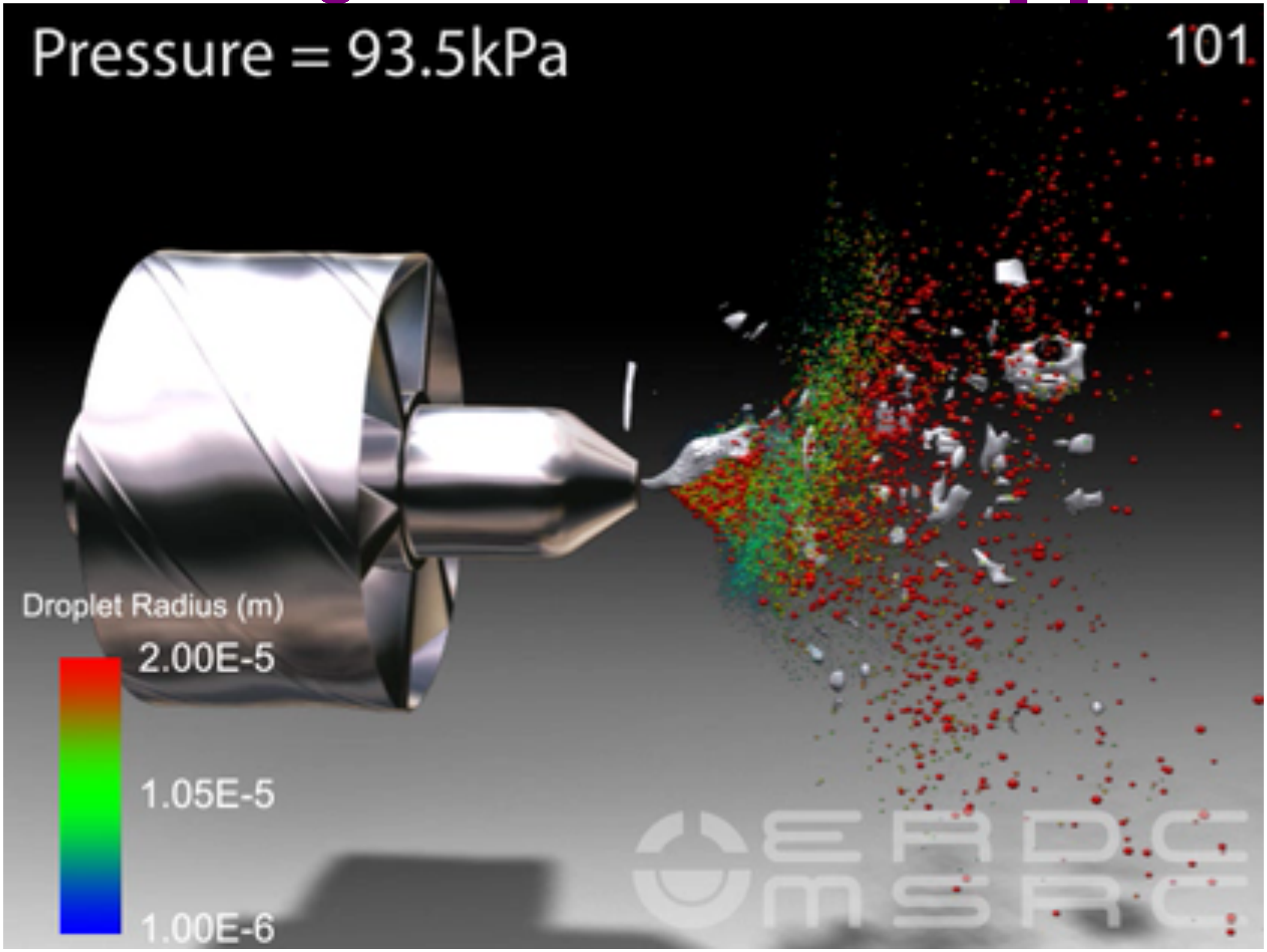
AXIAL

RADIAL

- Particle comparisons for 31-45 μm diameter bin
- Particle path seen to form a hollow-cone shape
- Positive axial velocity observed in VBB; Good trend noted

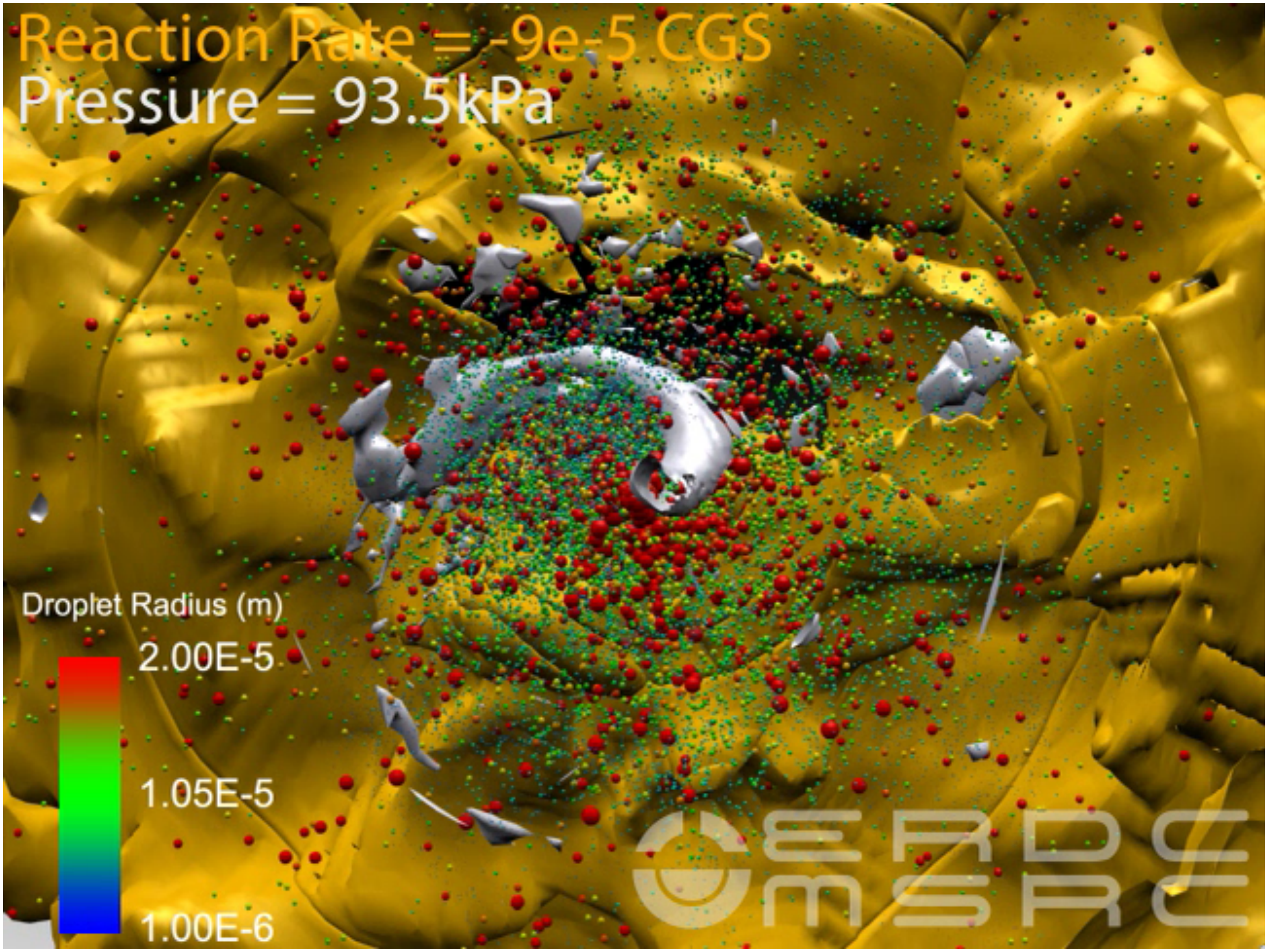
Patel and Menon, 2006, 2008

Reacting Case – Animation [1]



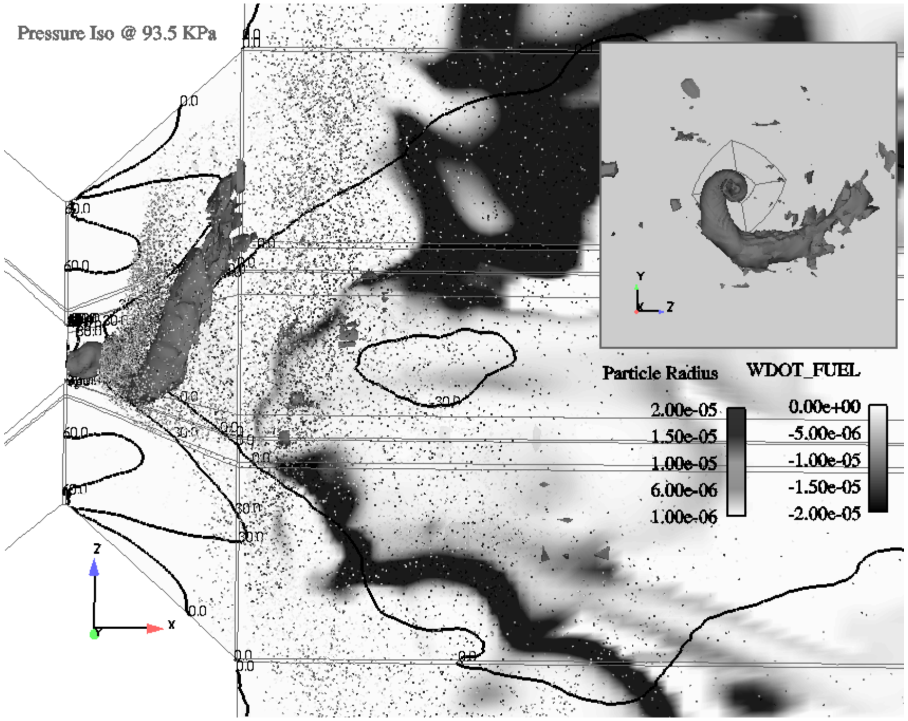
Patel and Menon, 2006, 2008

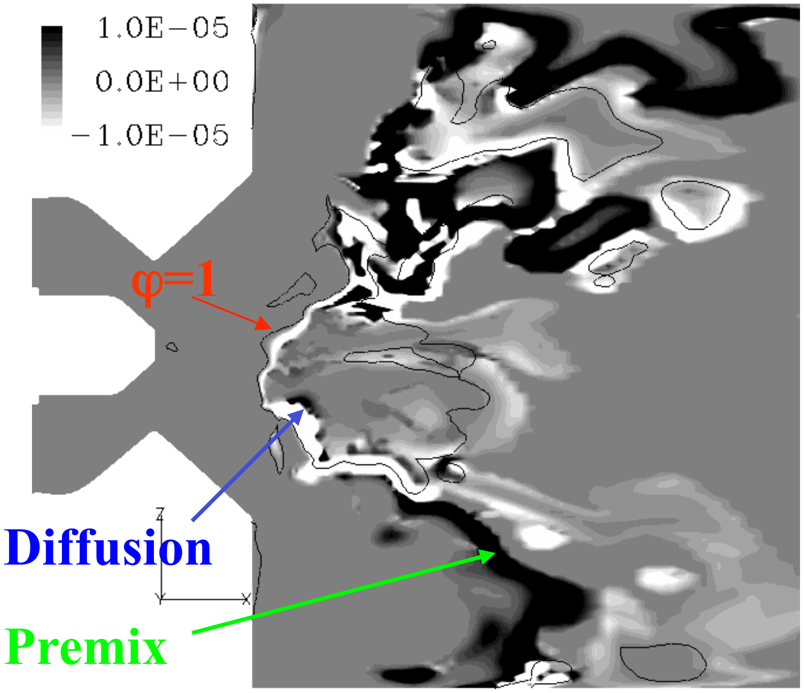
Reacting Case – Animation [2]



Patel and Menon, 2006, 2008

Reacting Case - Flame Structure

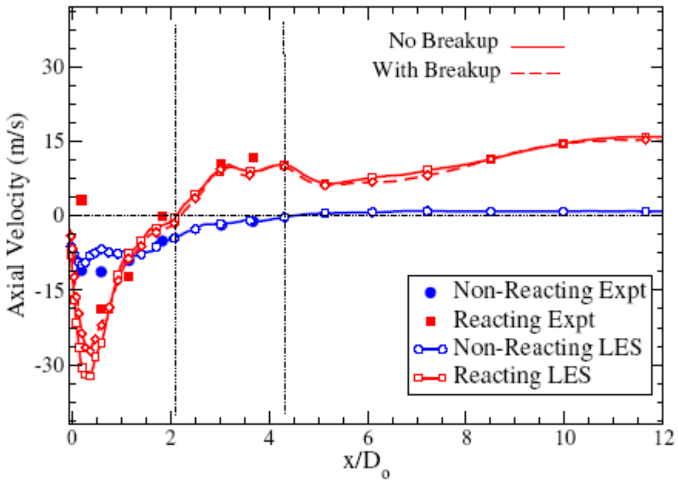


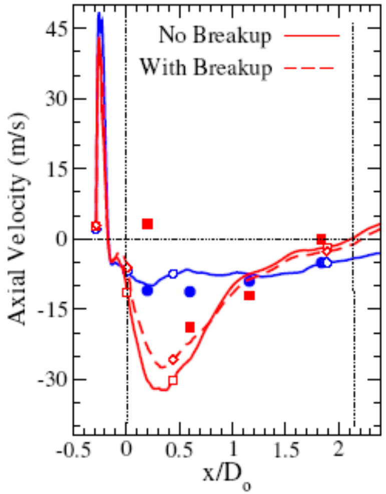


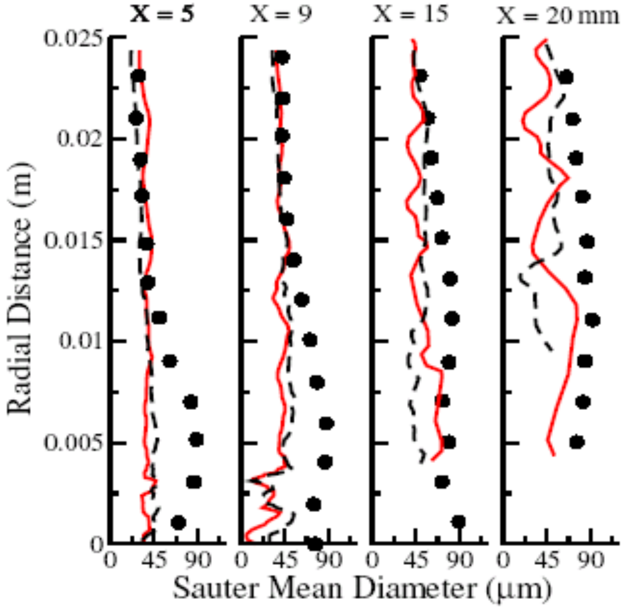
- Particle entrainment by the PVC is effective for dispersion
- VBB and Flame precessing with PVC motion
- Flame index shows presence of premixed & diffusion flames

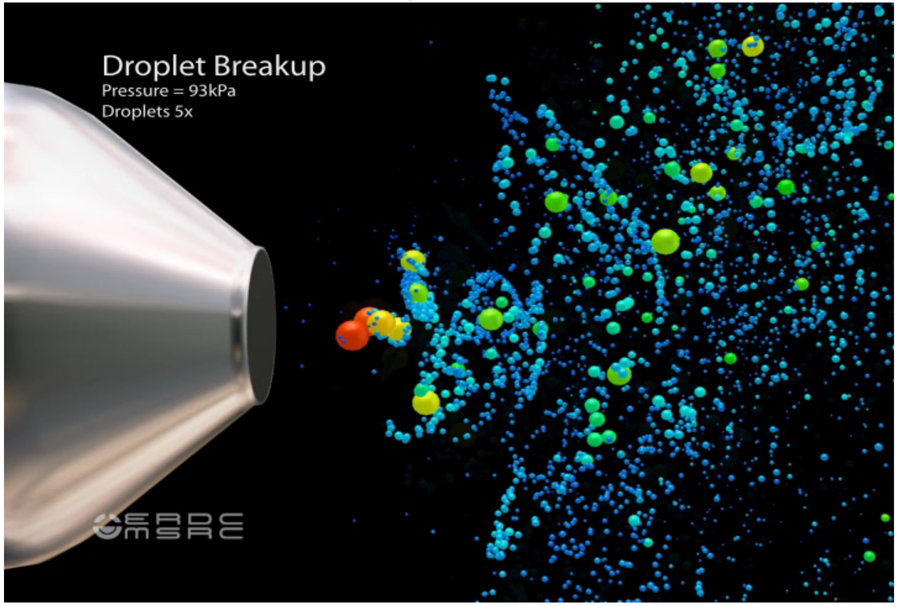
Patel and Menon, 2006, 2008

Effect of Spray Break-up Modeling





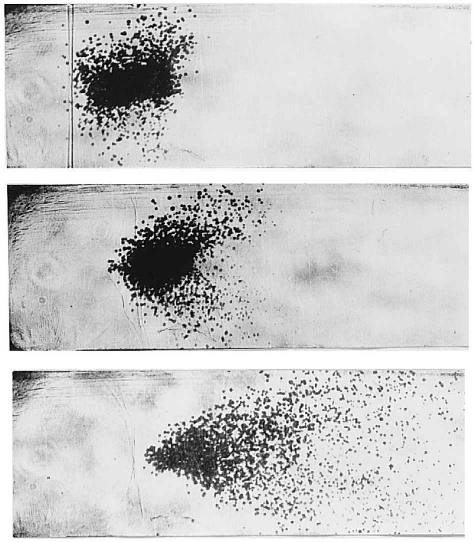




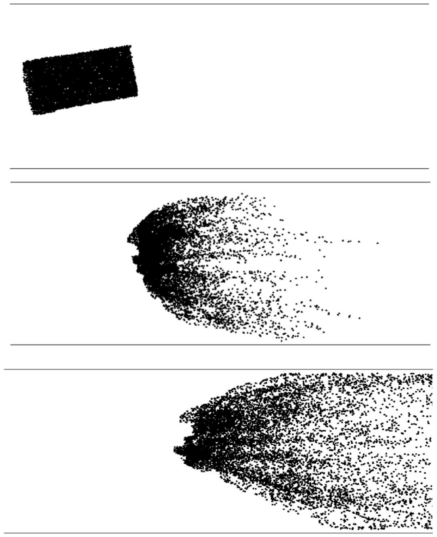
Patel and Menon, 2006, 2008

Eulerian Gas Phase Dense Modeling

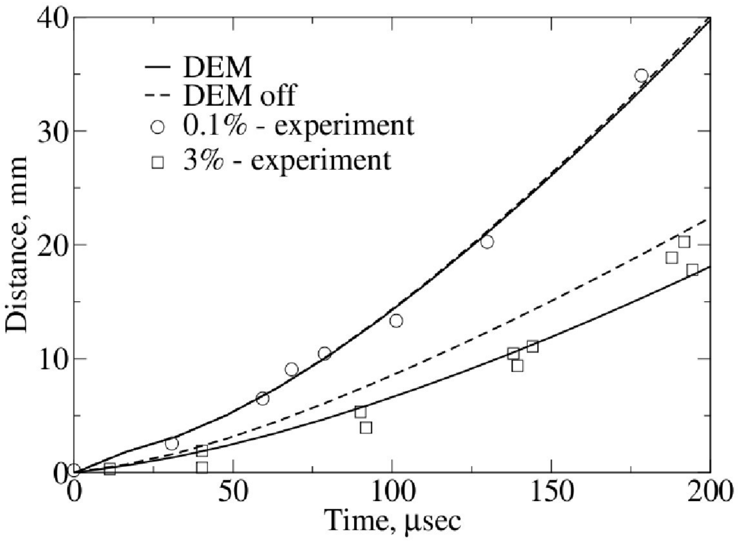
- Original E-E DEM approach [1] extended to E-L approach [2] to modify gas phase fluxes based on volume fraction loading



Experiment [3]



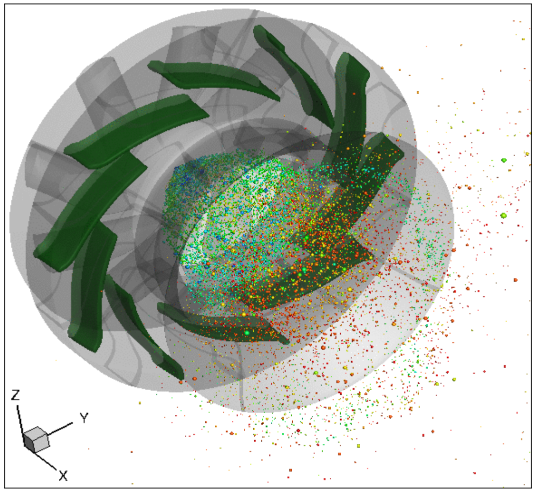
Simulation [2]

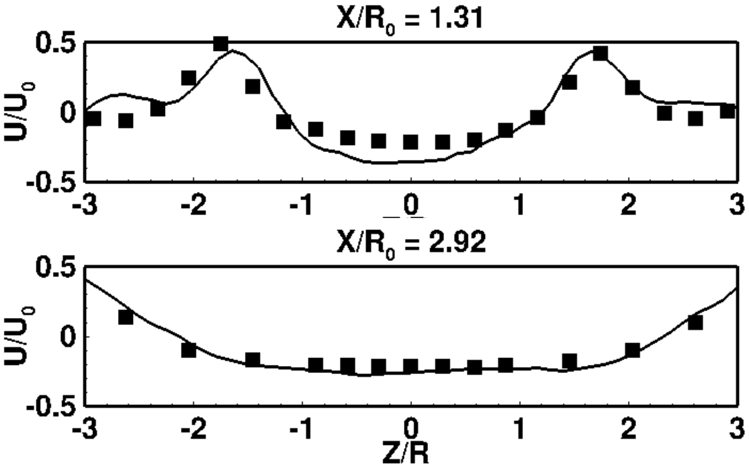


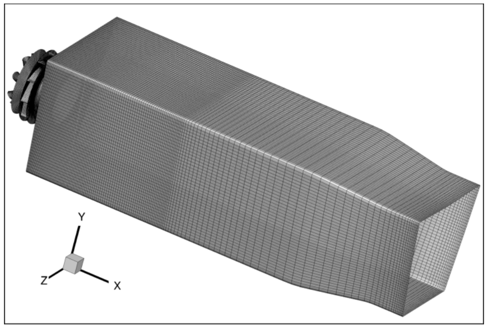
- **M=2.8 shock impact on dense cloud of 300 micron particles**
- **Dense core of particles form after shock impact**
- **Modified Eulerian gas phase fluxes necessary for dense case**

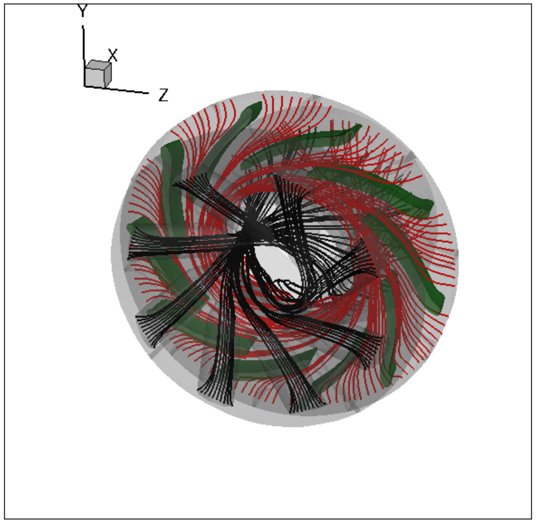
[1] Abgrall and Saurel, J. Comp. Phys., 186, 2003.
[2] Balakrishnan, Nance and Menon, Shock Waves, 20, 2010.
[3] Boiko et al., Shock Waves, 1997

CFM56 Experiments* in Georgia Tech

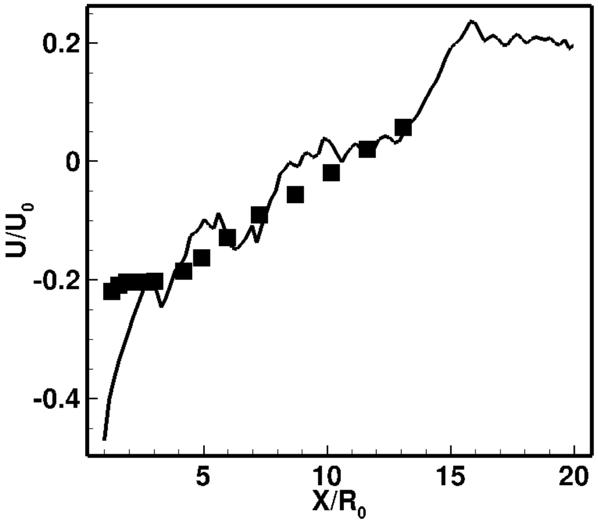






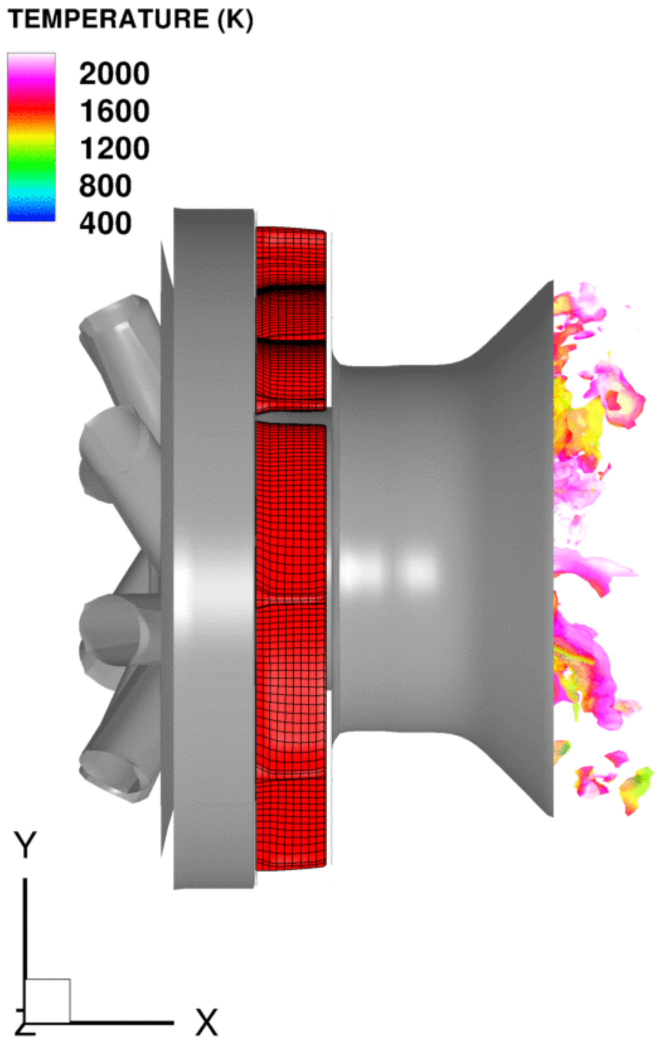


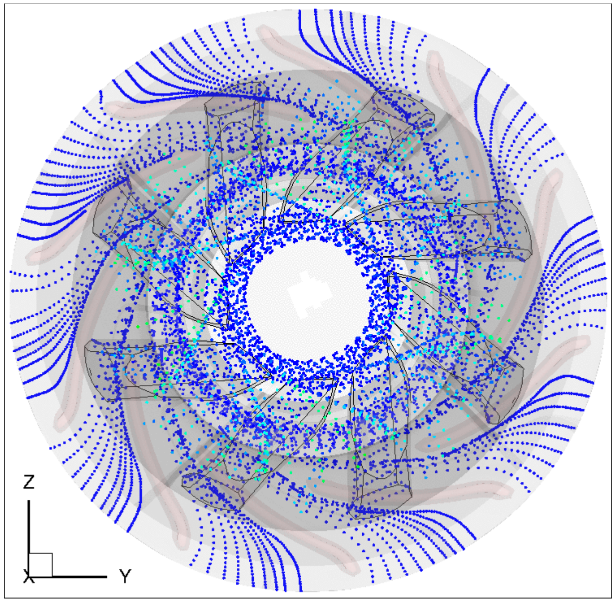
Primary: Red, Secondary: Black



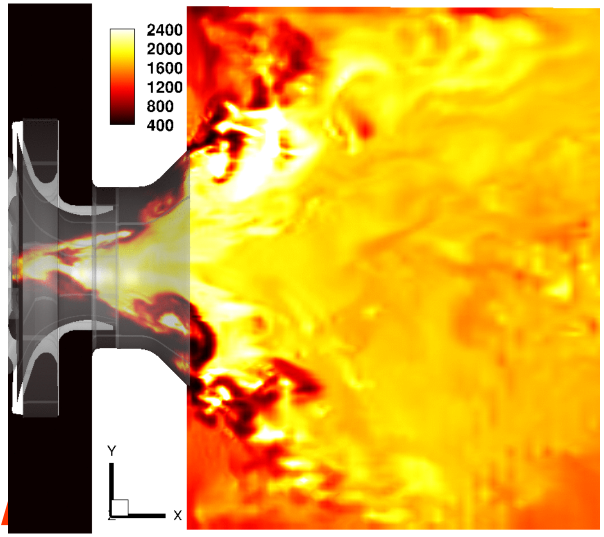
*Colby, Jagoda and Menon, ASME-GT2006-90974

Swirling Spray Combustion in CFM56





Counter-swirl streaklines



Temperature

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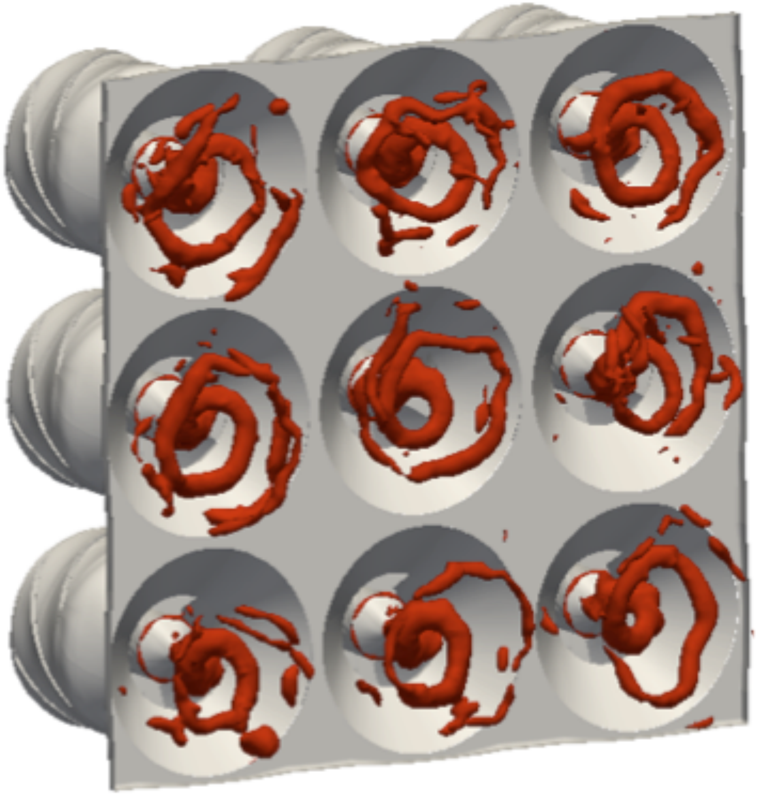
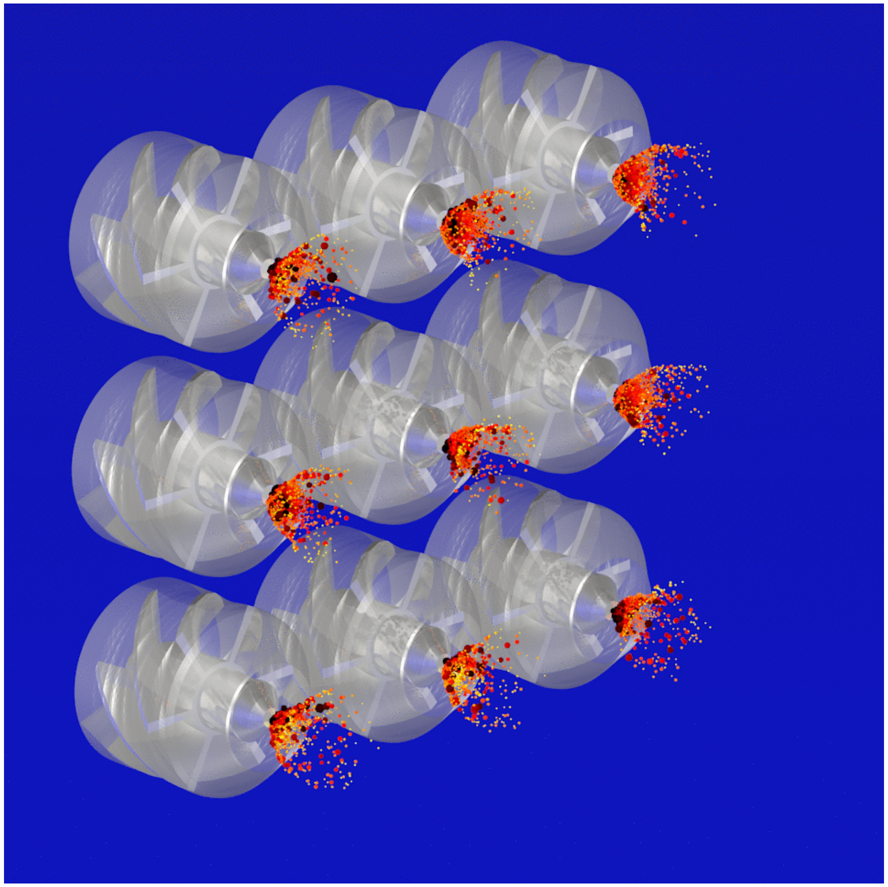
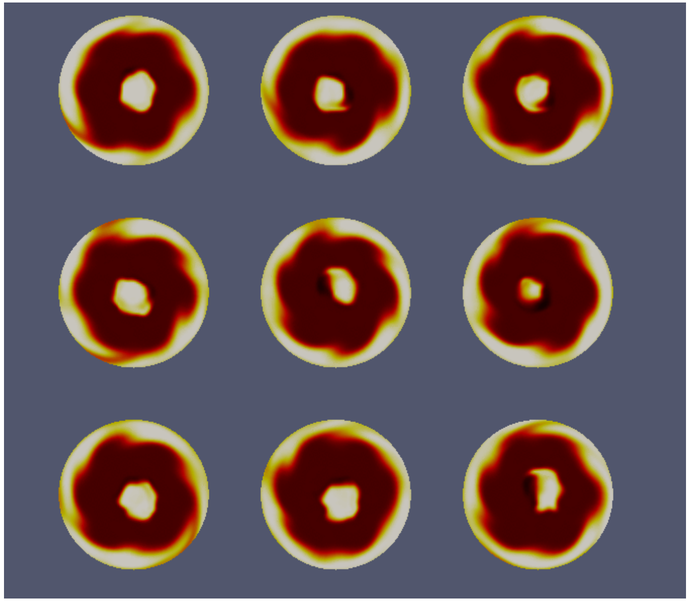
9-point LDI at High Pressure

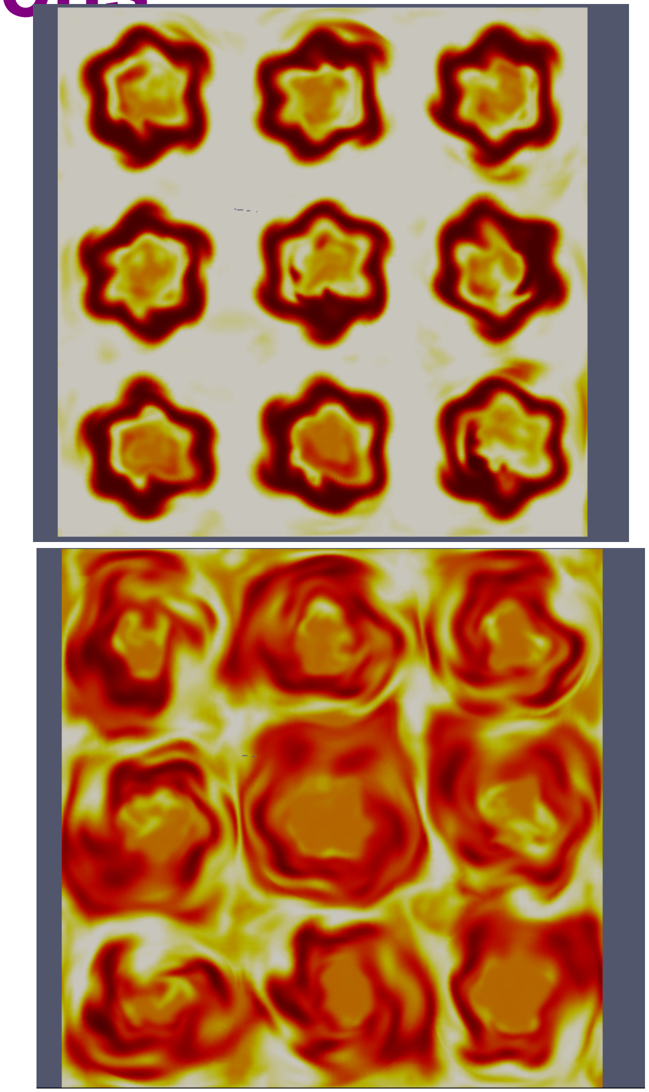




- **10-45M grid with grid refinement**
- **High pressure 10-27 atm (NASA test rig, Heath et al., 2010)**
- **Kerosene spray with emissions (CO and NO)**

9-point LDI: Injector-to-Injector Interactions





- All have same initial swirl but downstream interactions change mixing and flame structures
- Single injector studies cannot provide insight into this effect

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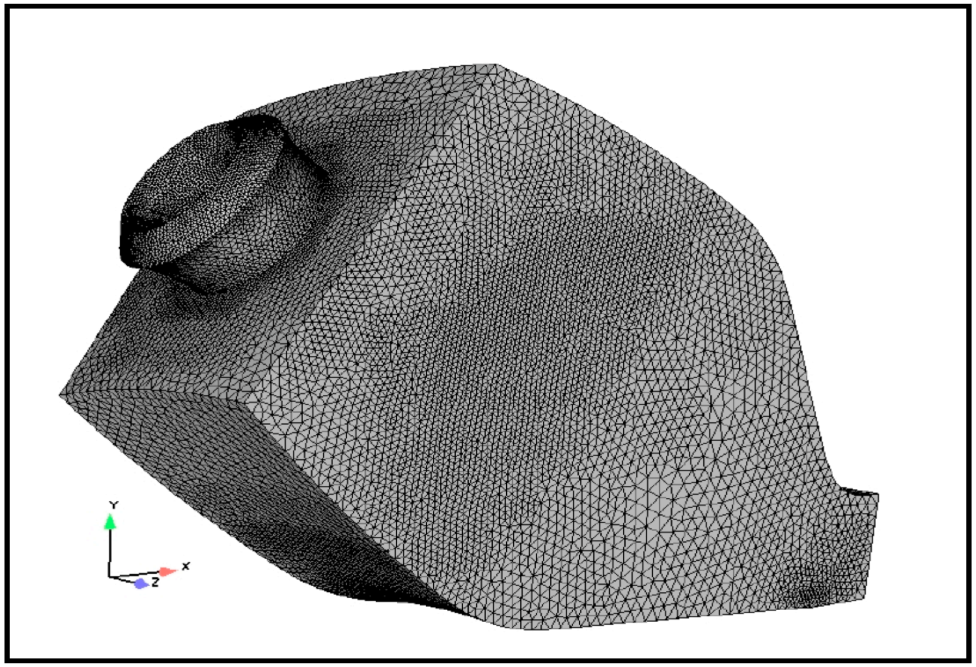
Gas turbines combustion studies: single sector vs full chamber ?

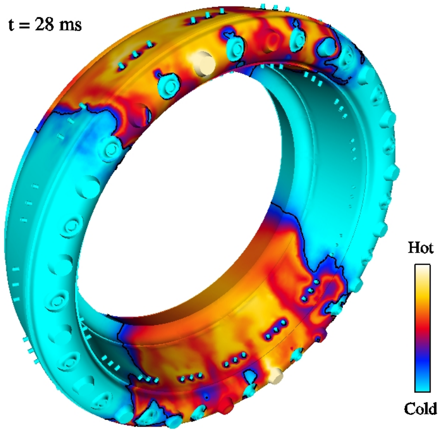
- "Real life": multi sector (10 to 24) combustion chambers
- Labs: most studies (CFD or experiment) addressing combustion issues are limited to single burners

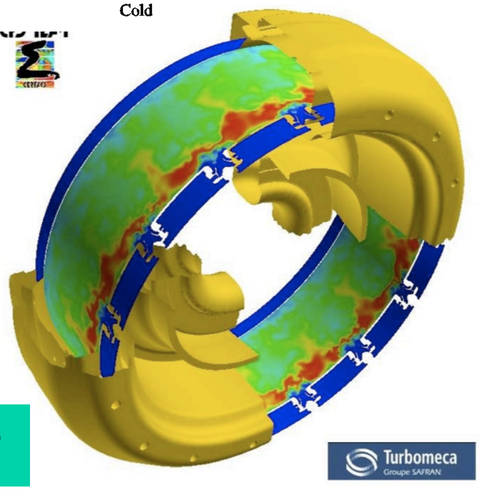


Courtesy T. Poinsot

Gas turbines specific mechanisms:

- Certain phenomena found in real gas turbines require LES of full combustion chambers:
  - *Ignition*
  - *Azimuthal modes*



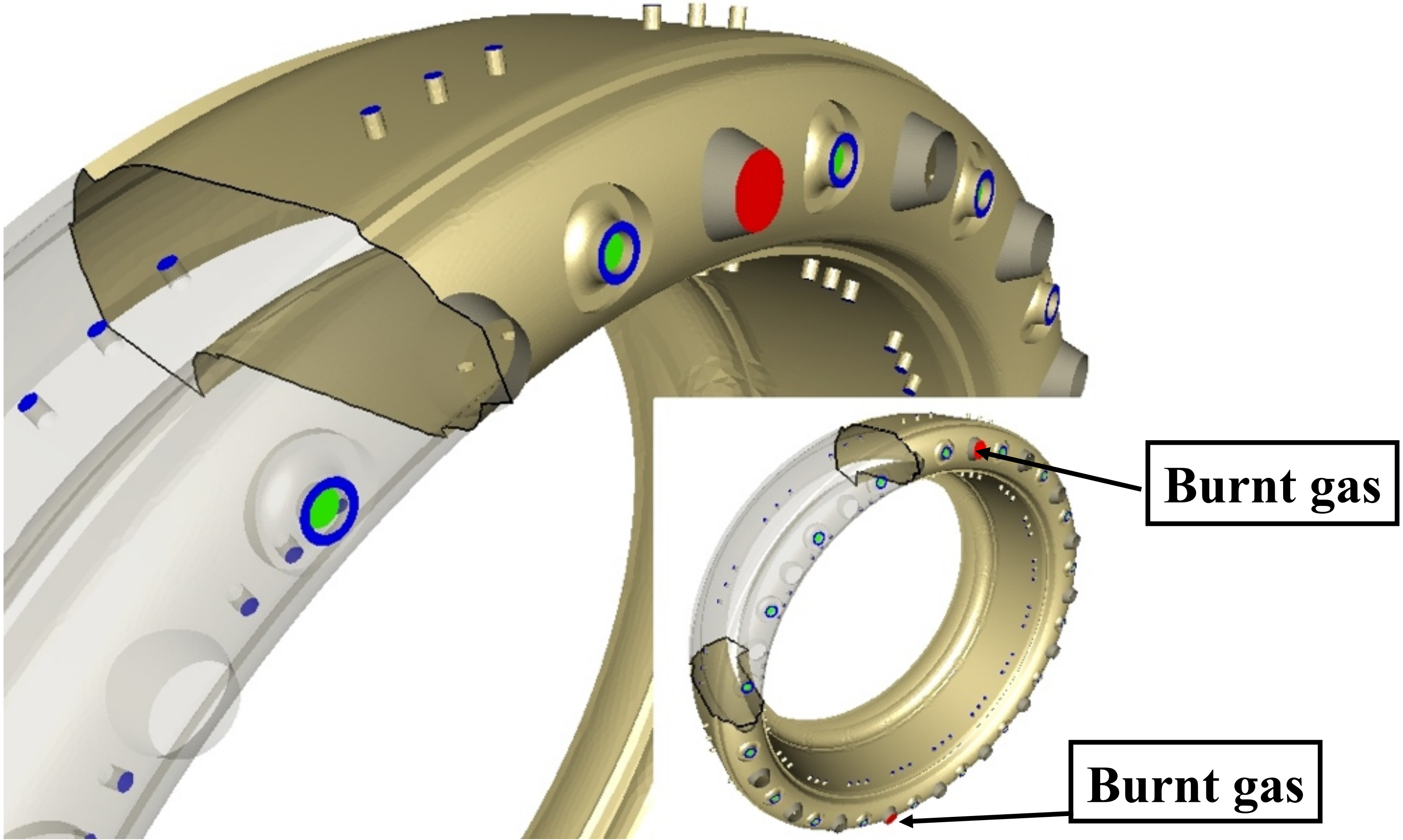


Can LES of a full chamber be performed ?

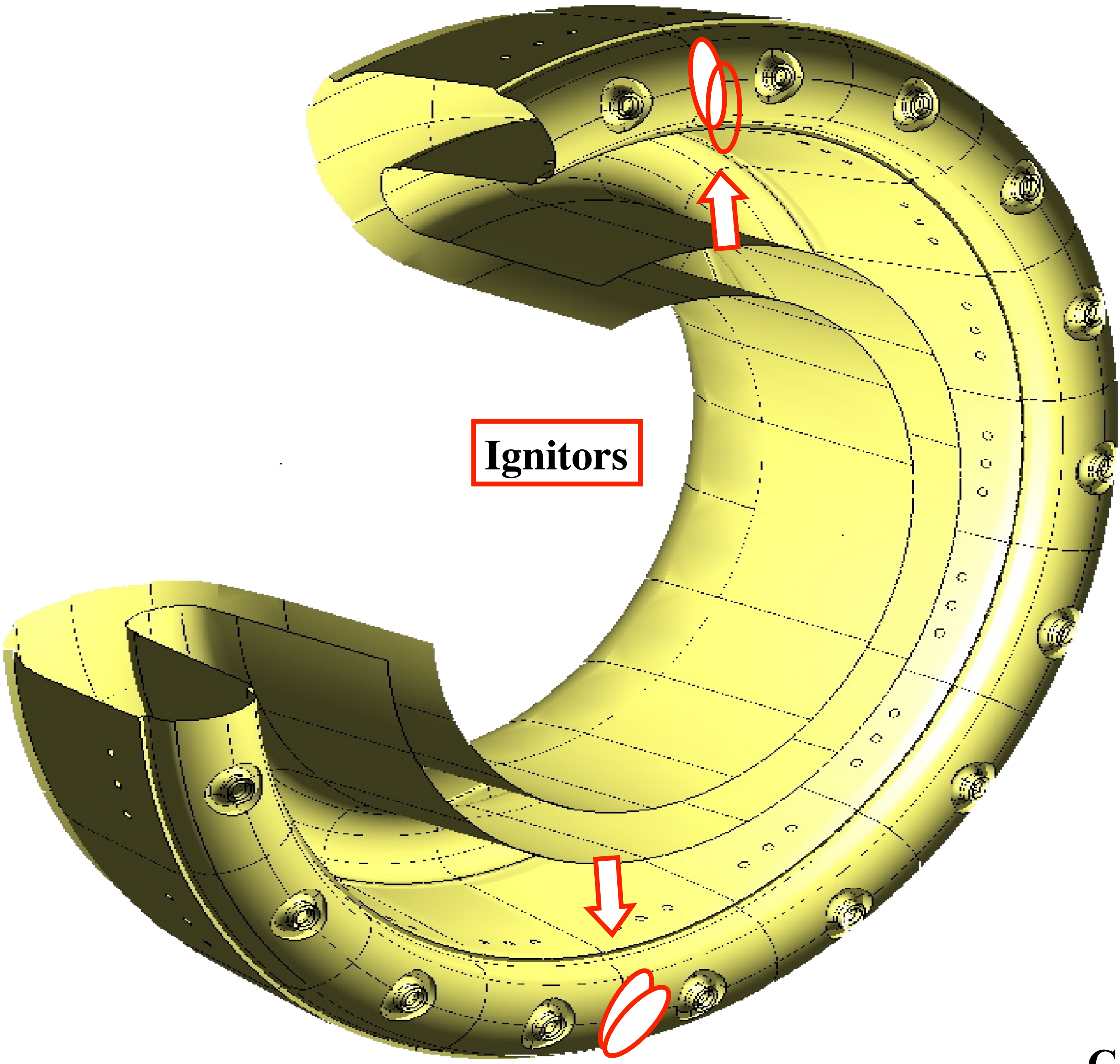
Courtesy T. Poinsot

LES of an ignition sequence

- A gas turbine demonstrator: 18 airblast swirled injectors + 2 ignition devices similar to jets injecting hot burnt gases



Courtesy T. Poinsot



Ignitors

Courtesy T. Poinsot

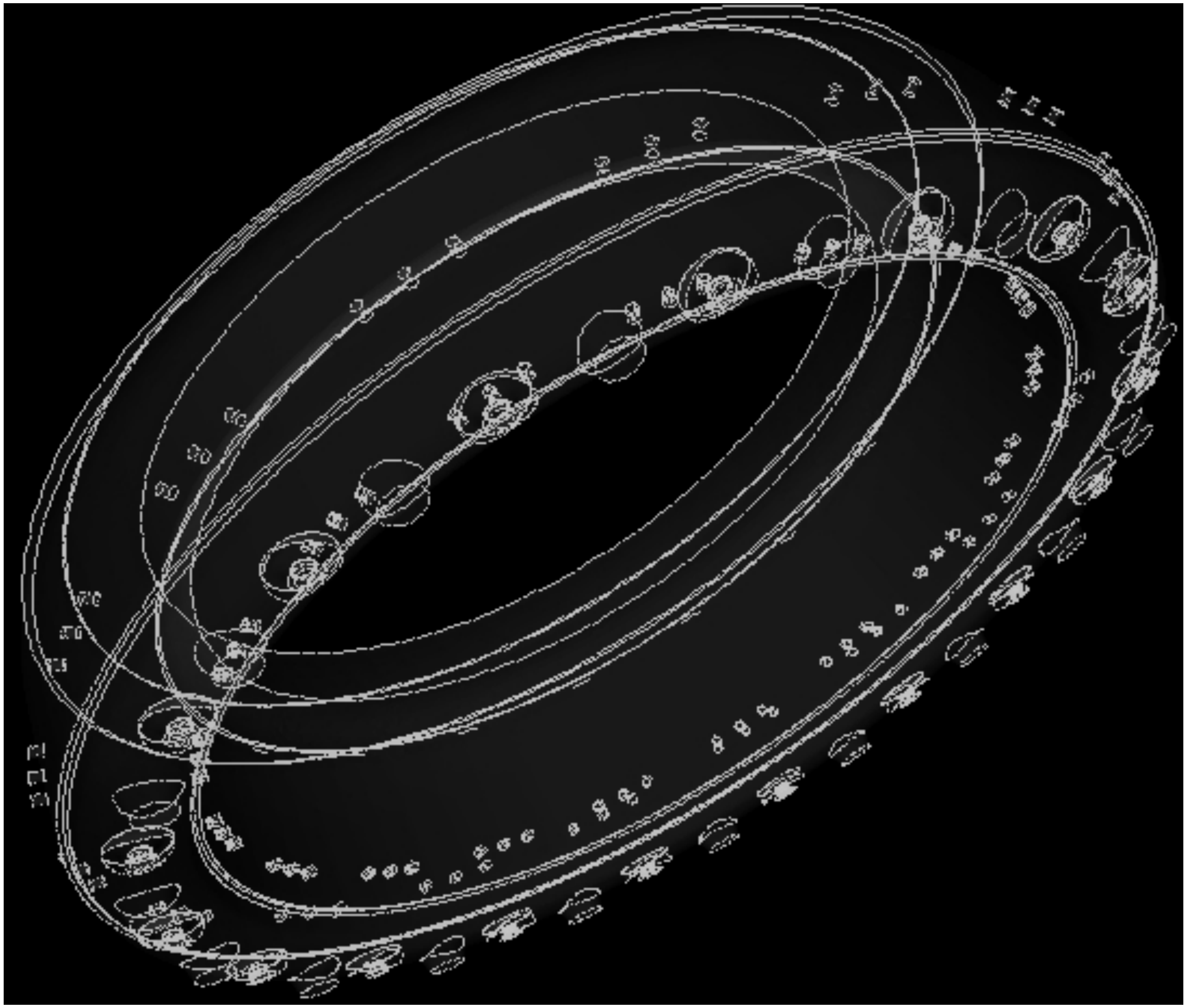
LES of an ignition sequence

- Numerics:
  - AVBP LES code: 3D turbulent compressible reactive Navier-Stokes solver [2], 2000 processors BG/L
- Chemistry, two-phase flow and flame /turbulence interaction models:
  - WALE model for sub-grid scale viscosity [3]
  - Euler-Euler monodisperse formulation for two-phase flow [6]
  - 19 million tetrahedral cells
  - JP10 1-step mechanism (surrogate for kerosene) [4]
  - Dynamic Flame Thickening TFLES [5]. F goes up to 20.

[2] V. Moureau *et al.*, High-order methods for DNS and LES of compressible multi-component reacting flows on fixed and moving grids, J. Comp. Phys., 2005
[3] F. Nicoud, F. Ducros, Subgrid-scale stress modelling based on the square of the velocity gradient, Flow Turb. and Combustion, 1999
[4] S. Li *et al.*, Chemistry of JP-10 ignition, AIAA Journal, 2001
[5] O. Colin, F. Ducros, D. Veynante, T. Poinsot, A thickened flame model for large eddy simulations of turbulent premixed combustion, Phys. Fluids, 2000
[6] Boileau M., Pascaud S., Riber E., Cuenot B., Gicquel L., Poinsot T. and Cazalens M. Investigation of two-fluid methods for Large Eddy Simulation of spray combustion in Gas Turbines. Flow, Turbulence and Combustion, 80(3):291-321, (2008).

Courtesy T. Poinsot

LES of an ignition sequence



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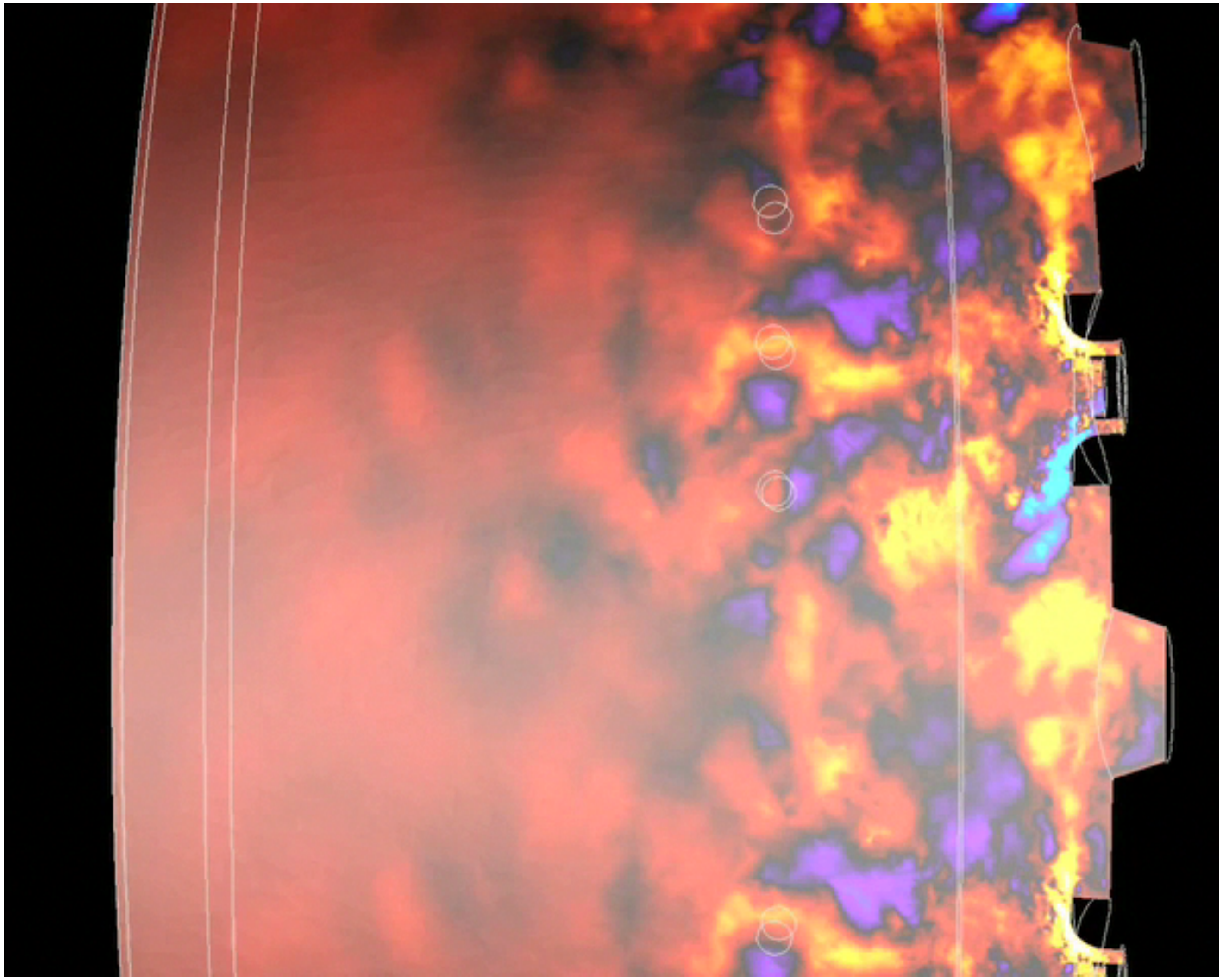
AIAA CFD for Combustion Modeling



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