Scalar Dissipation Rate and Spray Source Term Modeling for IC Engine LES

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LES for ICE
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LES Expectations

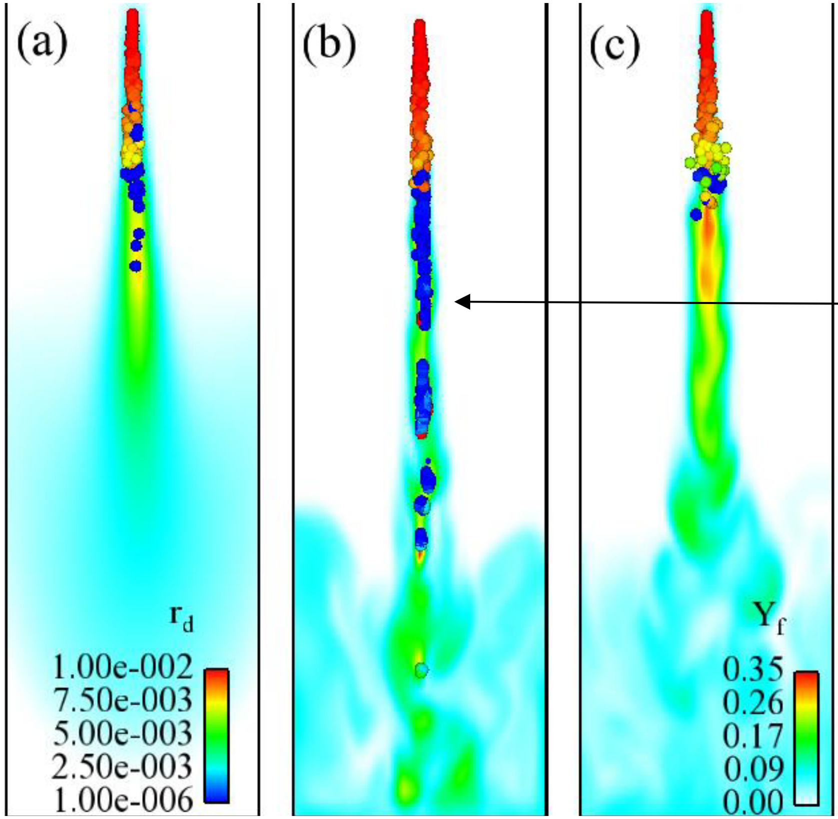
- More flow structures
  - Comes from non-linear terms in NS equations, not models
  - Achievable from:
    - Dense grids – models don’t do much
    - Better models – work on courser grids and let non-linear terms function
- Increased sensitivity
  - Capture new phenomenon
- Higher accuracy
  - Letting NS equations dominate solution

- Methodology
  - Non-viscosity model
  - Subgrid kinetic energy transport equation: k_{sgs}
  - Dynamic structure approach: $\tau_{ij} = c_{ij}\, k_{sgs}$

Diesel Sprays with LES

Liquid drops and vapor mass fraction

(D_{noz}=246μ, ρ_{amb}=30.2kg/m^3, T_{amb}=1000K, P_{inj}=135MPa)



RANS

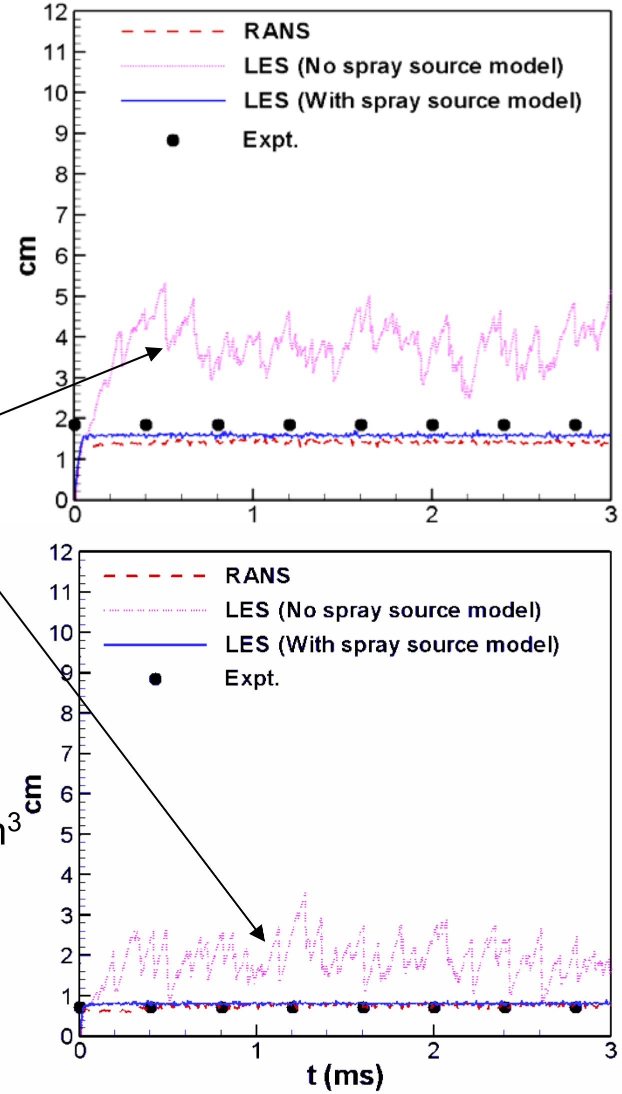
LES (No spray source)

LES (With spray source)

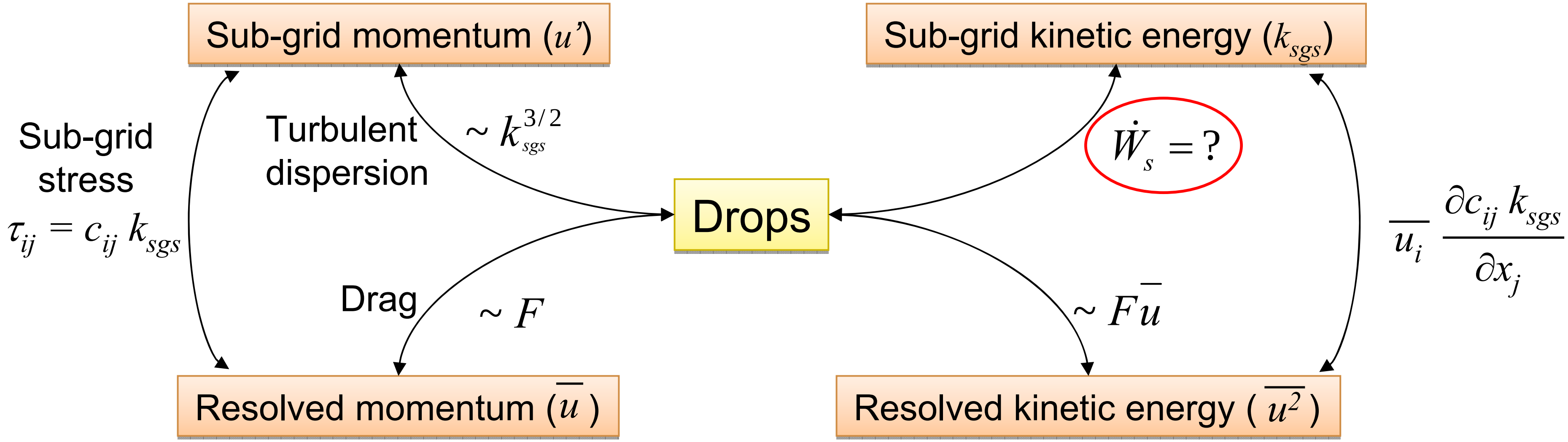
Excessive Penetration

ρ_{amb} = 7.3kg/m^3

ρ_{amb} = 30.2kg/m^3



Two-phase Interaction in LES and k_{sgs}



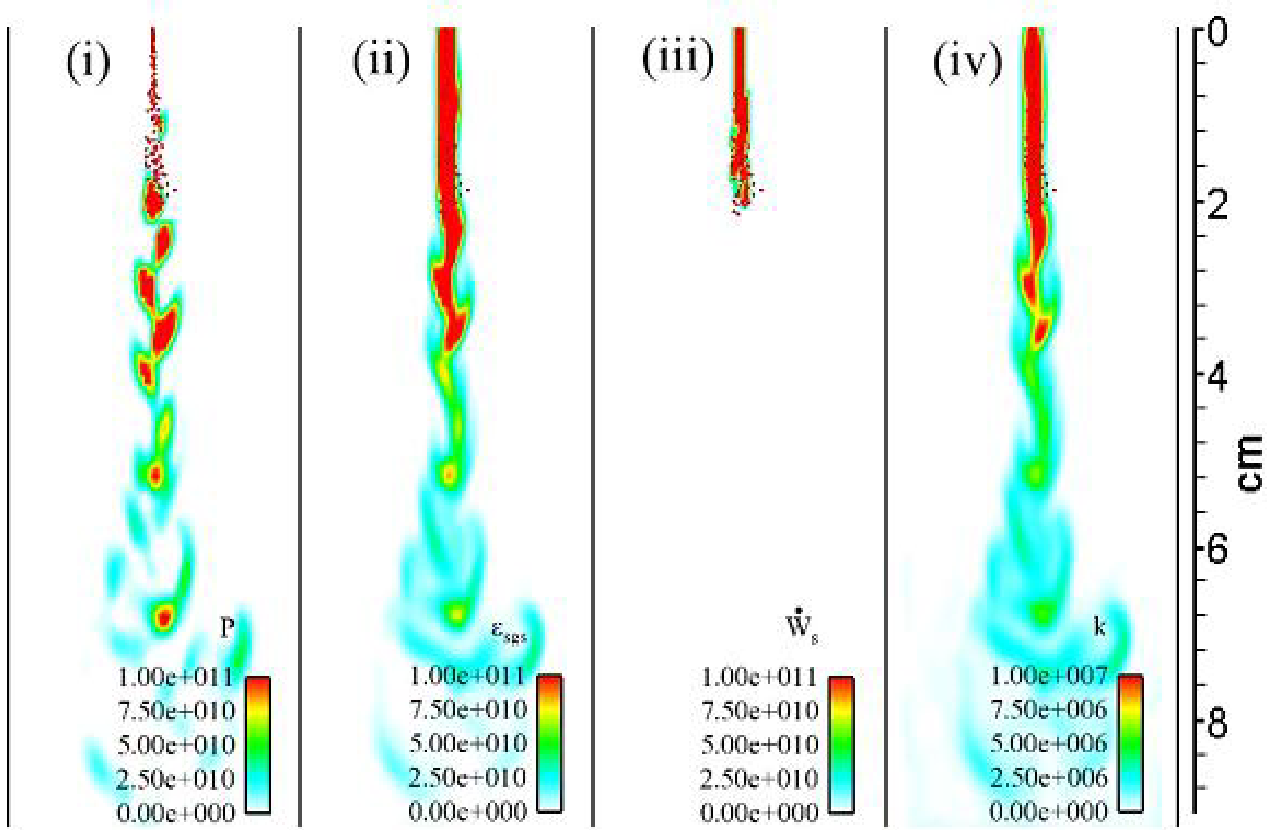
$$\frac{\partial \overline{\rho} k_{sgs}}{\partial t} + \frac{\partial \overline{\rho} \overline{u_j}\, k_{sgs}}{\partial x_j} = P + D - \varepsilon_{sgs} + \dot{W}_s$$

$$\dot{W}_s = -\left(\overline{F_i u_i} - \overline{F_i}\, \overline{u_i} \right) = -\overline{F_i} u_i^{sgs}$$

$$\dot{W}_s \approx \overline{F_i} \left(2\overline{u_i} - 3\overline{\overline{u_i}} + \overline{\overline{\overline{u_i}}} \right)$$

Sub-grid velocity from Approximate Deconvolution Method [Stolz & Adams 1999]

Terms in k_{sgs} Transport Equation



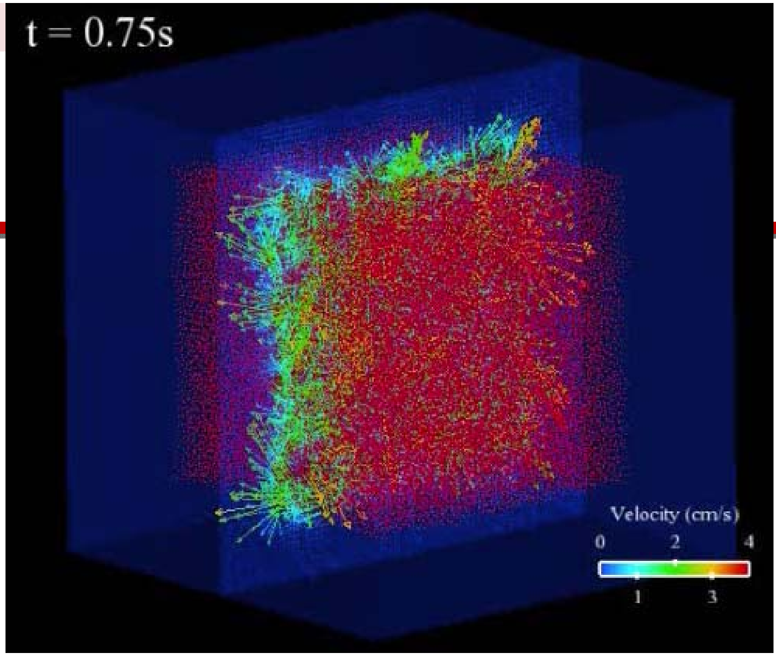
Sub-grid production

Sub-grid dissipation

Spray source term

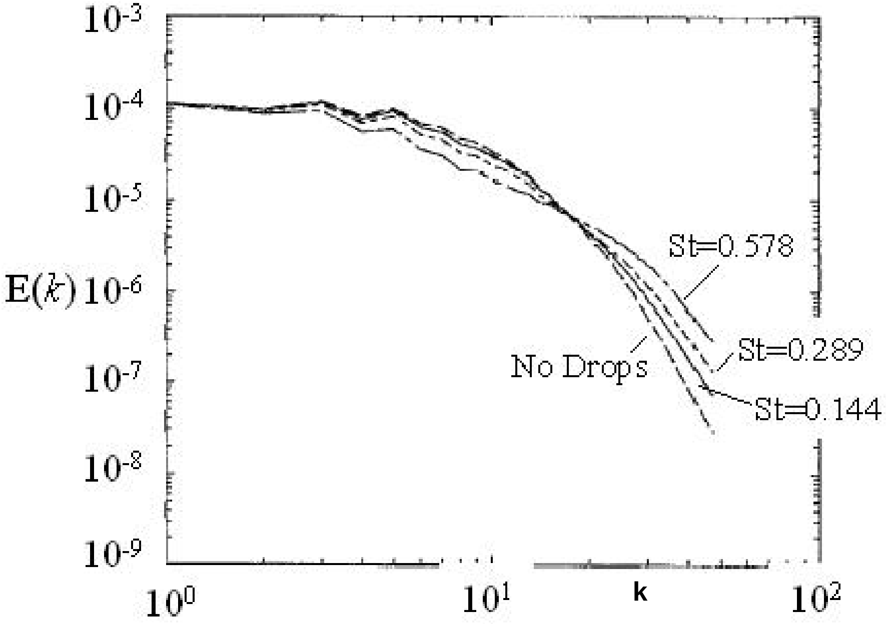
Sub-grid kinetic energy

Decaying Particle Laden Turbulence

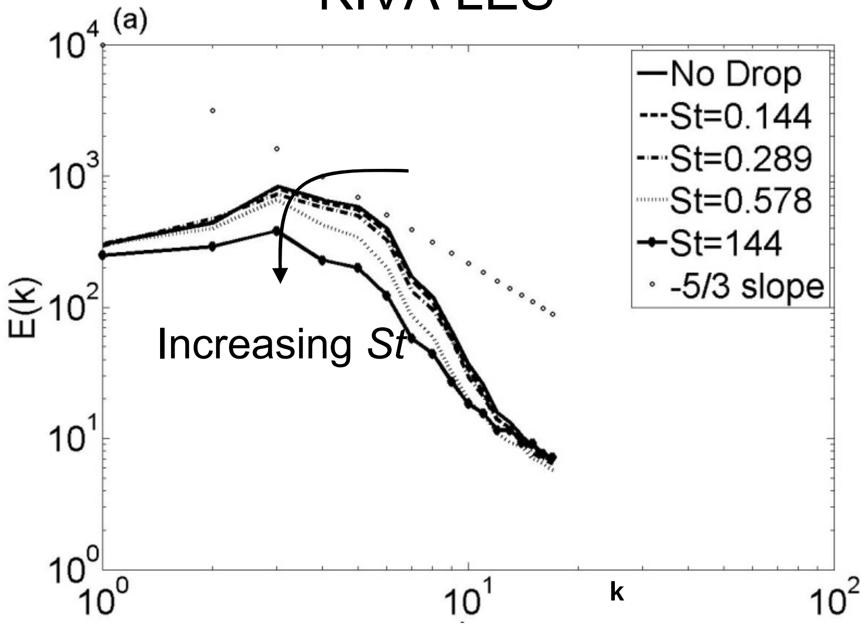


- Sink at small scales
- Source at large scales
- Stokes number dependent

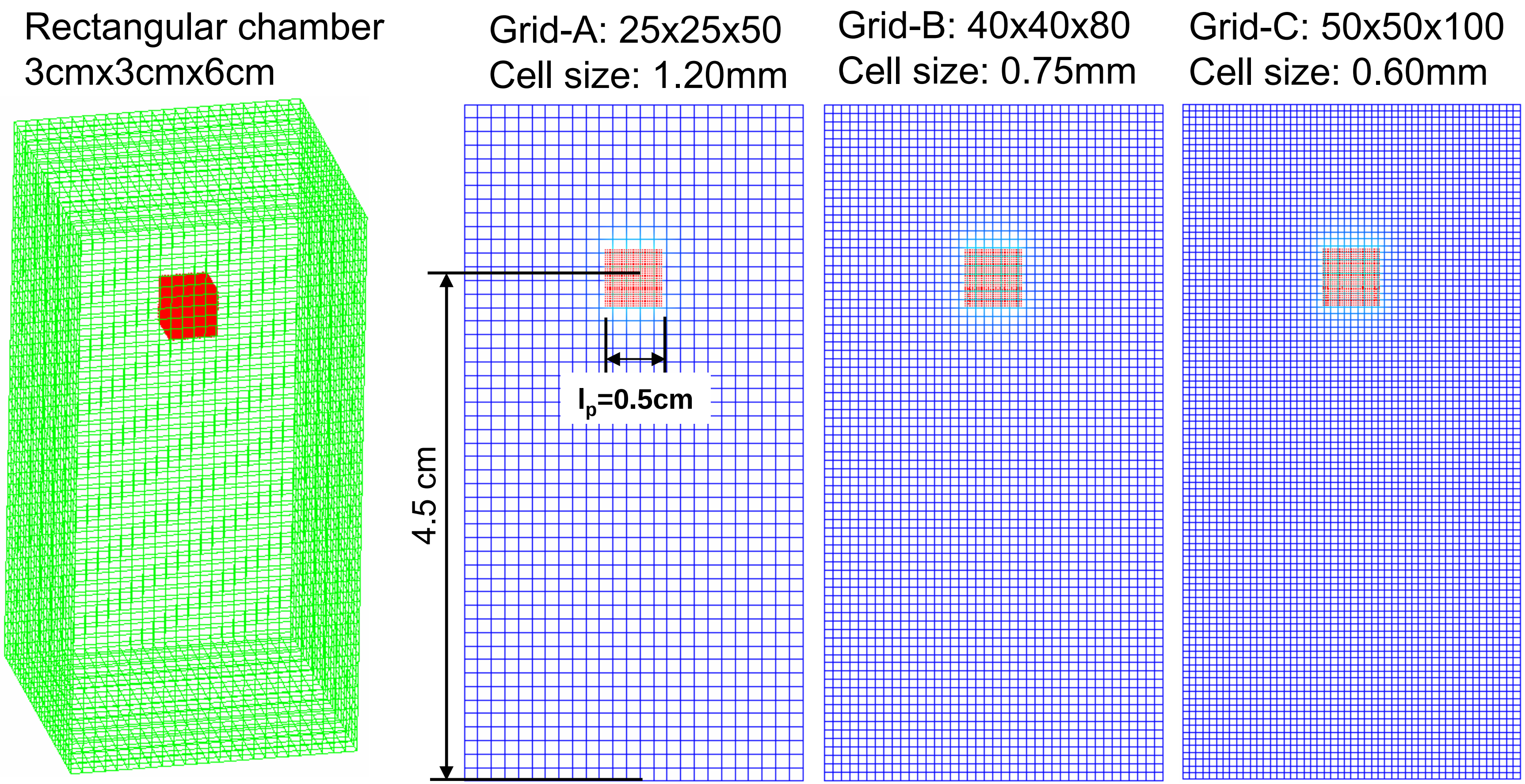
DNS (Elghobashi, 1993)



KIVA LES



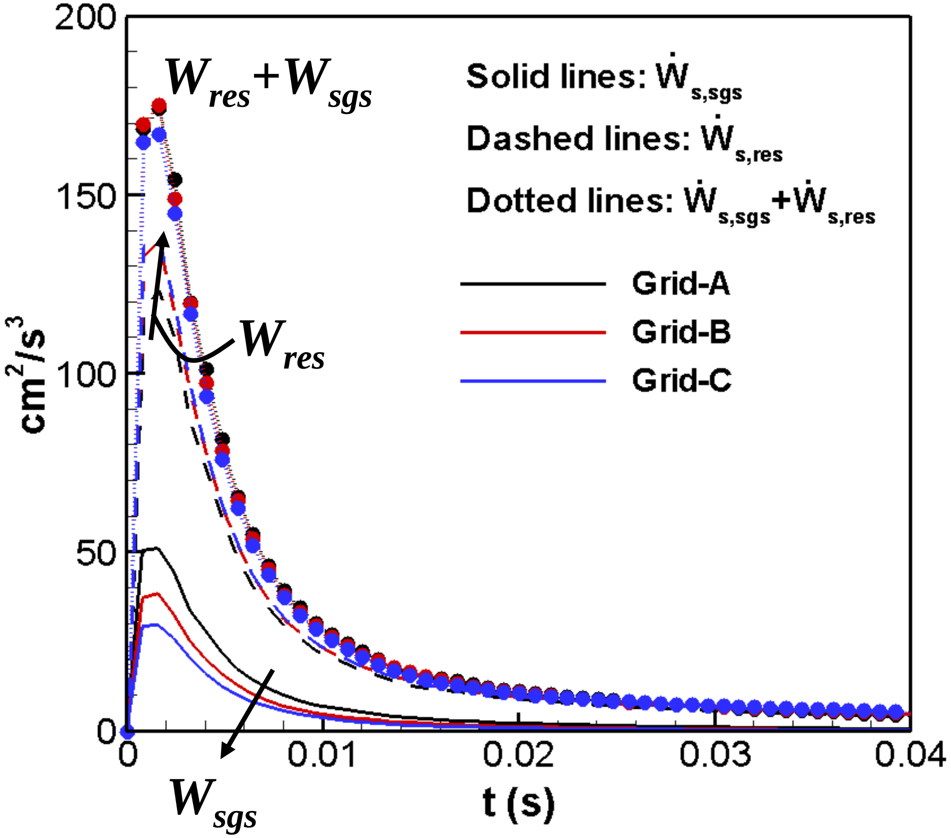
Testing Grid Dependence



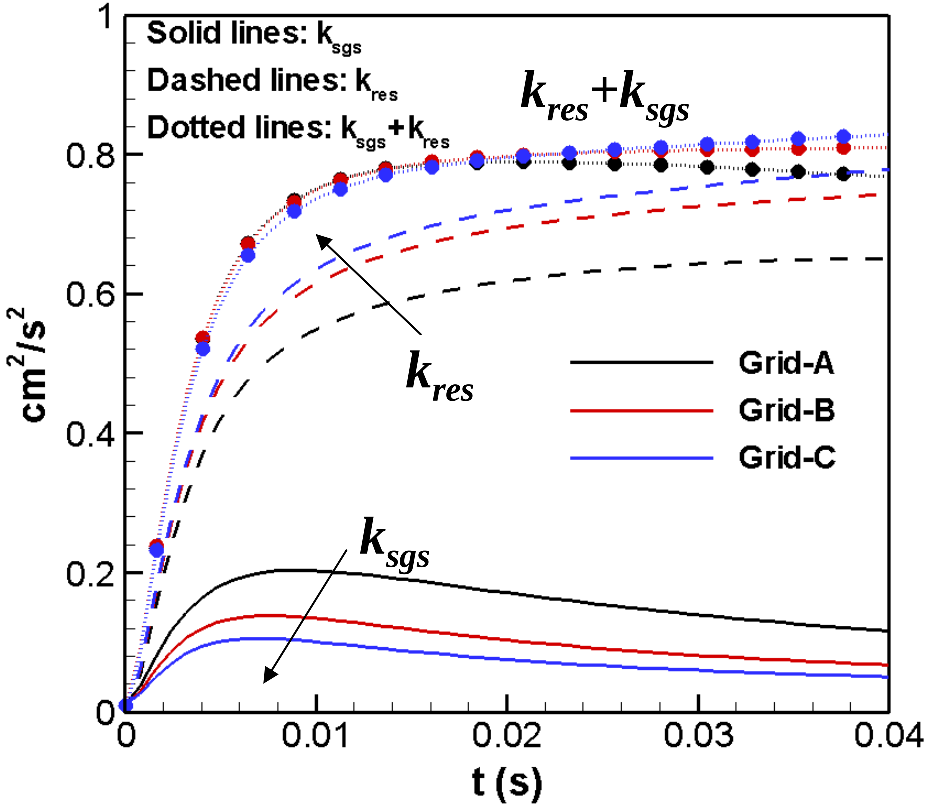
- Initially a cubic lattice of 30x30x30 droplet
- Loading ratios: $\Phi_V = N_p*(4/3*\pi*r_p^3)/l_p^3$; $\Phi_M = \rho_p/\rho_g*\Phi_V$
- Droplets imparted with downward velocity V_{inj} in a quiescent domain filled with N2

Results for Grid Study

Sub-grid and resolved **spray source terms**



Sub-grid and resolved **kinetic energies**

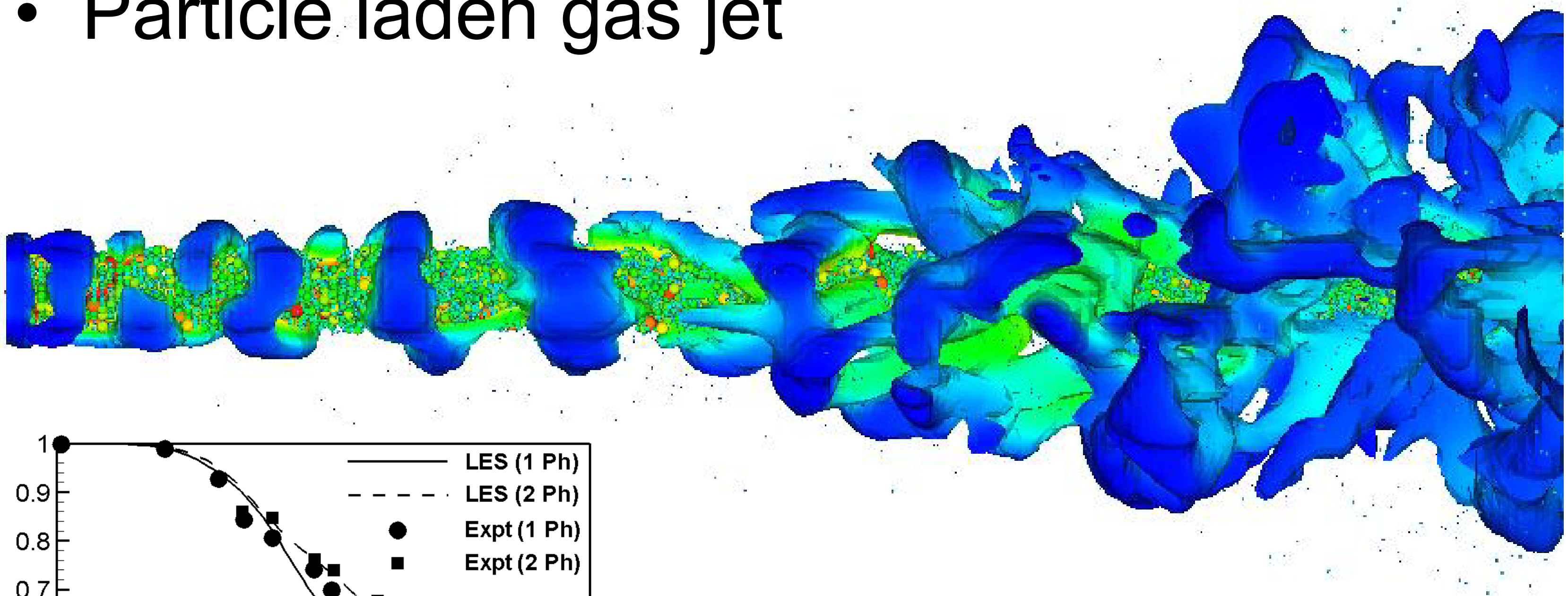


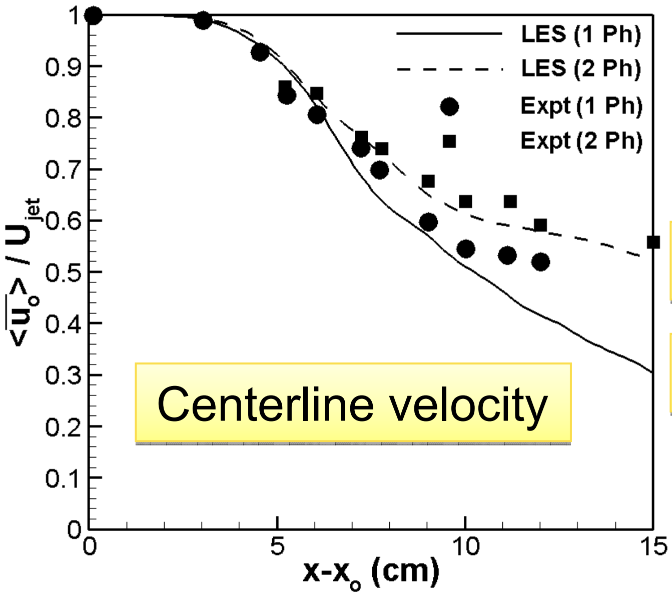
- Arrows indicate increasing grid resolution

(V=50cm/s)

LES Spray Modeling

- Particle laden gas jet

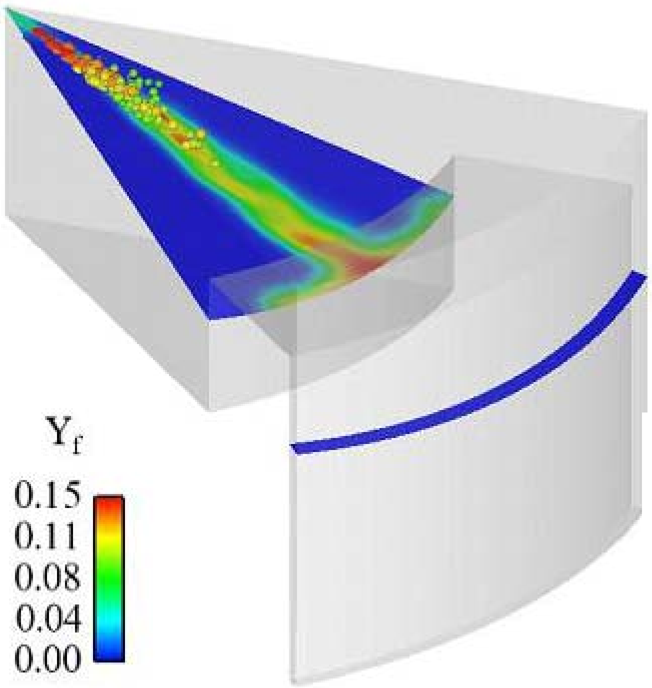


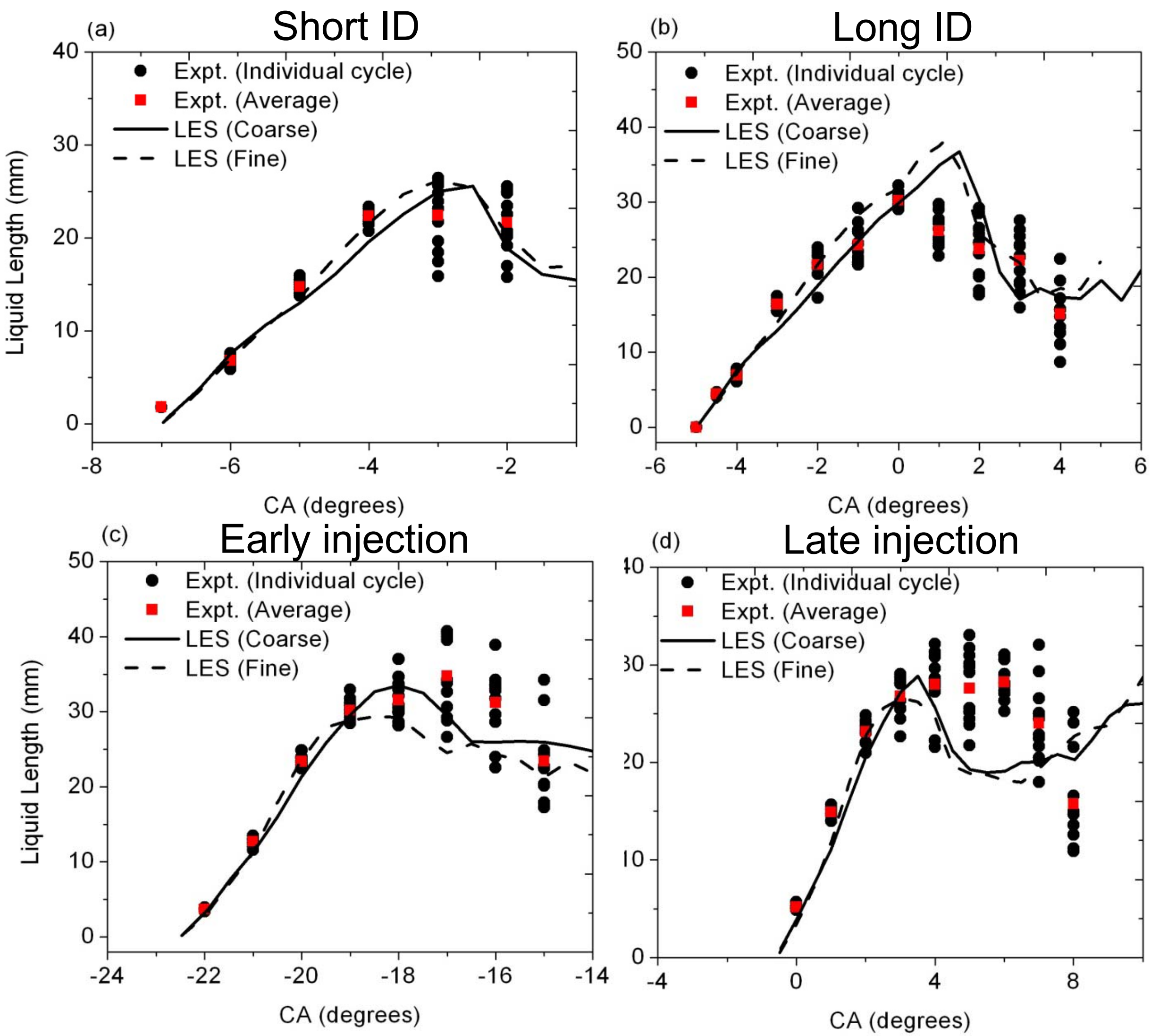


With particles

No particles

Spray Results from Engine Simulations

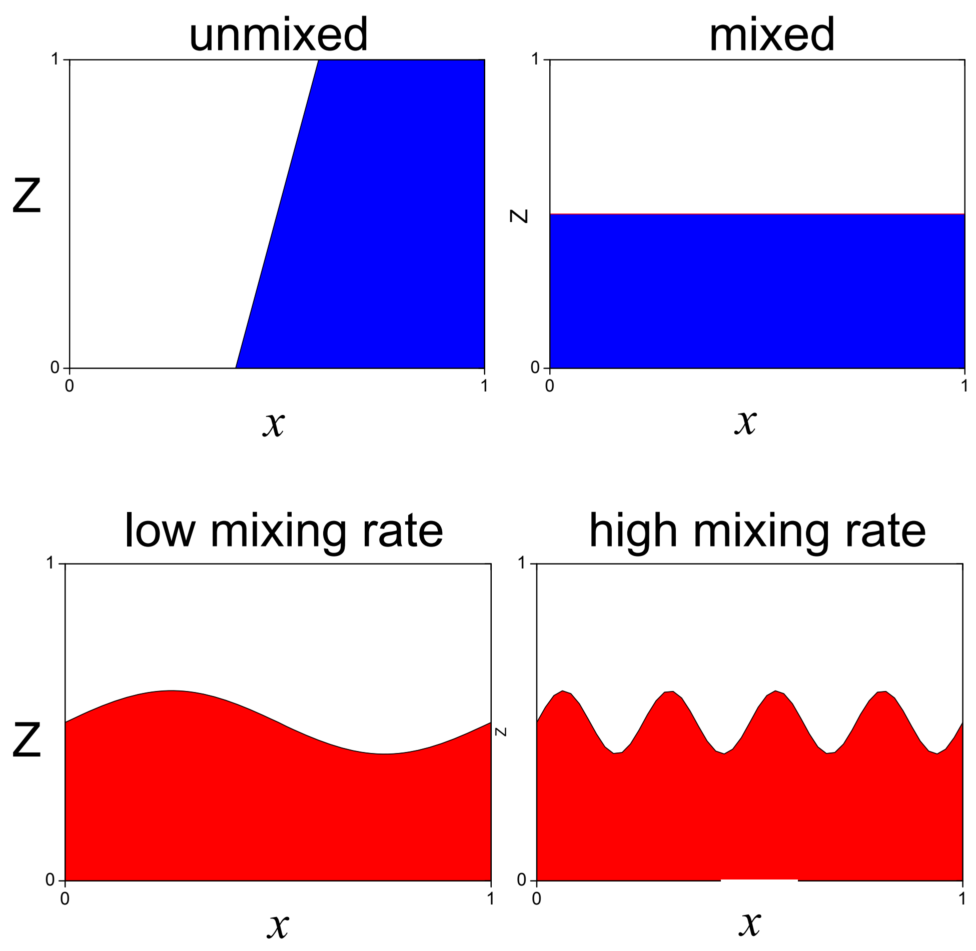




~80,000 cells at BDC
Data from Singh et al, 2007

Scalar Dissipation Rate

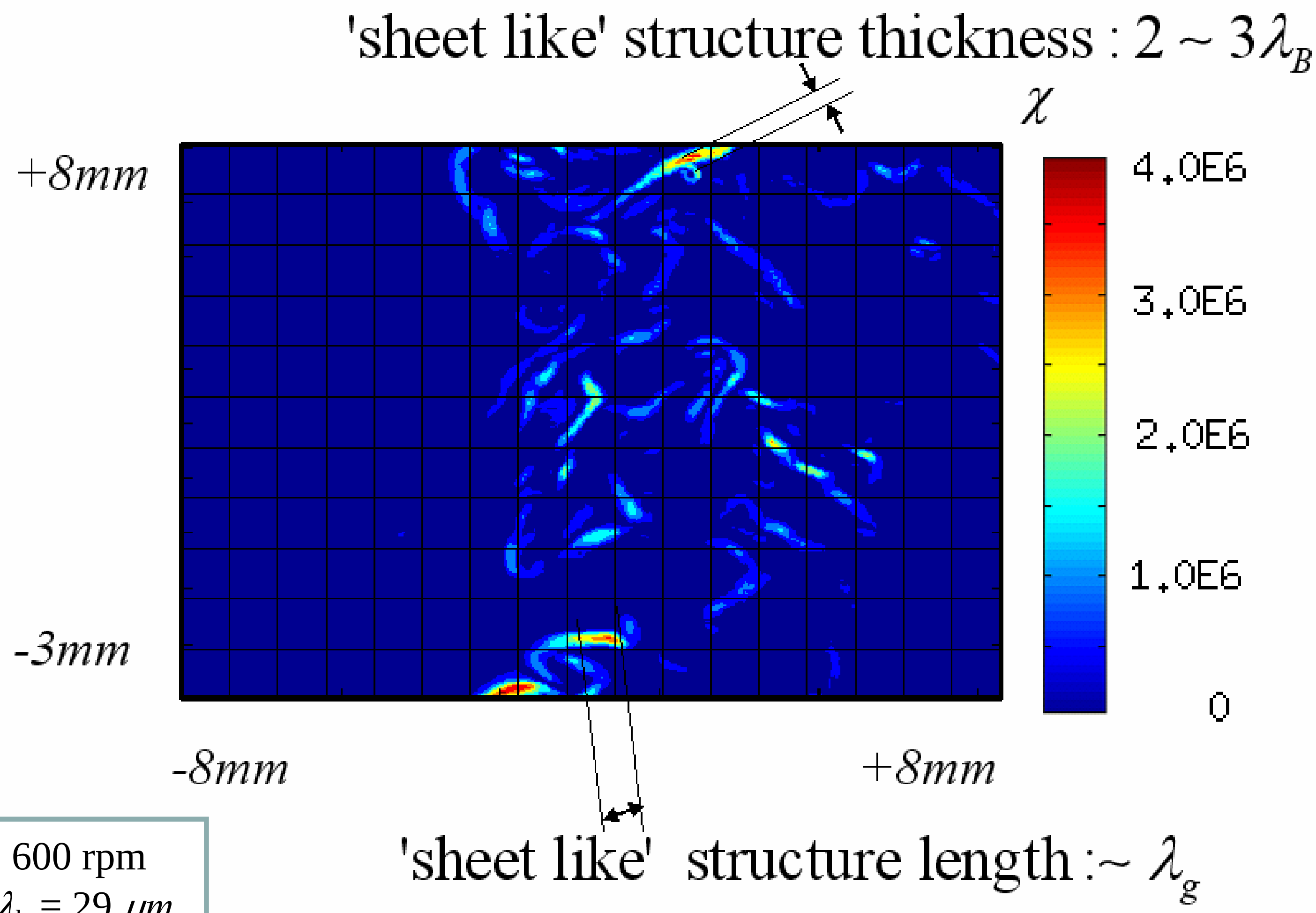
$$\chi = 2D \frac{\partial Z}{\partial x_i} \frac{\partial Z}{\partial x_i}$$



- Degree of mixing
  - Determine combustion mode
- Mixing rate for combustion
  - Combine with scalar variance
  - Determine reaction rate

$$\tau = \frac{\overline{Z''^2}}{\chi_{sgs}}$$

Measurements of χ in Engine Flow



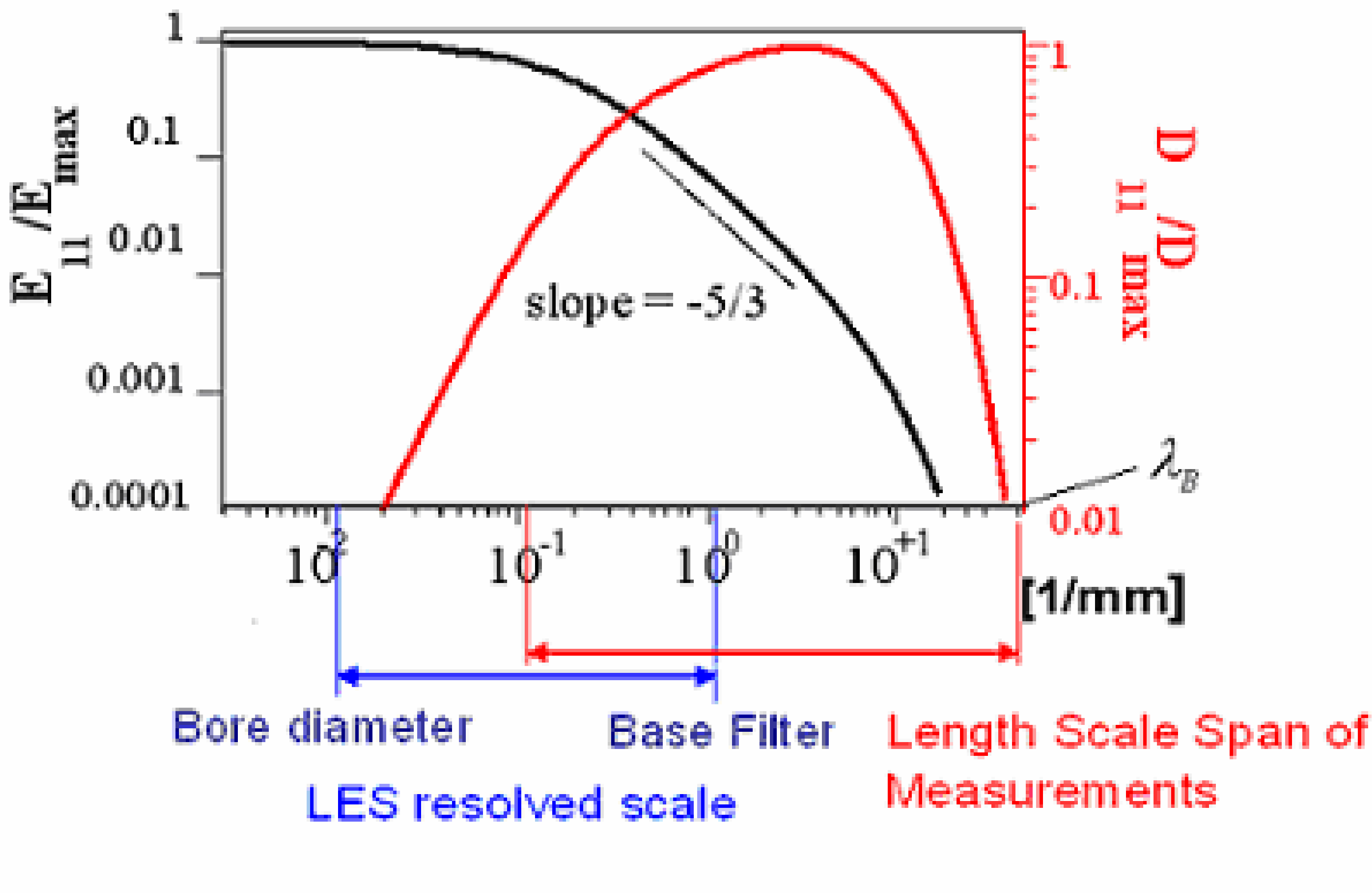
Batchelor scale

LES grid size: □

600 rpm
$\lambda_b = 29\ \mu m$

In-cylinder measurements courtesy of Ben Peterson and Jaal Ghandhi

Scalar Variance and Dissipation Spectra



Scalar Dissipation Model

$$\chi_{sgs}$$

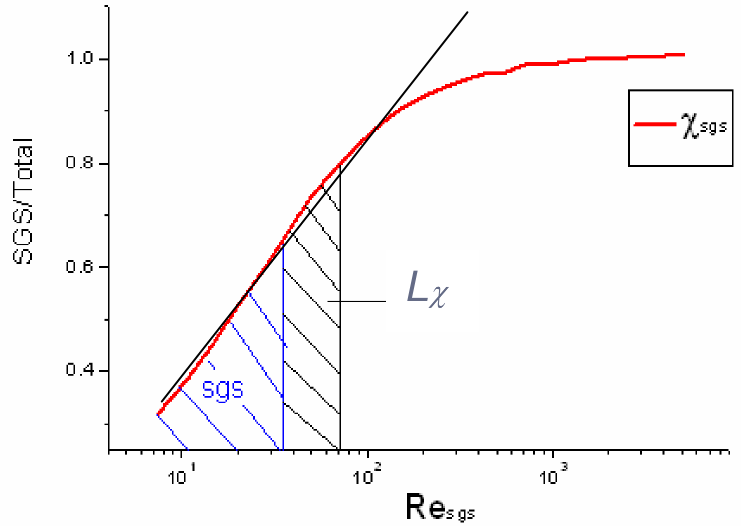
$$\chi_{sgs} = 2D\left(\overline{\frac{\partial Z}{\partial x_i}\frac{\partial Z}{\partial x_i}} - \frac{\partial \overline{Z}}{\partial x_i}\frac{\partial \overline{Z}}{\partial x_i}\right)$$

Scale similarity model

$$\chi_{sgs} = c(x)\left(\overline{\frac{\partial \overline{Z}}{\partial x_i}\frac{\partial \overline{Z}}{\partial x_i}} - \frac{\partial \overline{\overline{Z}}}{\partial x_i}\frac{\partial \overline{\overline{Z}}}{\partial x_i}\right)$$

Dynamic scaling factor

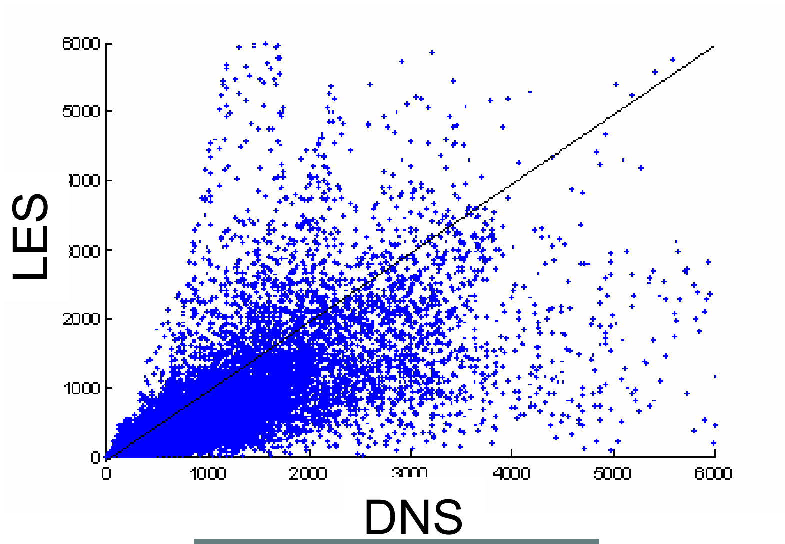
$$c(x) = \frac{\log\left(\mathrm{Re}_{sgs}\right)}{\log\left(\mathrm{Re}_{sgs}\left(\Delta_{test}/\Delta_{base}\right)^{4/3}\right) - \log\left(\mathrm{Re}_{sgs}\right)}$$



DNS data 512^3 Chumakov (2007)

A priori Test Using Forced Isotropic DNS

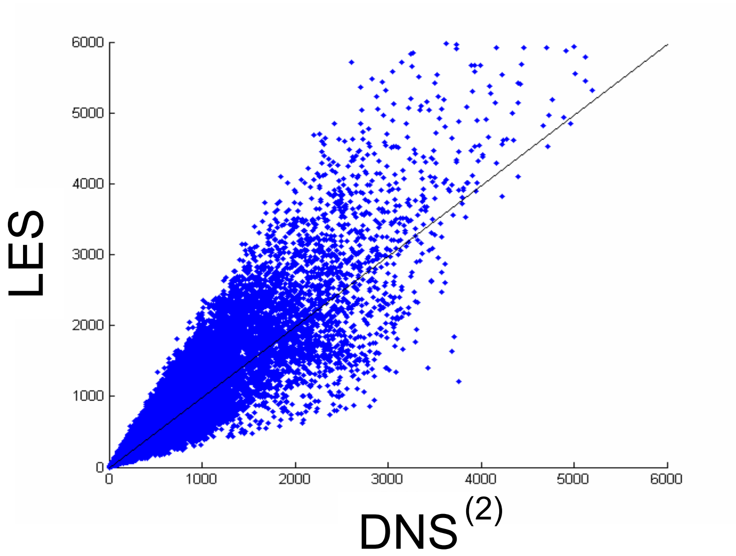
RANS Concept Model [1]



$$\overline{\chi} = 2\frac{\varepsilon_{sgs}}{k_{sgs}}\overline{Z''^2_{sgs}}$$

$$\overline{Z''^2_{sgs}} = (\overline{\overline{Z}\,\overline{Z}} - \overline{\overline{Z}}\,\overline{\overline{Z}})$$

Dynamic Similarity Model



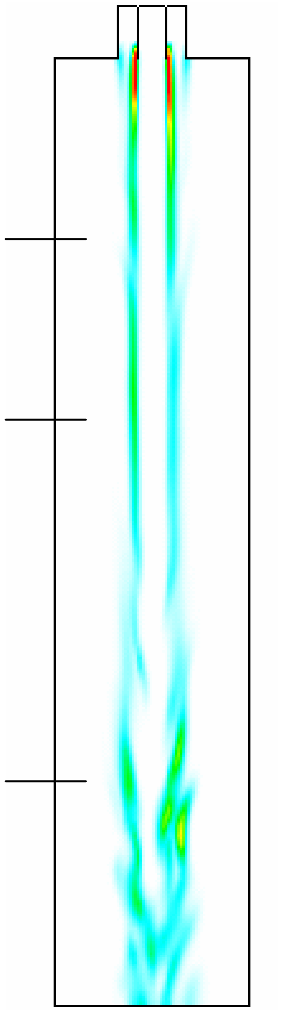
Model has a higher correlation with true dissipation rate

1. C. Jiménez, F. Ducros, B. Cuenot and B.Bédat "Subgrid scale variance and dissipation of a scalar field in large eddy simulations ", *Phys. Fluids*, **13(6)**, (2001).

2. Chumakov, S.G., "Scaling properties of subgrid-scale energy dissipation", *Phys. Fluids*, **19** (2007)

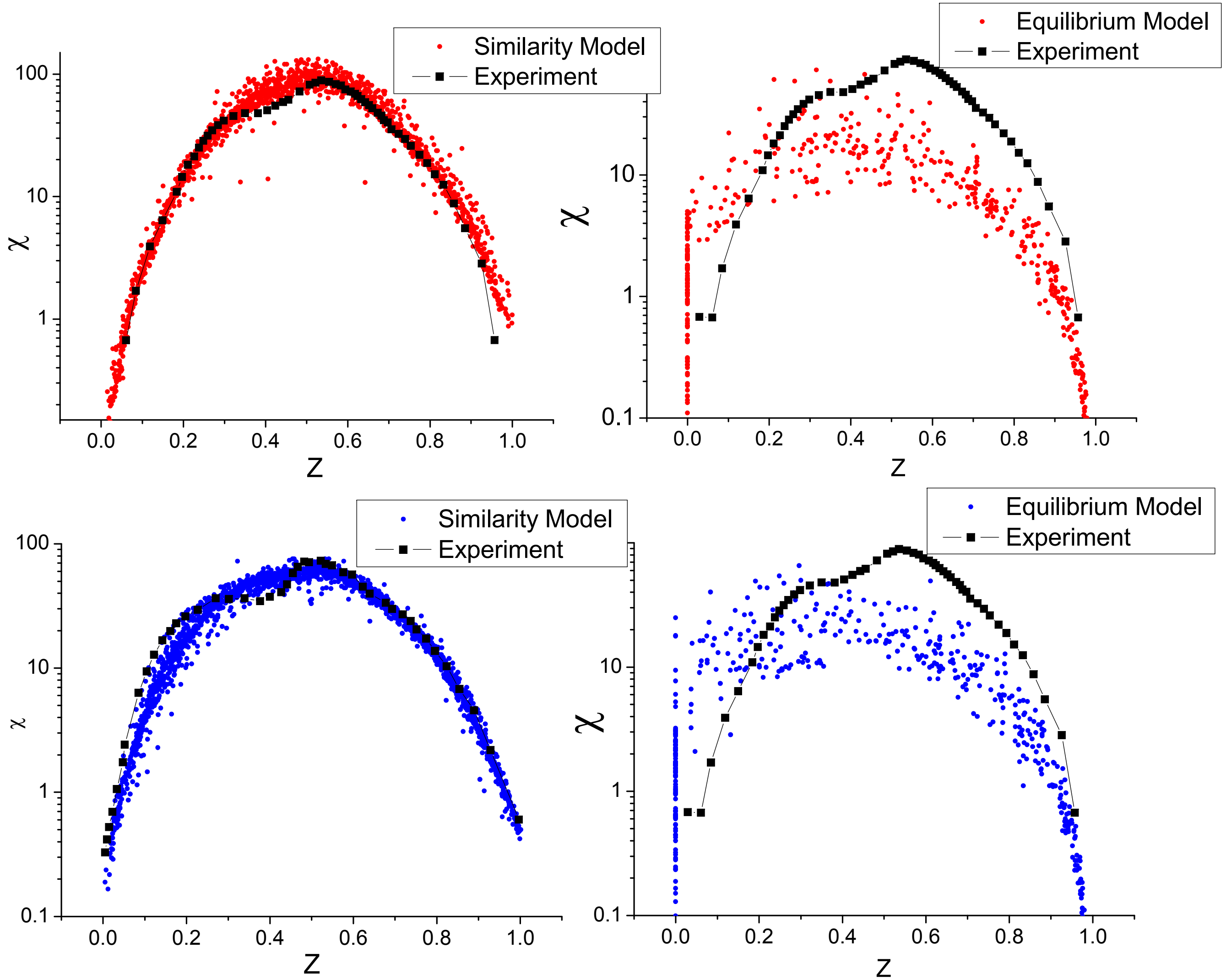
$$\left(\Delta_{base} / h \approx 9\right)$$

Model Evaluation in Sandia Flame E

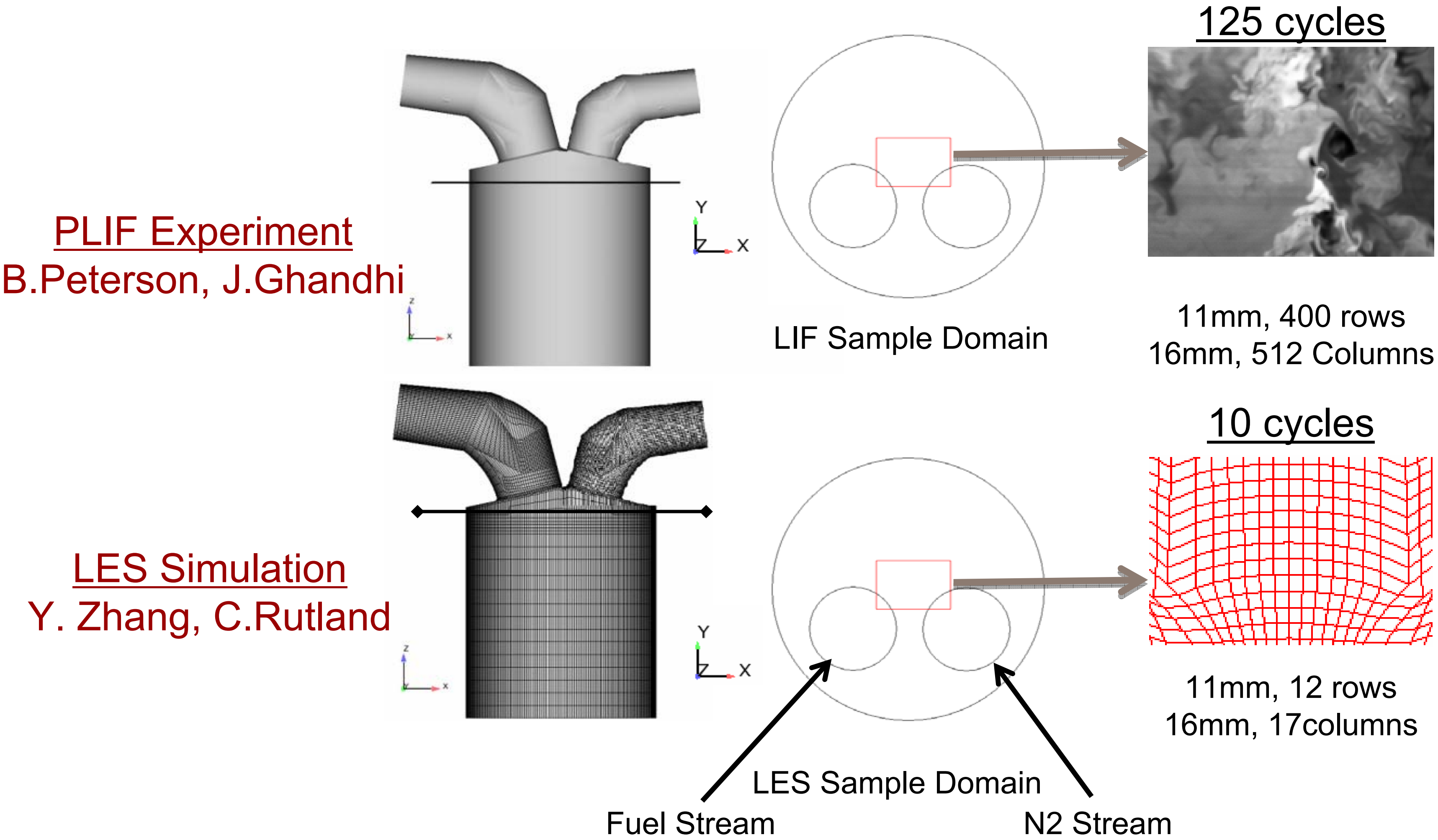


Extinction Region (x/d=7.5)

Re-ignition Region (x/d=15)

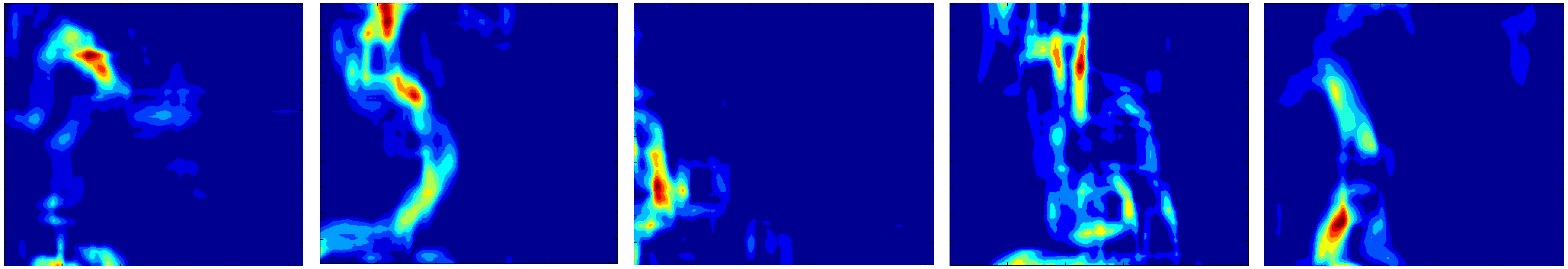


Engine Experiments and Simulations

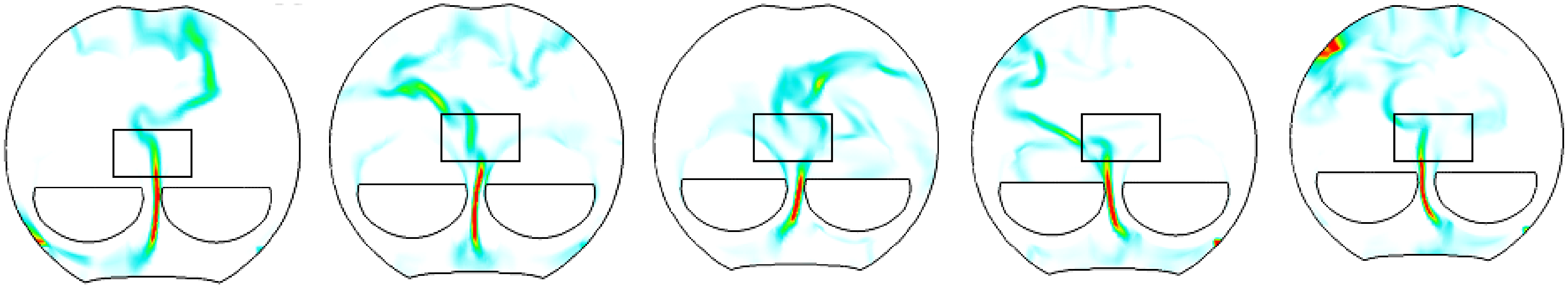


Cycle-to-Cycle Variation of χ

Engine Results

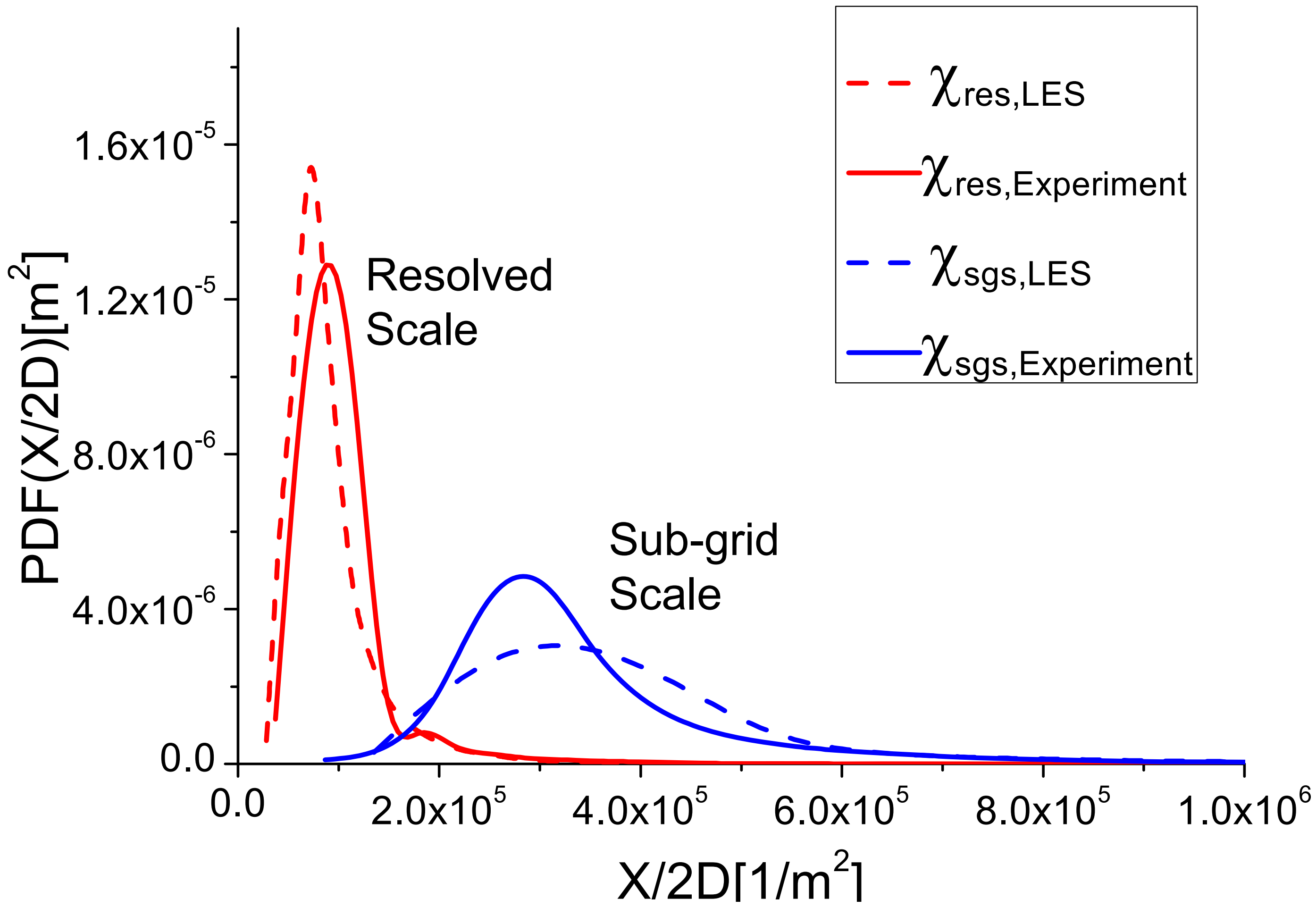


LES Results



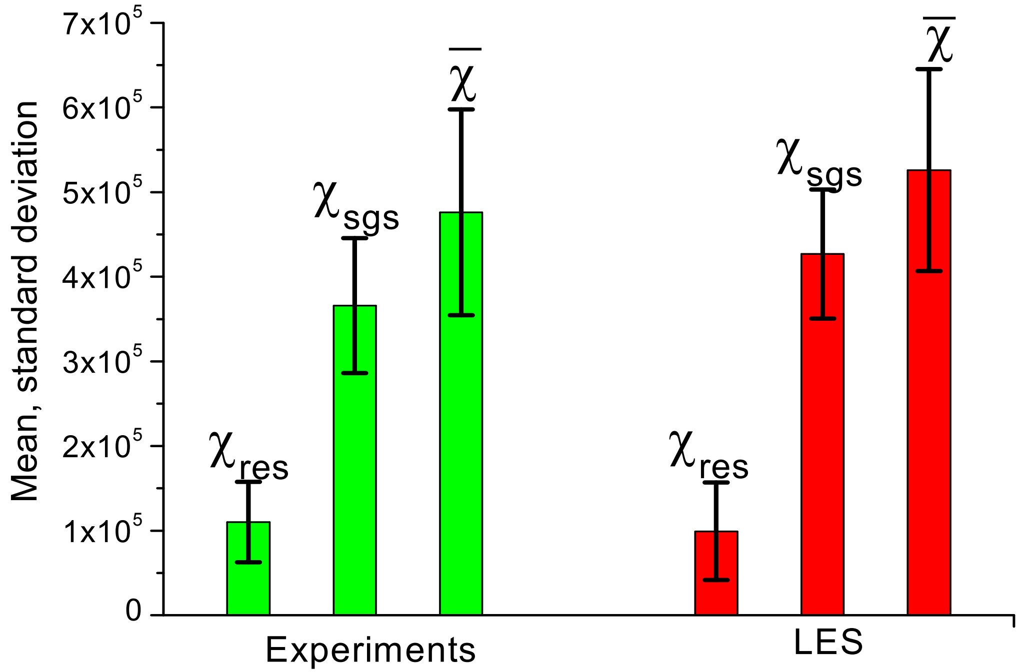
(120CA ATDC)

Ensemble PDF: Resolved and Sub-Grid



‘Cylinder’ Average Comparison

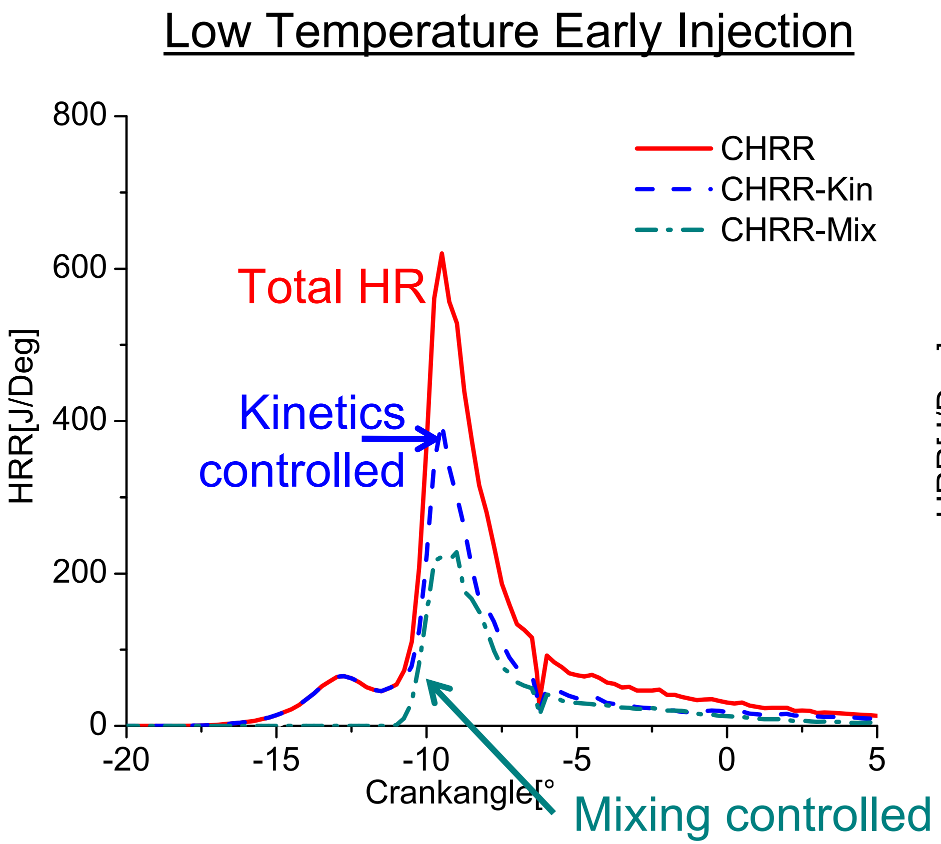
Sampling domain mean and standard deviation

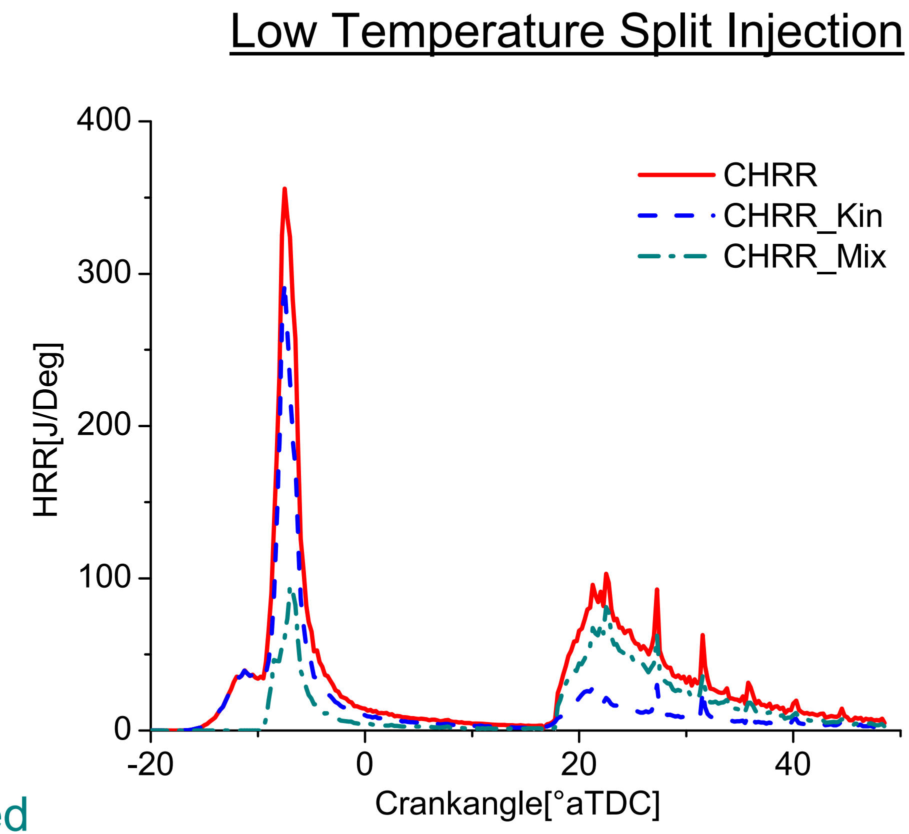


- LES can capture the ‘cylinder’ average mean and variation
- The ratio of sub-grid to resolved:
  - 3.7 for experiments
  - 4.2 for LES

Combustion Example

- 2 mode combustion model using new χ_{sgs} model





Sandia Cummins N-14 optical engine

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http://www.erc.wisc.edu/

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