Using ODT to Model Flame Propagation in Wildland Fire Fuel Beds

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Introduction

- Wildland fire modeling represents an imporant and highly complex process
  - Wide range of length and timescales.
  - Multi-phase flow in non-uniform configurations.
  - Complex combustion with variable fuel properties.

- Physics-based models
  - PDE's, 3D, "resolved"
  - Complex, Costly
  - Too much information

- Empirical models
  - Cost effective
  - Less flexible

Multi-scale modeling: how to couple and transmit essential information between large and small scales

Flame Spread

- Understanding the rate of flame propagation through fuel beds is of crucial importance in the overall problem.
- Flame spread occurs via heat transfer:
  - Radiative
  - Convective
- Focus on fine fuels:
  - grasses, pine needles, brush, small branches.
- Radiatitive heating competes with convective cooling
  - Fuel is not heated to ignition by radiation.
- Flame spread requires direct flame bathing.
  - Intermittent
  - Turbulent

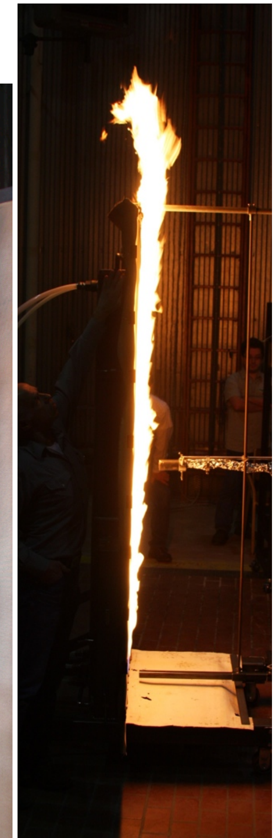
Radiation and Flame Bathing

Approach

- Consider lab-scale buoyant fires
  - Pool fires
  - Wall flames
  - Artificial fuel beds with cross flow.
- Predicting the flame spread requires knowlege of the intermittent turbulent flame edge.
  - Flame expansion
  - Fuel product accumulation
  - Fuel spacing
  - Wind speed.
-

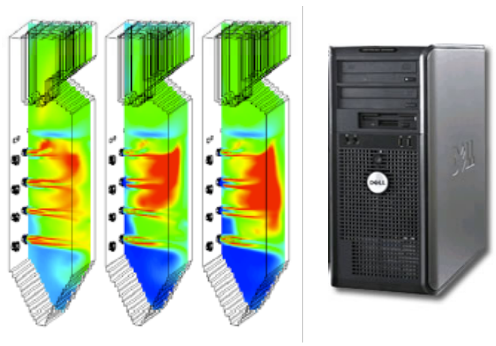
Flame Wall Experiment

- Vertical burner panel
- Ethylene feed 1.75 L/m^2*min
- Statistically steady
- Examine flame expansion
  - vary fuel flow rate
- Heat flux
- Temperature profile
- Flame intermittency



Simulation Approaches

- Three major simulation approaches
- Levels of turbulence modeling
  - **RANS** → inexpensive; but mean only
  - **LES** → expensive; capture large eddies, but miss flame structure
  - **DNS** → cost prohibitive; but full resolution

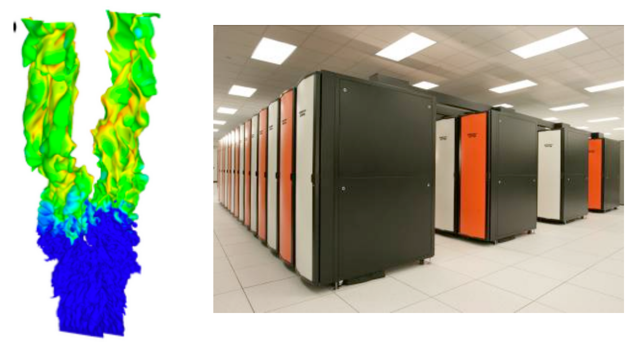


RANS

Engineering Design, Optimization

LES

Advanced Engineering,Research



DNS

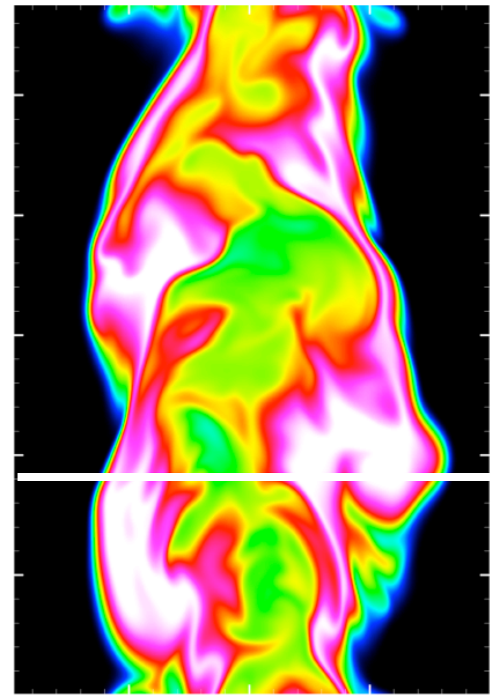
Research, Model Developement

(Subgrid Modeling Required)

Computational Cost

One Dimensional Turbulence (ODT)

- ODT compromise
  - Full resolution of diffusive-reactive flame structure: heat, species, mass, momentum
  - But only 1-D: line of sight through the flame
    - Most flows have a dominant strain direction.
  - Turbulent advection modeled through stochastic “eddy events”
  - Provides structure and statistics of intermittent flame brush.
  - One space direction + an evolution coor
    - time → temporal ODT
    - space → spatial ODT
  - Model is computationally affordable.
    - O(10) min per realization
    - O(100) realizations for statistics



ODT Formulation—Diffusive Advancement

- Evolve reactive-diffusive equations with periodic eddy events.
- Lagrangian control volume formulation.
- Fully adaptive mesh.
- Implicit or explicit detailed chemistry.
- Implied low-Mach assumption.
- Boussinesq buoyant acceleration.
- Line velocities treated as scalars for eddy dynamics
  - 1-D → direct cell dilitation

Mass

$$\rho \Delta x = C$$

Species

$$\frac{dY_i}{dt} = -\frac{1}{\rho \Delta x}(j_e - j_w) + \dot{m}_i'''$$

Momentum

$$\frac{du_k}{dt} = -\frac{1}{\rho \Delta x}(\tau_{xk,e} - \tau_{xk,w}) - \frac{1}{\rho}\frac{dP}{dy}\delta_{yk}$$

Energy

$$\frac{dh}{dt} = -\frac{1}{\rho \Delta x}(q_e - q_w) + \frac{1}{\rho}\frac{dP}{dt}$$

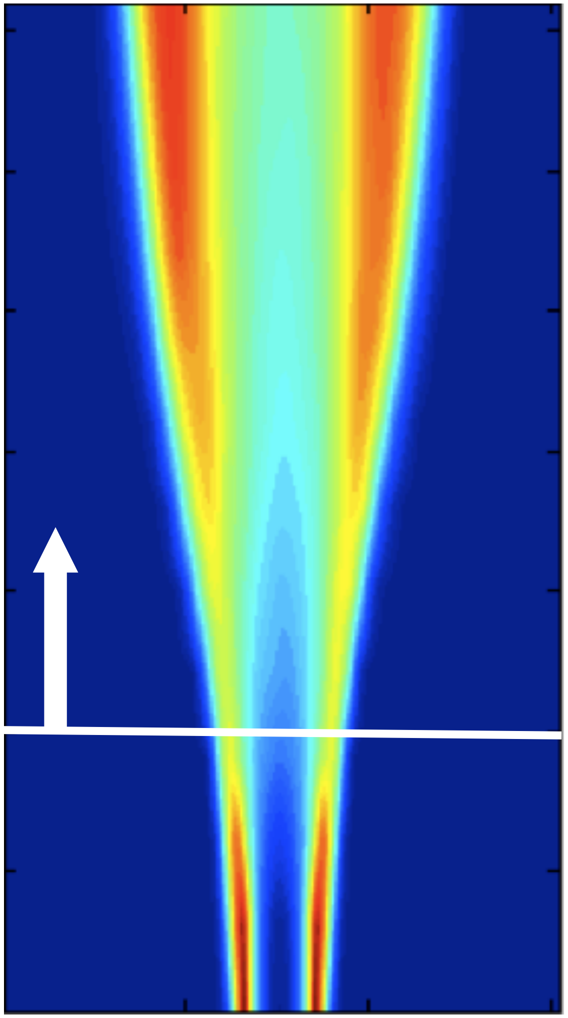
$$j_i = -\frac{\rho Y_i D_i}{X_i}\frac{dX_i}{dx}$$

$$\tau_{xk} = -\mu \frac{du_k}{dx}$$

$$q = -\lambda \frac{dT}{dx} + \sum_i h_i j_i$$

Spatial Formulation

- Temporal ODT
  - Advance stationary line in time
  - Channel flow, homogeneous turbulence, temporally-evolving jet, etc.
- Spatial ODT
  - Advance line axially in space under assumed "steady" flow field.
  - Boundary layer approximations applied.
  - A formal analysis shows:
    - $t \rightarrow x$: $(d/dt) = (d/dx)*(dx/dt) = (d/dx)*v$
    - divide through by velocity
    - Cell mass flux, not mass, is conserved

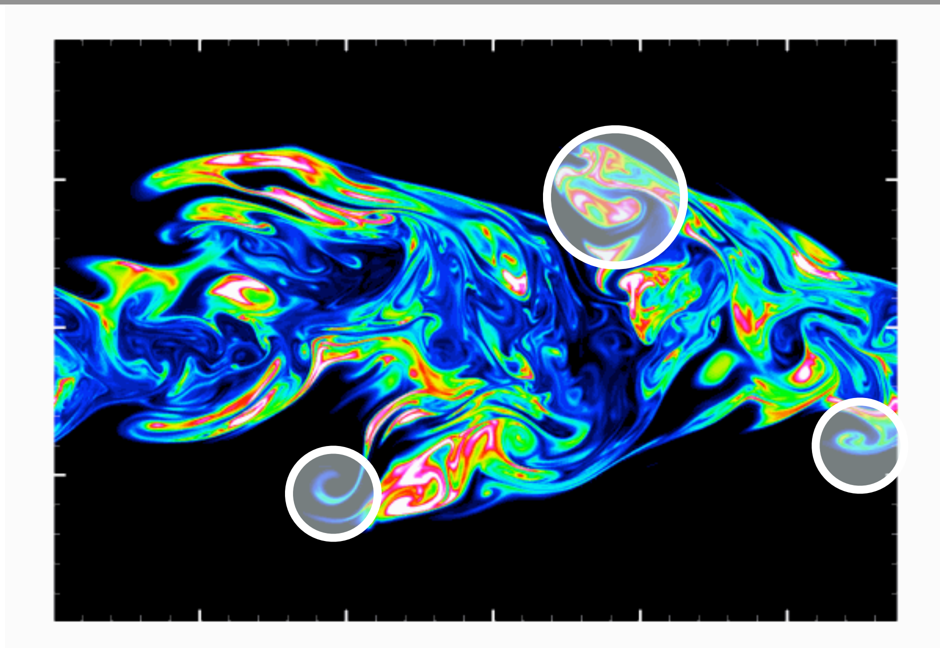


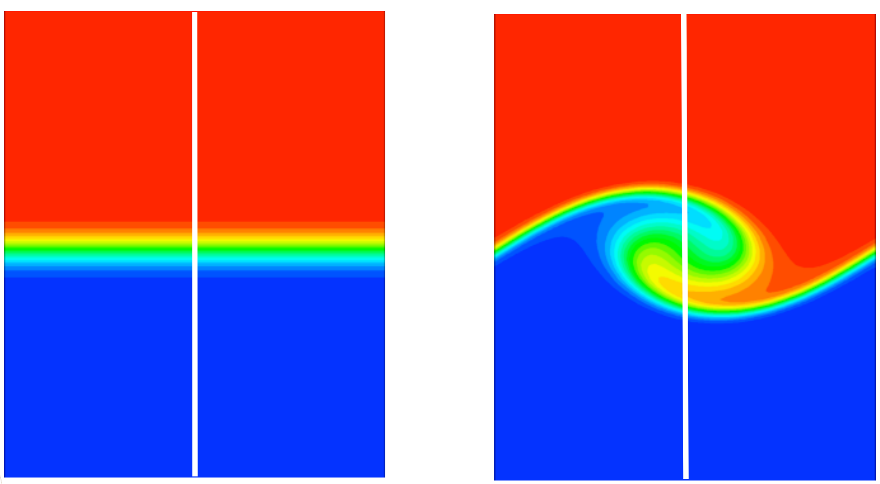
ODT Formulation—Eddy Events

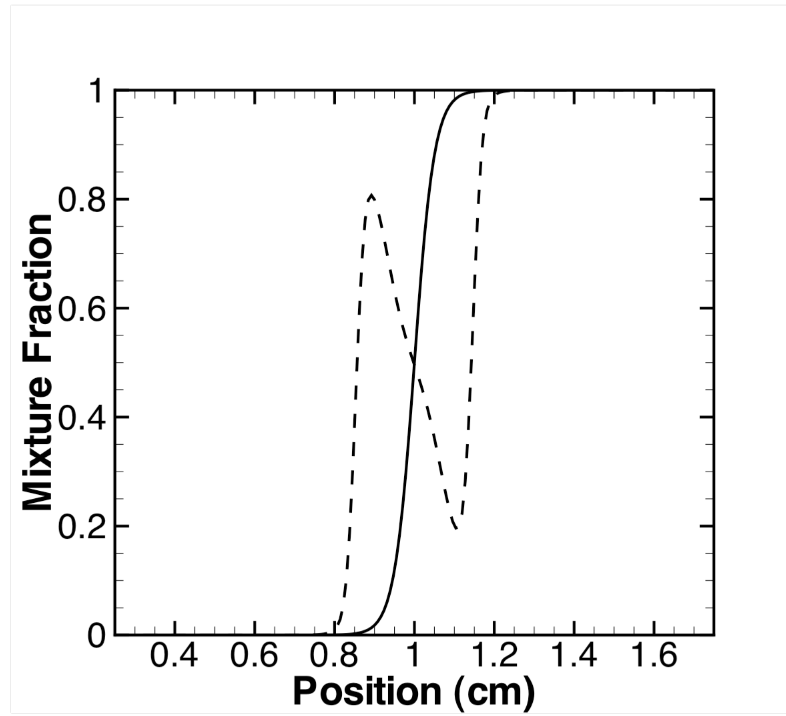
- Turbulent advection modeled via stochastic eddy events.
- Re-map portions of the domain in a manner consistent with turbulent scaling laws.
  - Inertial scaling $E(\kappa) = C\varepsilon^{2/3}\kappa^{-5/3}$ depends on
    - Local energy transfers
    - Non-dissipative energy transfer
    - ε is the only dependent parameter, and $\varepsilon = u^2/\tau$, with $\tau = l/u$
- As turbulence cascades, timescales decrease, strain increases
- The Kelvin-Helmholtz instability is fundamental in turbulence

http://upload.wikimedia.org/wikipedia/commons/8/8e/KHI.gif

ODT Formulation—Eddy Events

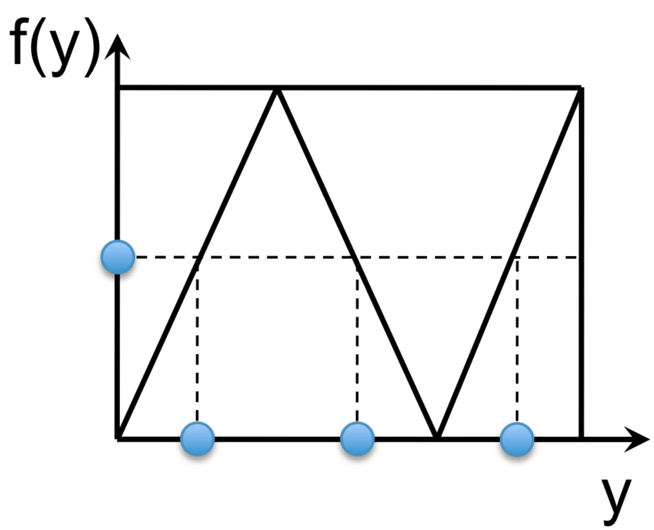


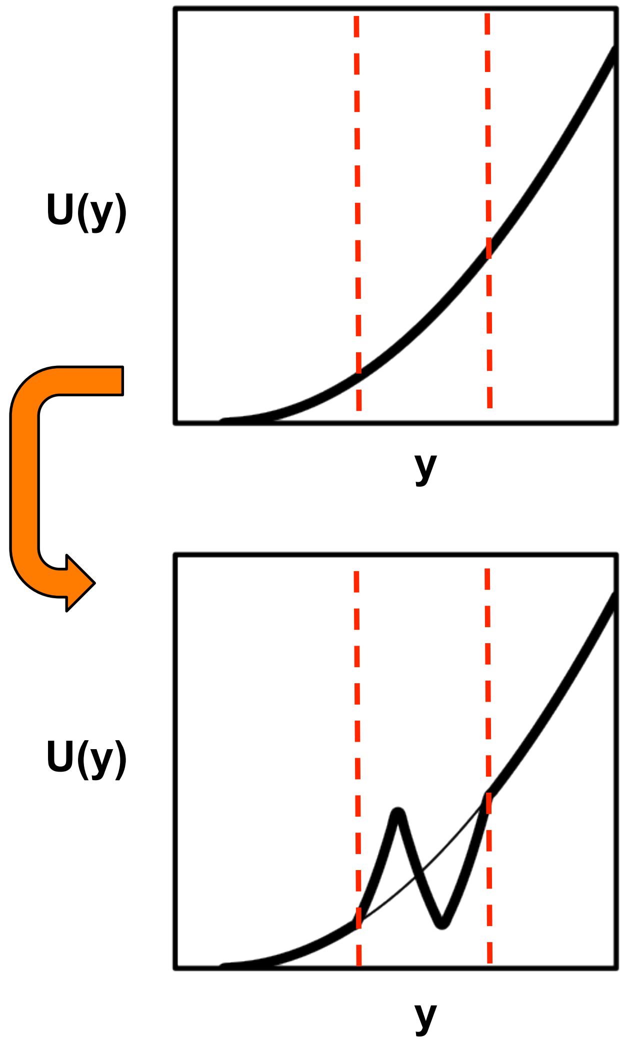




Triplet Map

- Triplet map written in terms of the inverse map
  - Fluid at f(y) is moved to y
- Procedure
  - Make 3 copies of a profile
  - Compress the domains by factor of 3
  - Invert the middle copy.





Eddy Rate Distribution

- Eddy events are consistent with inertial scaling
  - local
  - non-dissipative (u^2 is conserved)
  - consistent timescale: τ~l/u
- Determine eddy rate: time, location, size:
  - $\lambda(x_o,l)$ is eddy rate per unit eddy size, per unit domain length
  - Eddies sampled from joint PDF $P(x_o,l)=\lambda/\Lambda$, and accepted with acceptance probability P_a
  - In practice $P(x_o,l)$ is unknown, and the rejection method used
  - E is a measure of the kinetic energy in the eddy and includes a viscous penalty for very small eddies

$$\lambda(x_o,l)$$

$$\Lambda = \iint \lambda(x_o,l)dx_o dl$$

$$P(x_o,l) = \frac{\lambda}{\Lambda}$$

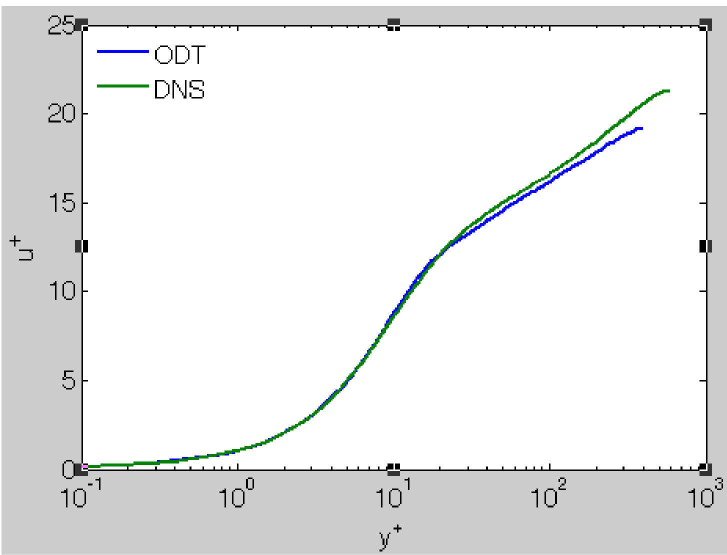
$$\Lambda\Delta t_s = P_a = \frac{\lambda(x_o,l)\Delta t_s}{P(x_o,l)}$$

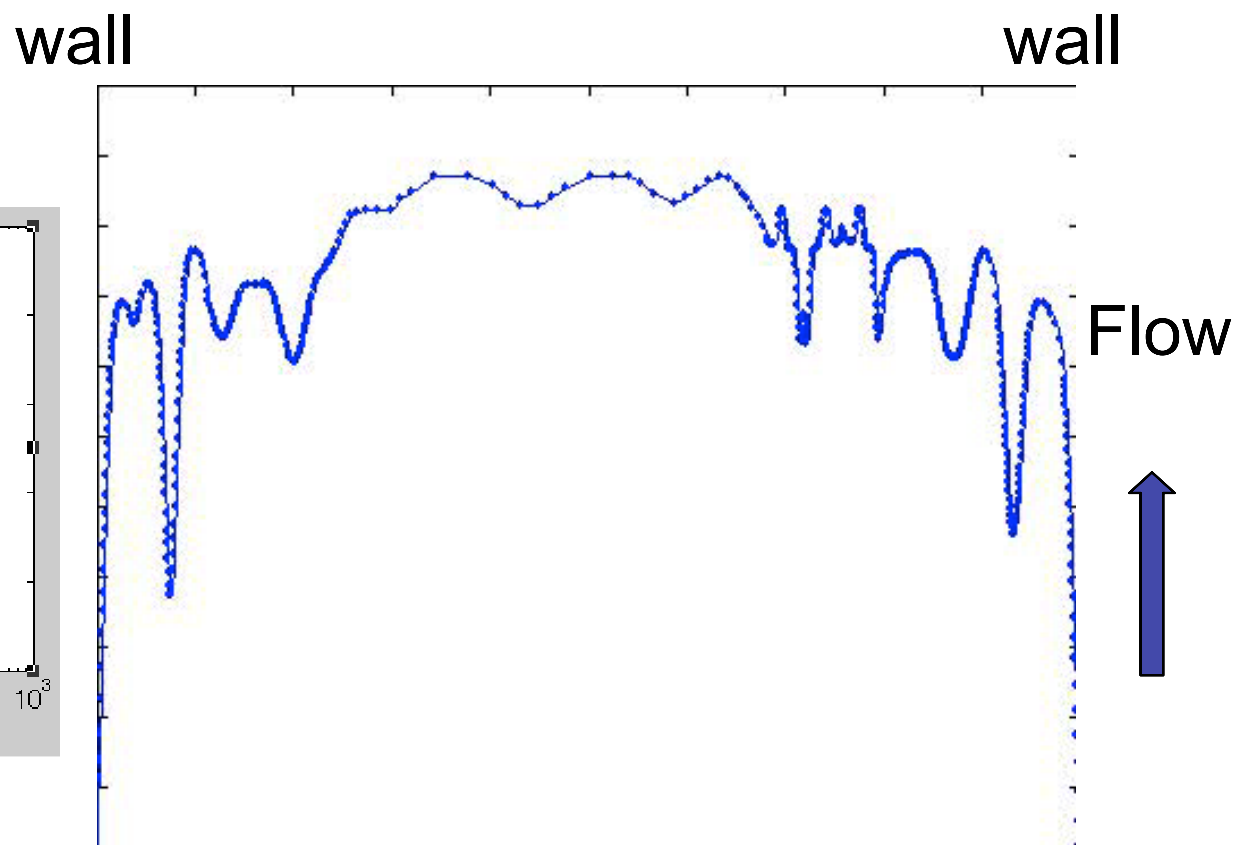
$$\lambda = \frac{1}{l^2\tau}$$

$$E = \frac{1}{2}\rho l\bar{u}^2 = \frac{1}{2}\rho l^3/\tau^2$$

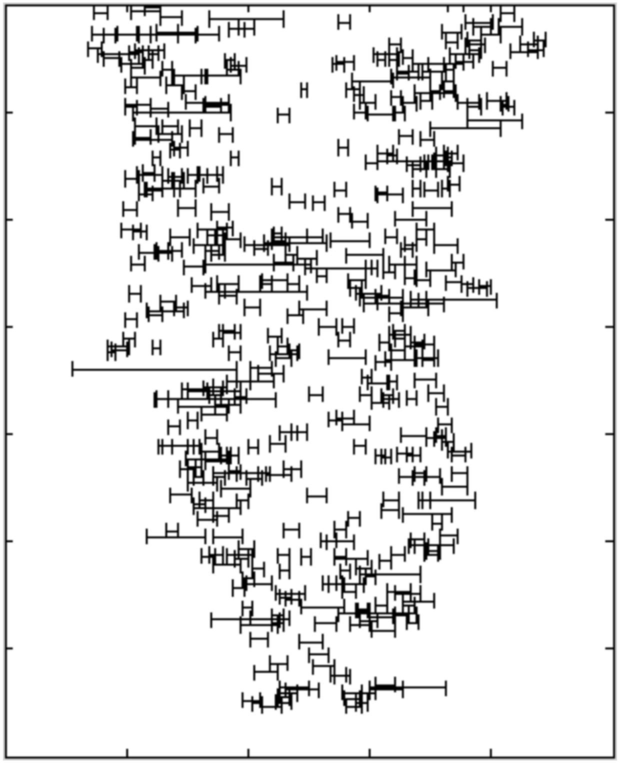
$$\frac{1}{\tau} = C\sqrt{\frac{2E}{\rho l^3}}$$

ODT Validation—Channel Flow





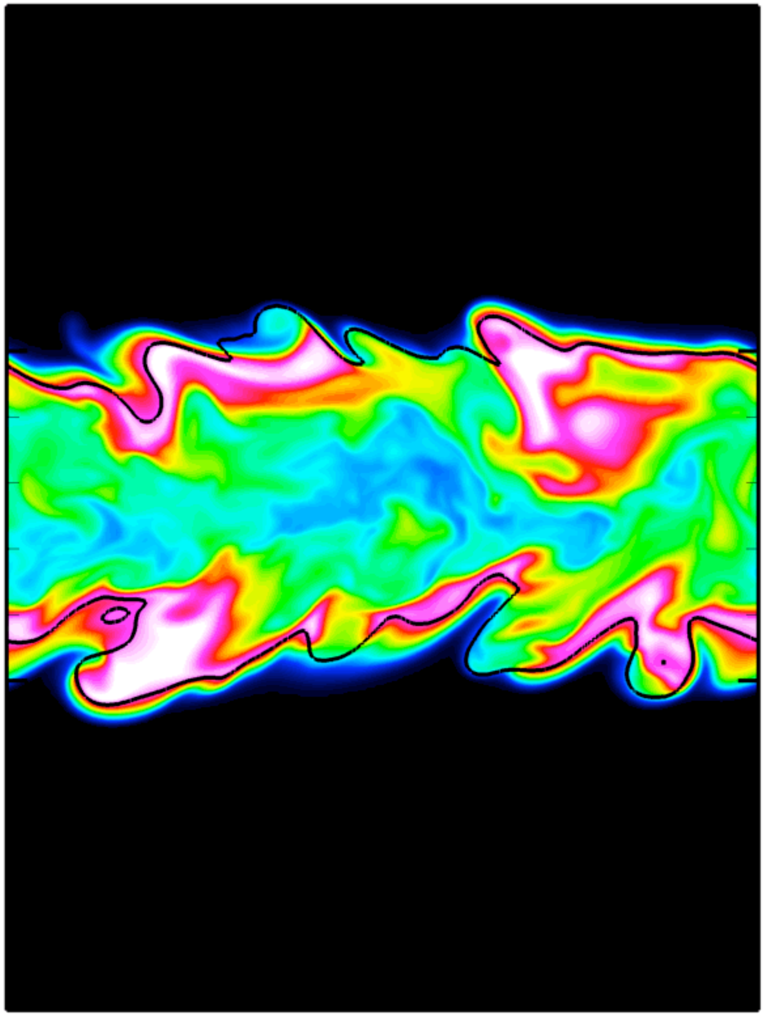
ODT Application—Ethylene Pool Fire



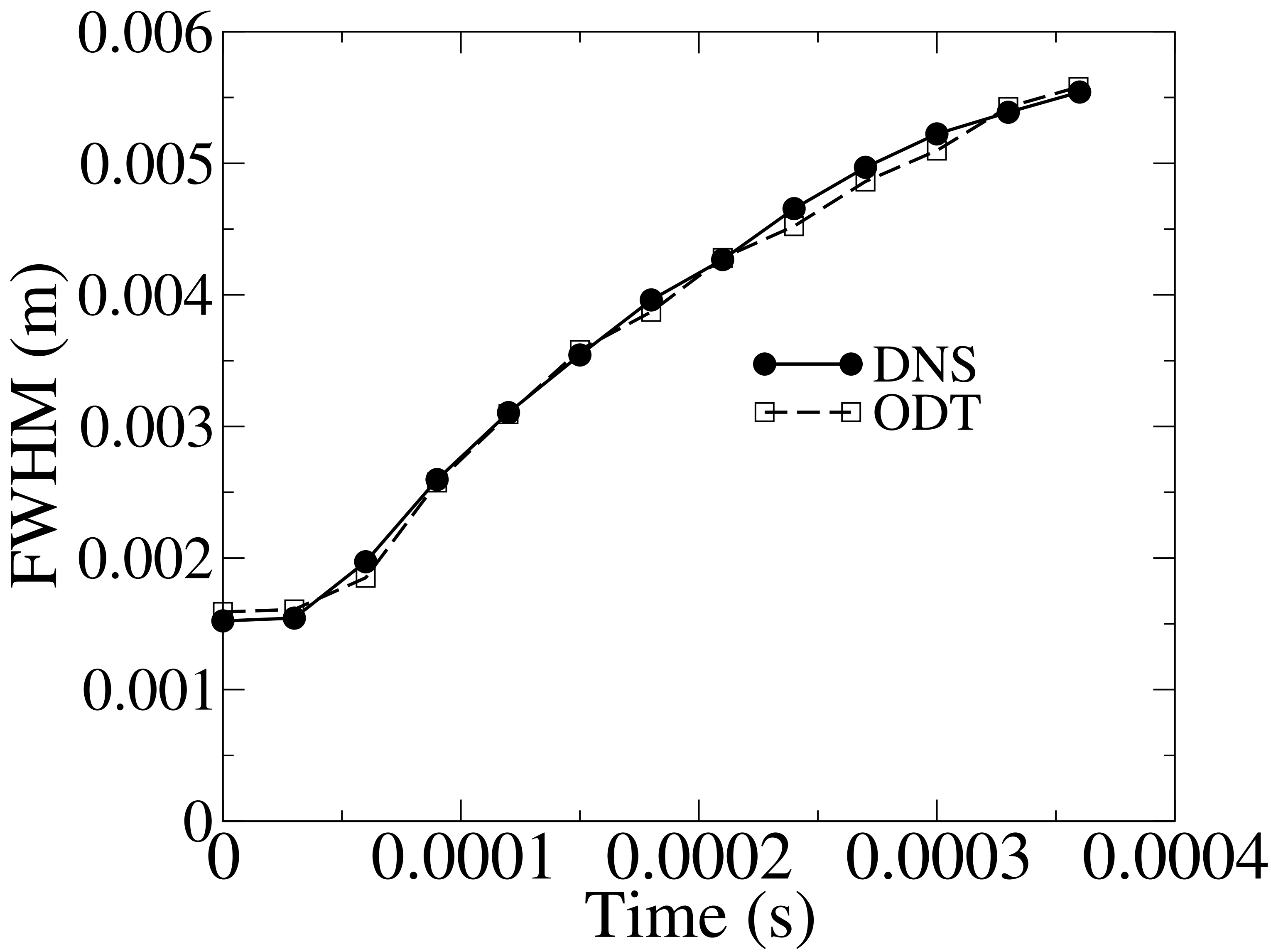
- Buoyant ethylene pool fire
- 5x7 meters
- One realization, run on the order of 100 realizations
  - Around 30 minute computation time each.

DNS Validation

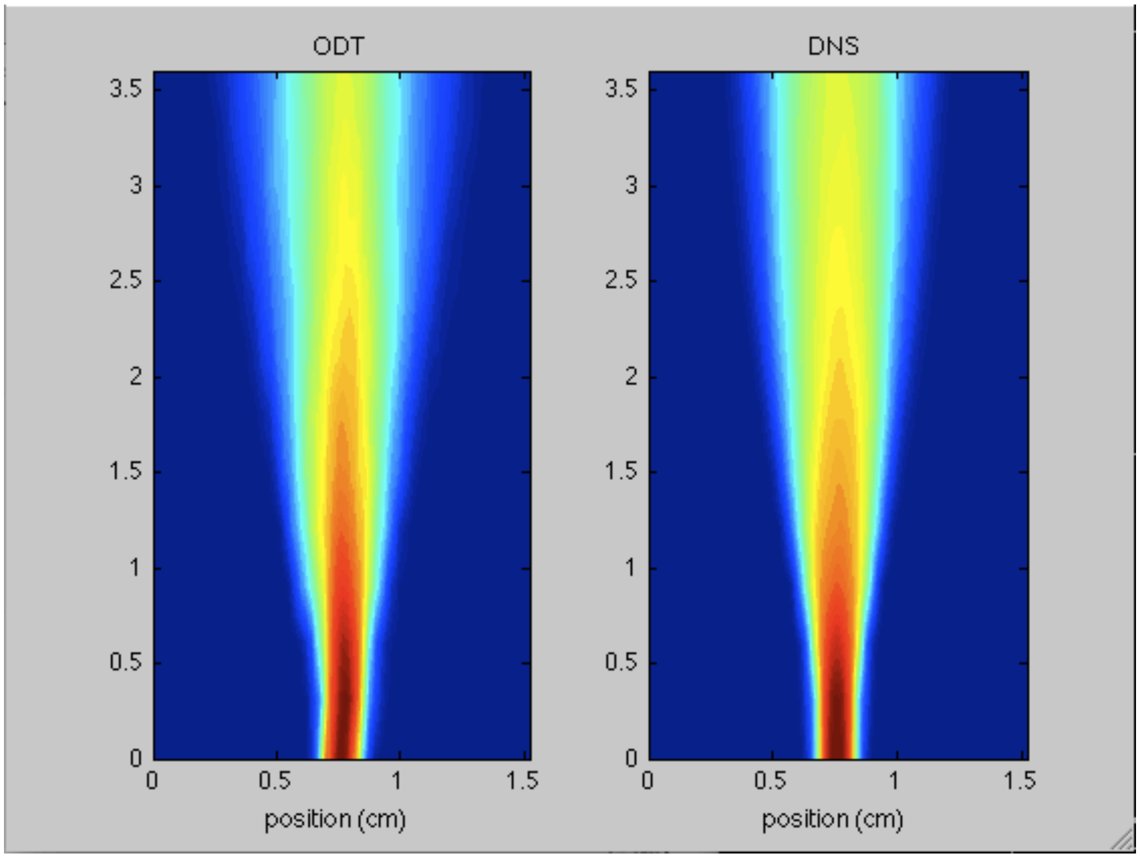
- Compare ODT to temporally-evolving DNS
- Planar ethylene jet
- Extinction, reignition
  - Three cases with varying Da
- Tune the ODT parameters
- Compare means, fluctuations
  - T, mixture fraction, species

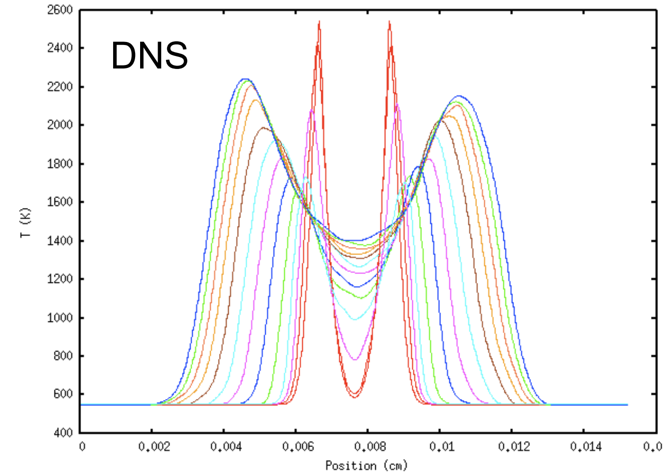


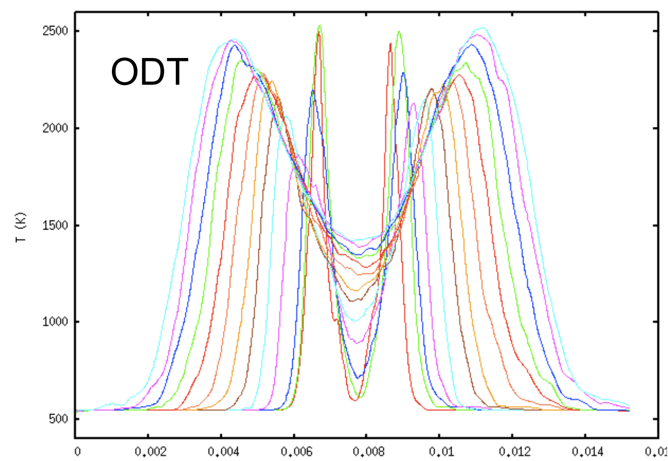
ODT / DNS - Jet spread rate



ODT / DNS - Mixture Fraction, Temperature







Conclusions

- ODT is a promising method to examining flame structure
  - Applied successfully to a wide range of problems
  - Computationally affordable
    - Allows many parametric studies
  - Intermittent flame interface
  - Statistics of time temperature histories
  - Capture overall flow characteristics as well as fine structures