Three Questions

Jim Driscoll, University of Michigan

1. What models are best - to predict measured values of Flame Surface Density and Turbulent Burning Velocity ?

2. Do Σ and S_T increase with u' - or do the curves level off ?

3. Can new cinema-PIV tell us the correct physics - to add to LES , and to assess DNS?

Turbulent premixed combustion: flamelet structure and its effect on turbulent burning velocities,
J.F. Driscoll, Progress in Energy and Combust. Sci. 34, 2008, p. 91.

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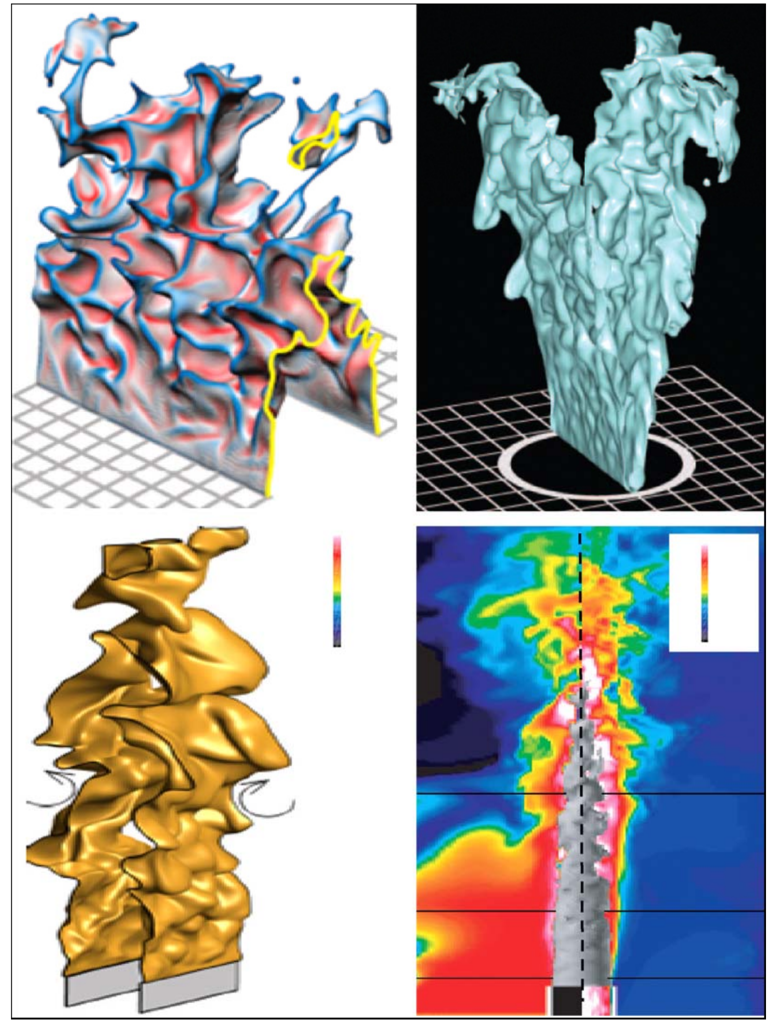
What models are best - for flame height, S_T, FSD ?

DNS

LES with subgrid G-eqn

LES with subgrid FSD balance



Bell, Day, Grcar

Sankaran and J.H. Chen

Pitsch and Duchamp de Lagenest

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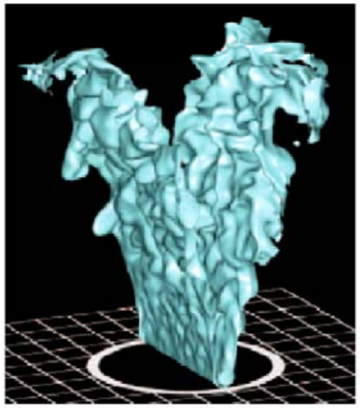
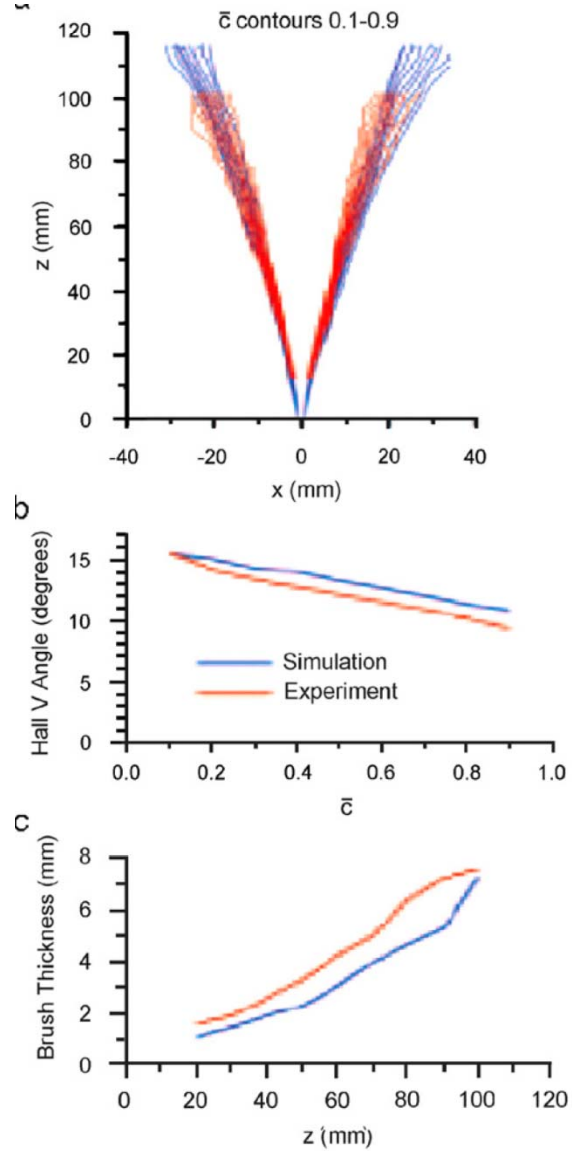


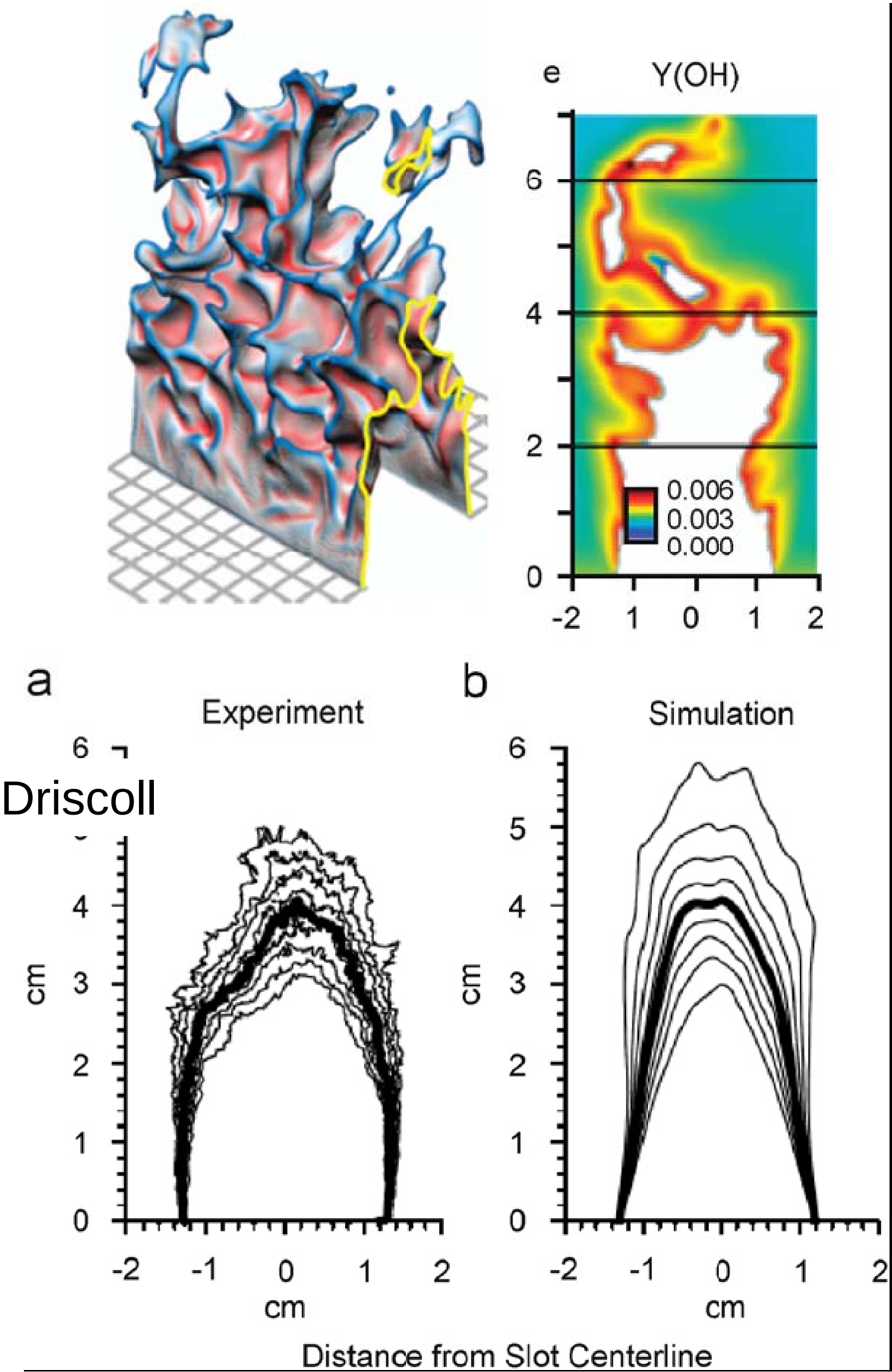
DNS of Bell, Day, Cheng, Shepherd



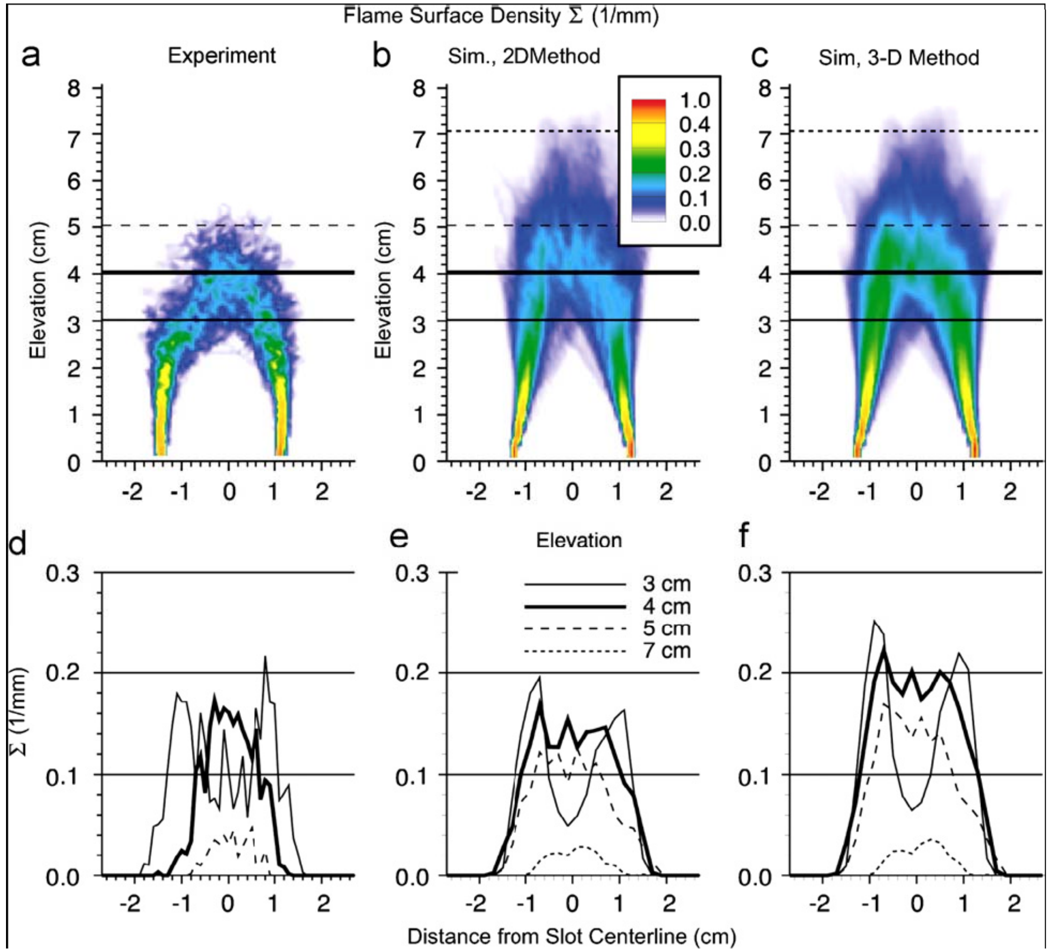
Flame Height

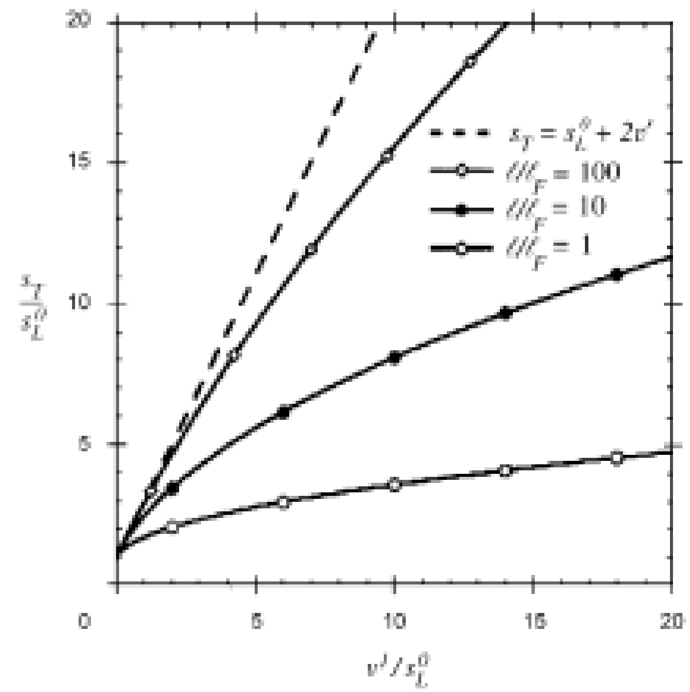
Bell, Day, Grcar,
Filatyev, Driscoll

Experiment of Filatyev and Driscoll

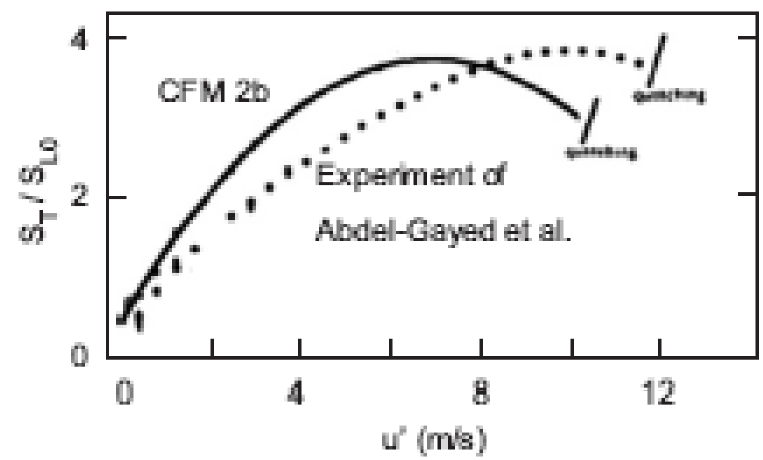


Flame Surface Density



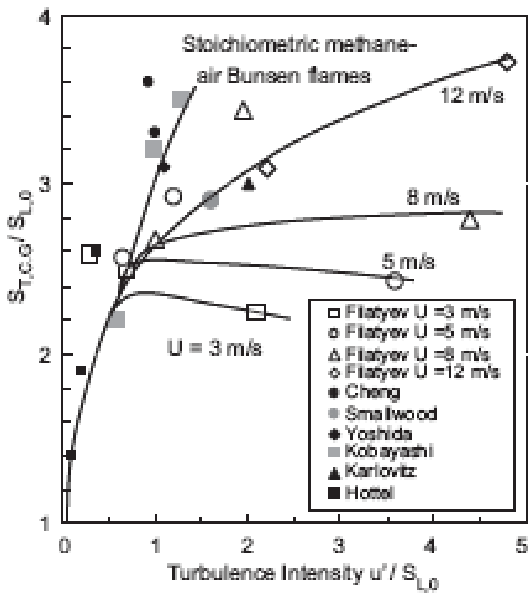


S_T computed by Peters using G-eqn
General agreement with Bradley data



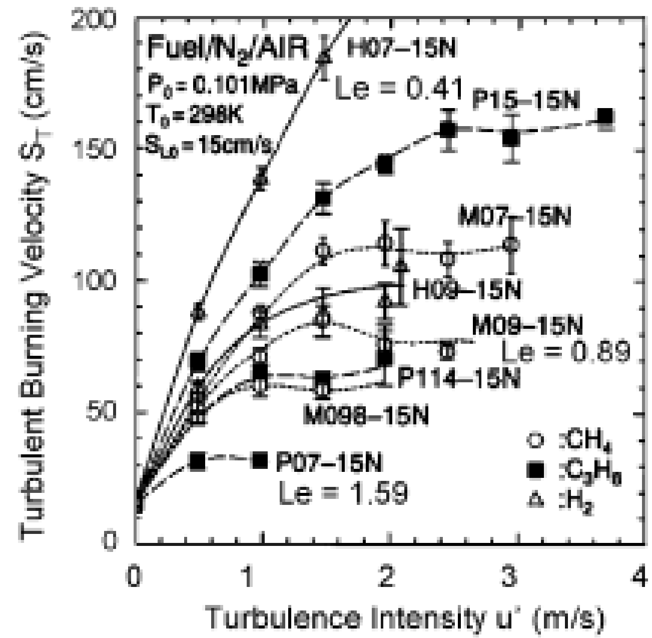
S_T computed by Coherent Flamelet Model of Duclos – agrees with Bradley

Do S_T and Σ increase with u',
or do curves become flat ?

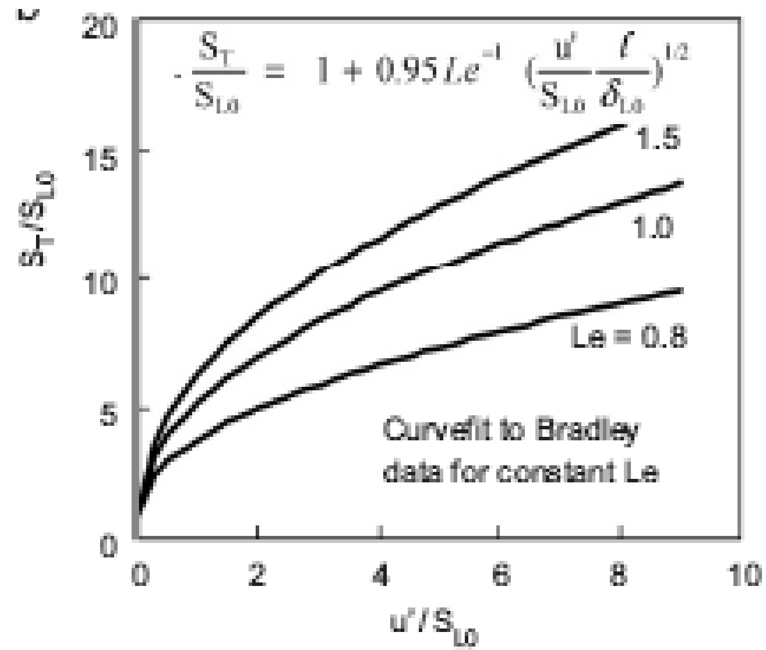


Filatyev and Driscoll

Kido



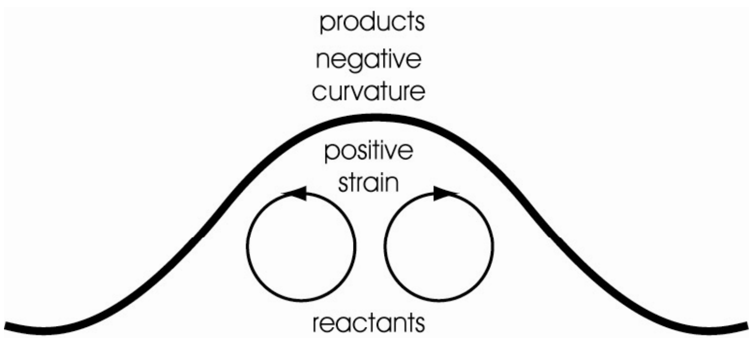
Bradley



Role of vortices vs. hydrodynamic instability

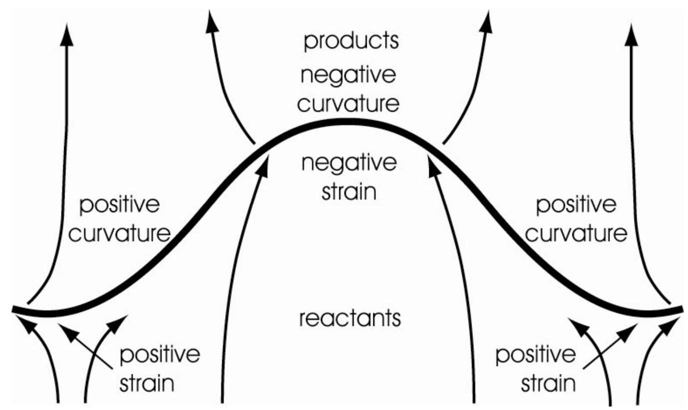
Classic vortex idea

- positive strain rate is correlated with negative curvature
- so $R_{strain\text{-}curvature}$ = negative



Hydrodynamic instability

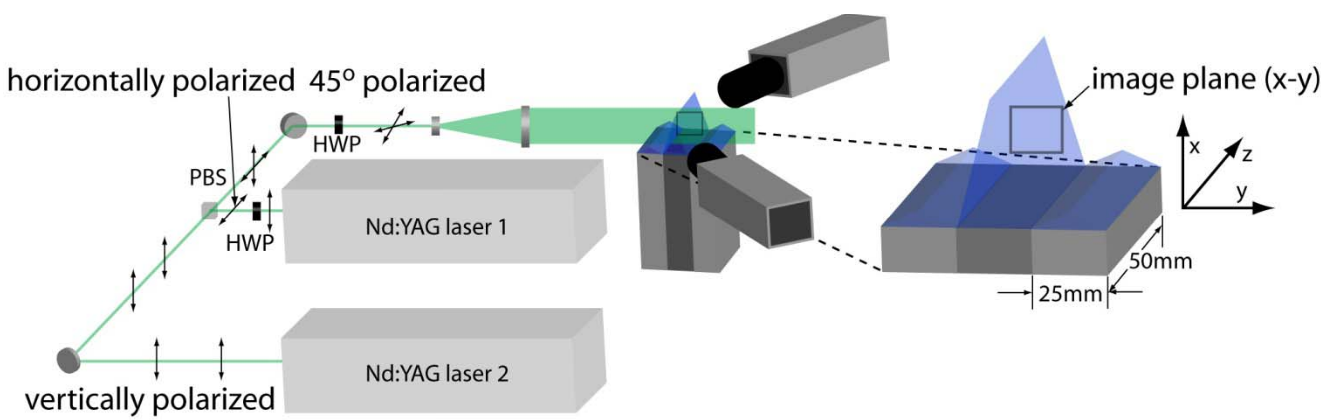
- Converging & diverging streamlines
- Positive strain rate correlates with positive curvature
- so $R_{strain\text{-}curvature}$ = positive



Visualize: turbulent eddies, flame, hydrodynamic instability

Cinema Stereo-PIV

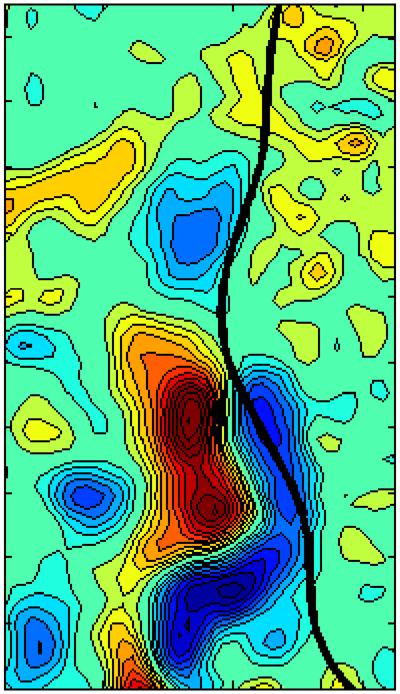
- PIV images at 1,111 frames /sec
- Two high-rep-rate Nd:YAG lasers, Phantom digital cameras
- 12.8 mm x 18.2 mm field of view, 140 µm vector spacing
- slot Bunsen flame, U = 1 m/s, methane/air,
- $\varphi = 0.7$, $u'/S_{L0} = 2.3$



Pair of turbulent eddies wrinkling flame

Vorticity (ω_z) between -700 s^{-1} (blue) and 700 s^{-1} (red)

- Field of view: 6 mm x 10.5 mm, Δt = 0.9 ms
- Reactants on left, flow is upward



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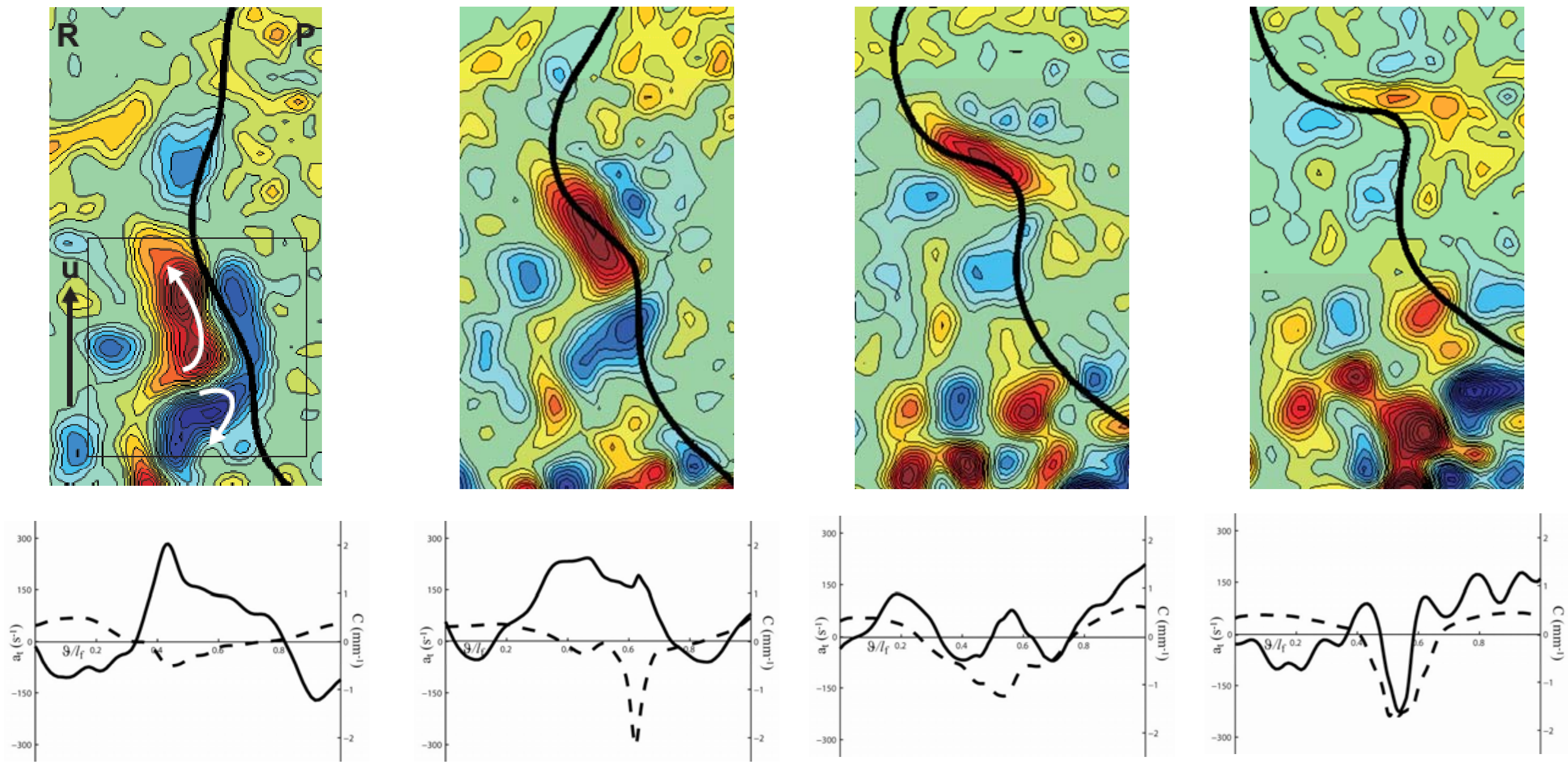
Pair of Turbulent Eddies Wrinkling Flame

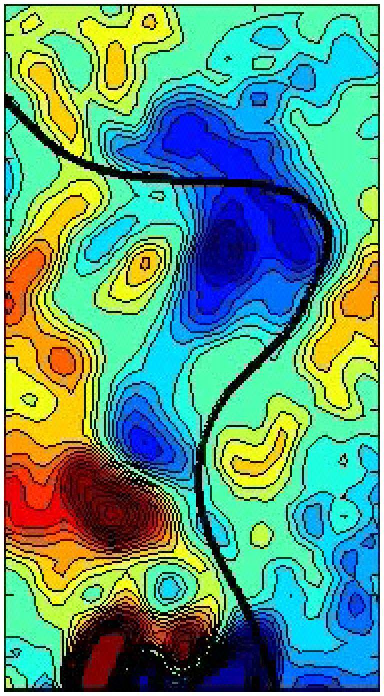


t = 0 ms | t = 1.8 ms | t = 3.6 ms | t = 5.4 ms

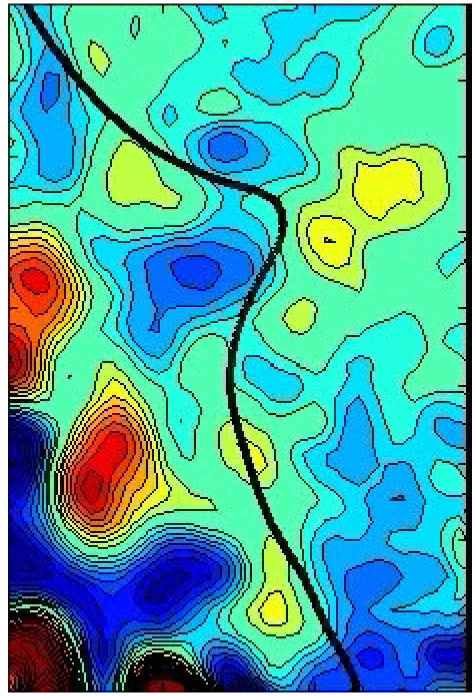
Initially strain and curvature are negatively correlated, Strong vortex, no hydro. instab.

Later strain and curvature are positively correlated – Vortex gone, hydro. instabil.

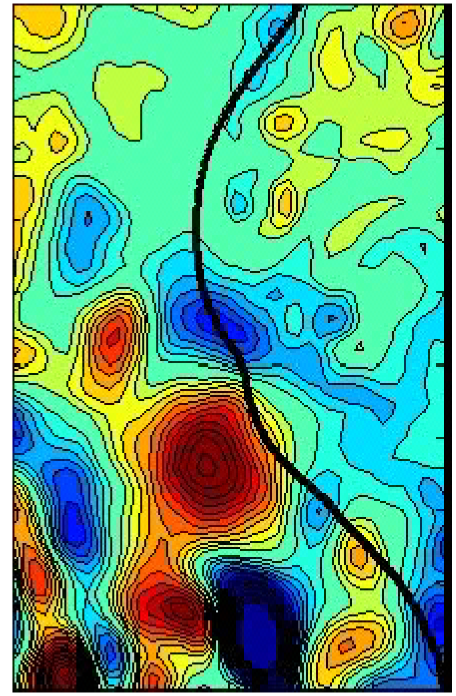
Not all turbulent eddy pairs do the same thing



Eddy pair at bottom create large wrinkle, then are destroyed

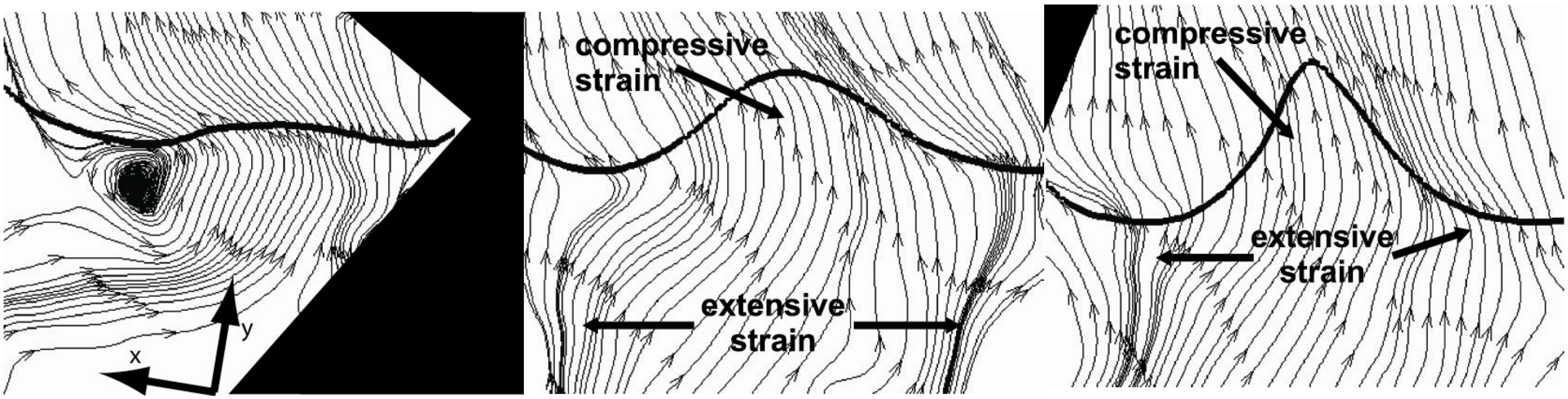


Stronger eddy pair at bottom create only small wrinkle



Strong eddy pair creates no wrinkle but turns flame 90^{o}

Cinema-PIV identifies events dominated by Hydrodynamic Instability

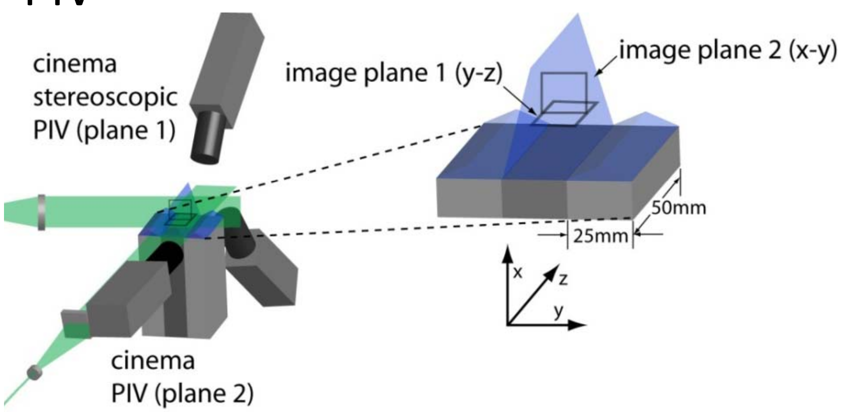


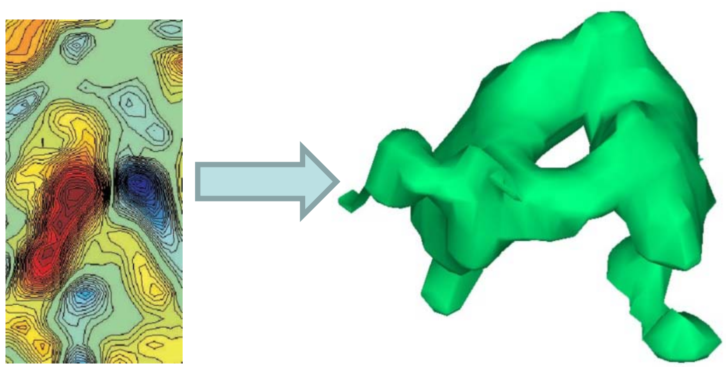
t = 0 ms　　　t = 6.3 ms　　　t = 12.6 ms

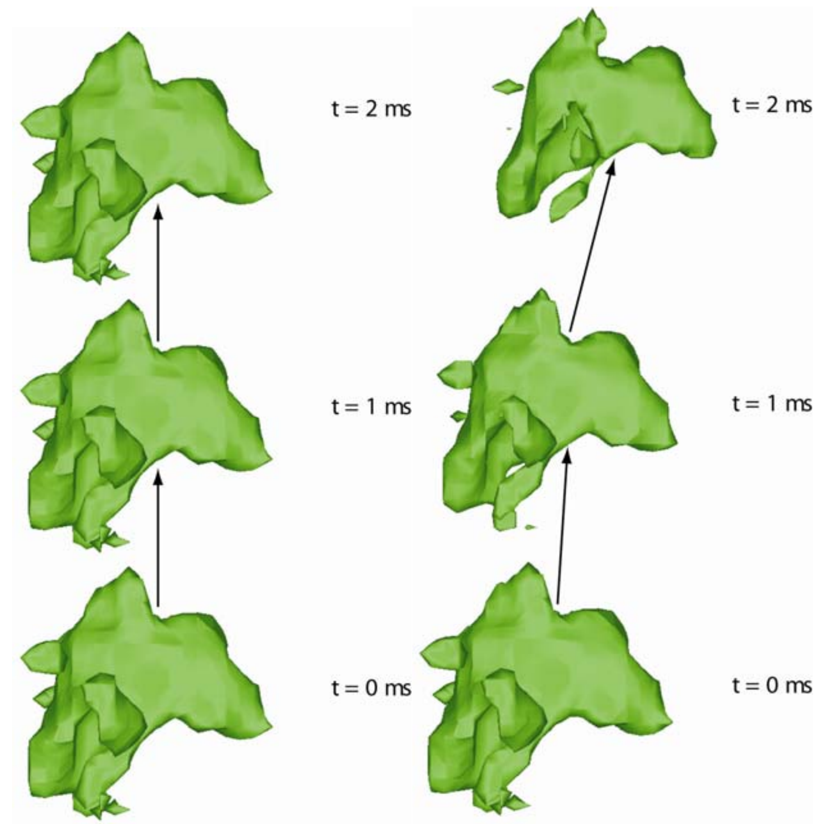
- vortex is a perturbation only - creates a flame wrinkle
- Regions of diverging and converging streaklines agree with theory
- expected strain rate pattern of a hydro. instab. occurs
- Wrinkle grows into cusp, vortex is long gone

Future work

- Statistical description of straining and wrinkling of flames
- Expand to 3D measurements using Orthogonal-Plane Cinema-Stereoscopic PIV



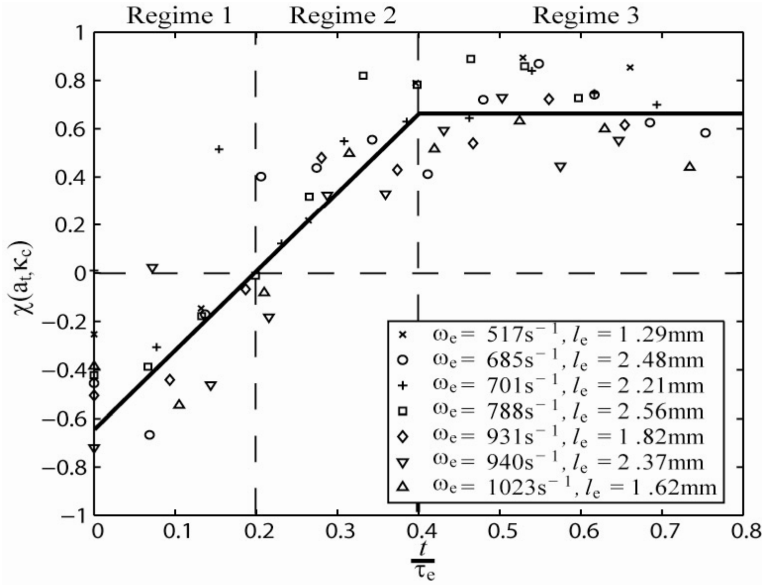


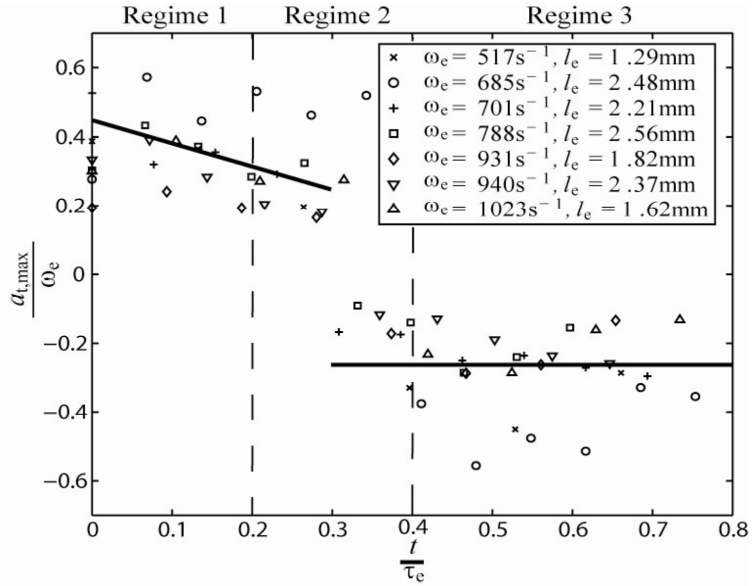


Results

Temporal evolution of the strain rate

- Strain-curvature correlation changes sign as wrinkle develops
- Magnitude of strain from hydrodynamic instabilities similar to that during vortex interactions
- Strain rate exerted on flame not characterized by vorticity field





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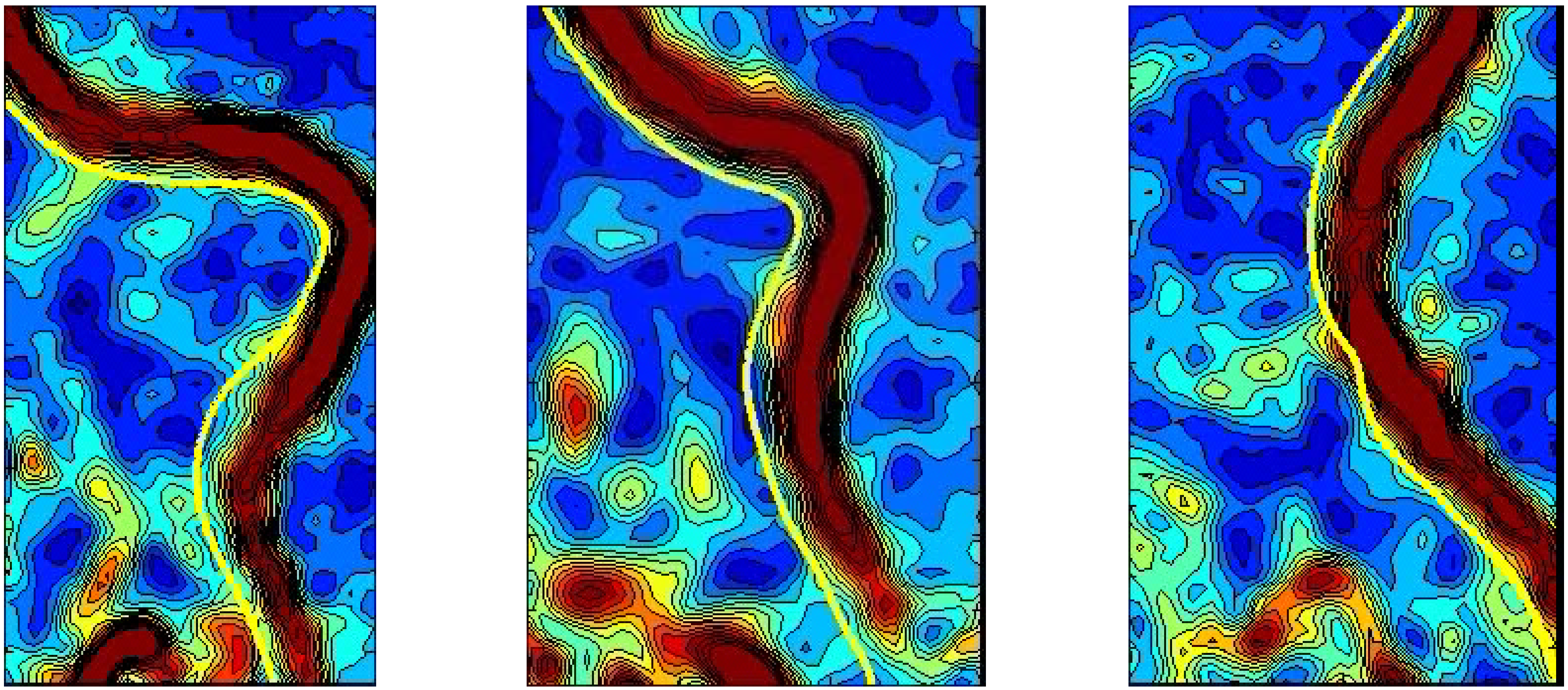
Results

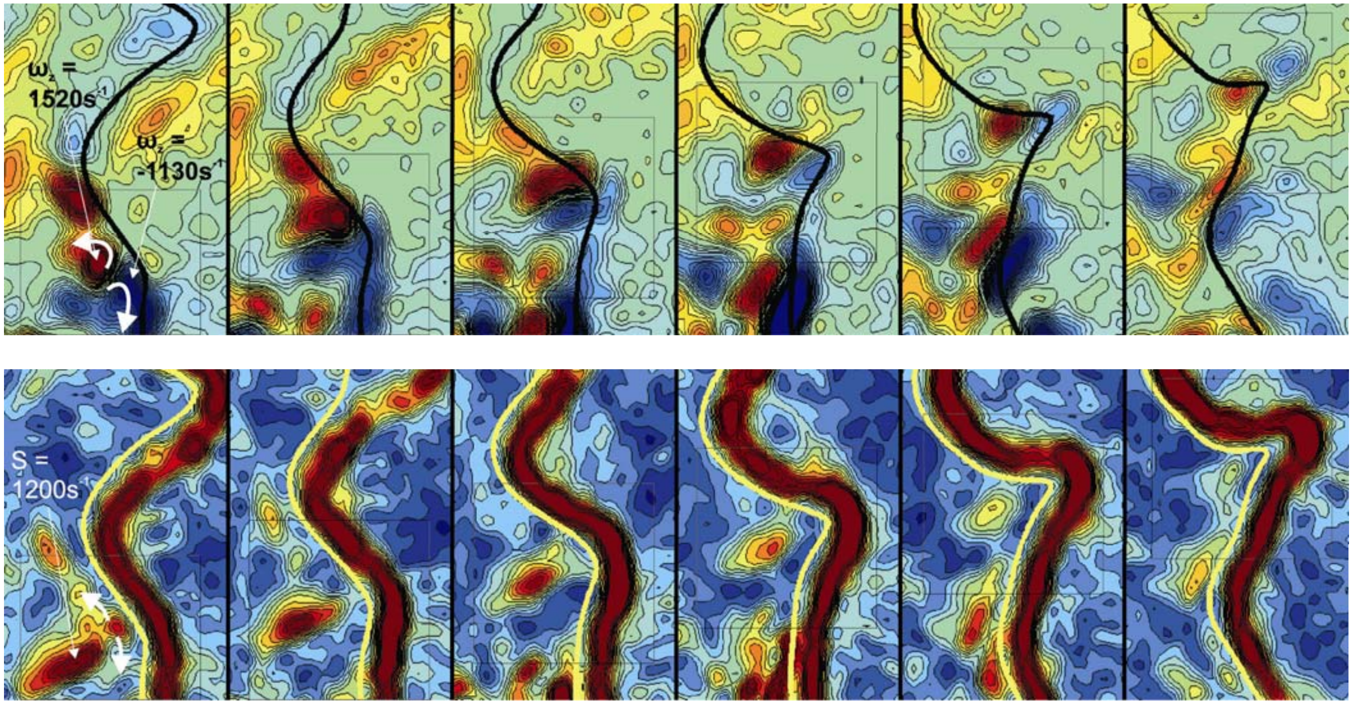
- Contours of S between 0 s^{-1} (blue) and 700 s^{-1}(red)
- Flame is thick yellow line
- Flame acceleration appears as S



Results

Interaction 1

- Strong vortical and strain-rate structures
- Large wrinkle and considerable surface area



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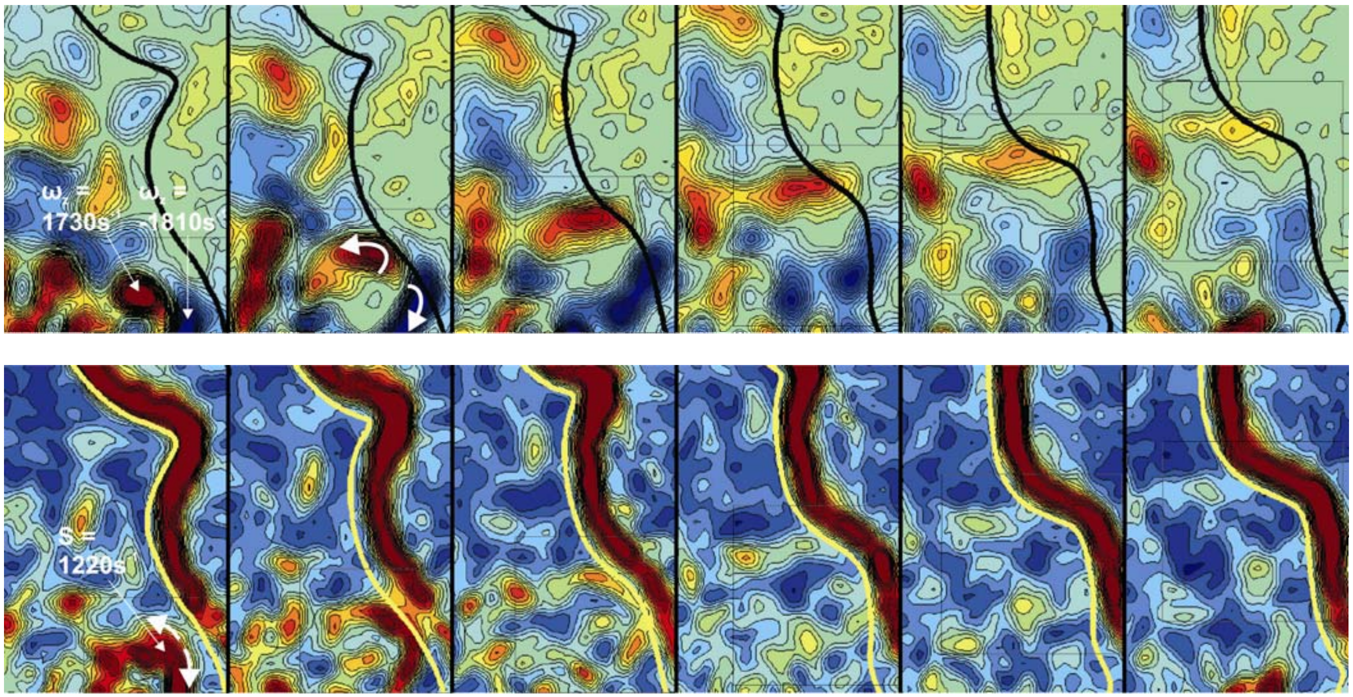
Results

Interaction 2

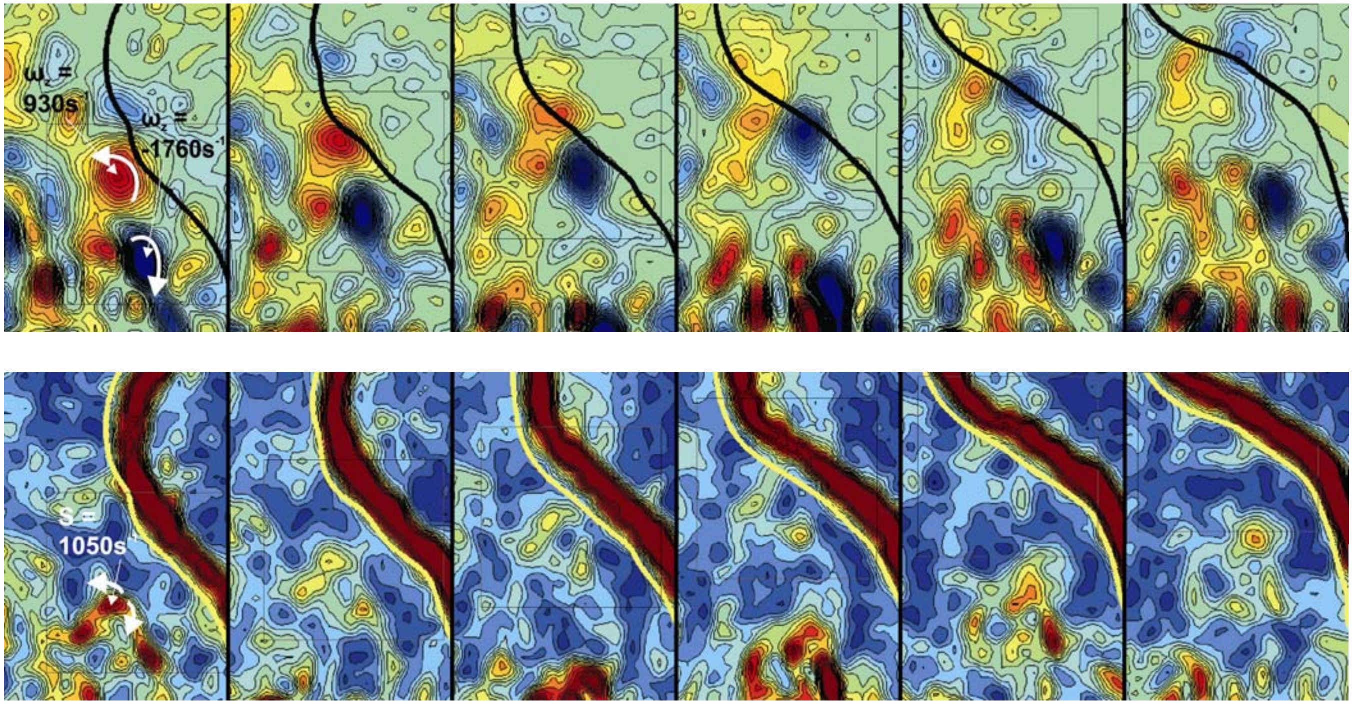
- Strong vortical structures, strain-rate structure quickly attenuates
- Smaller wrinkle and less surface area



Results

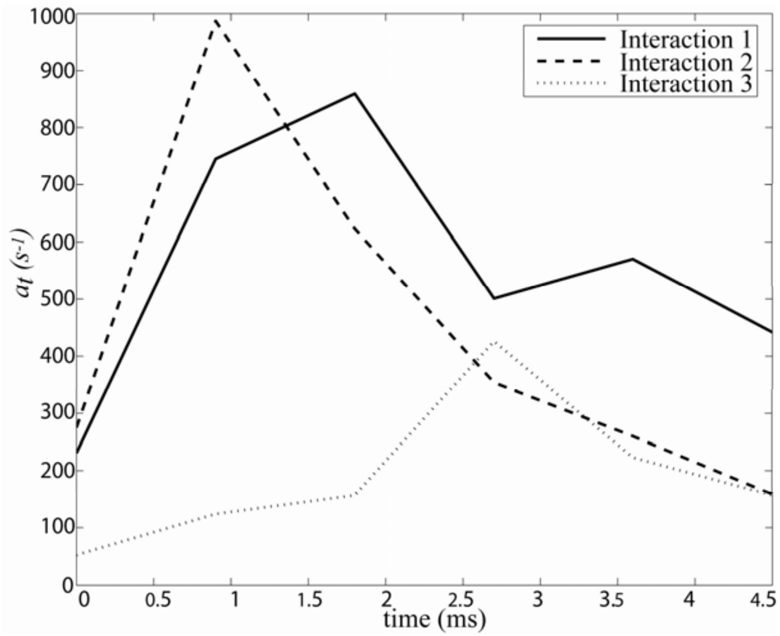
Interaction 3

- Strong vortical structures, weak strain rate structure
- Little generation of flame surface area

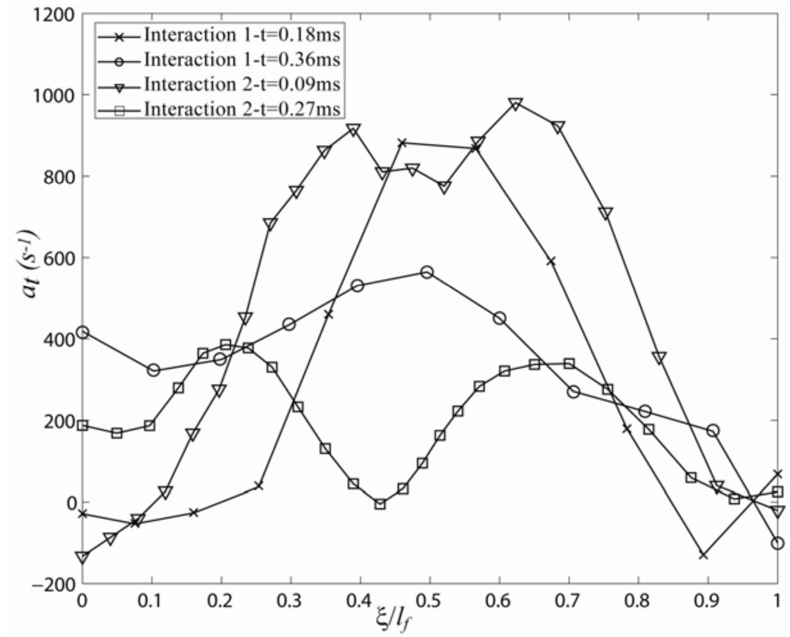


Results

Strain rate on the flame surface



Strain-rate structures describe strength and residence time of strain rate on flame

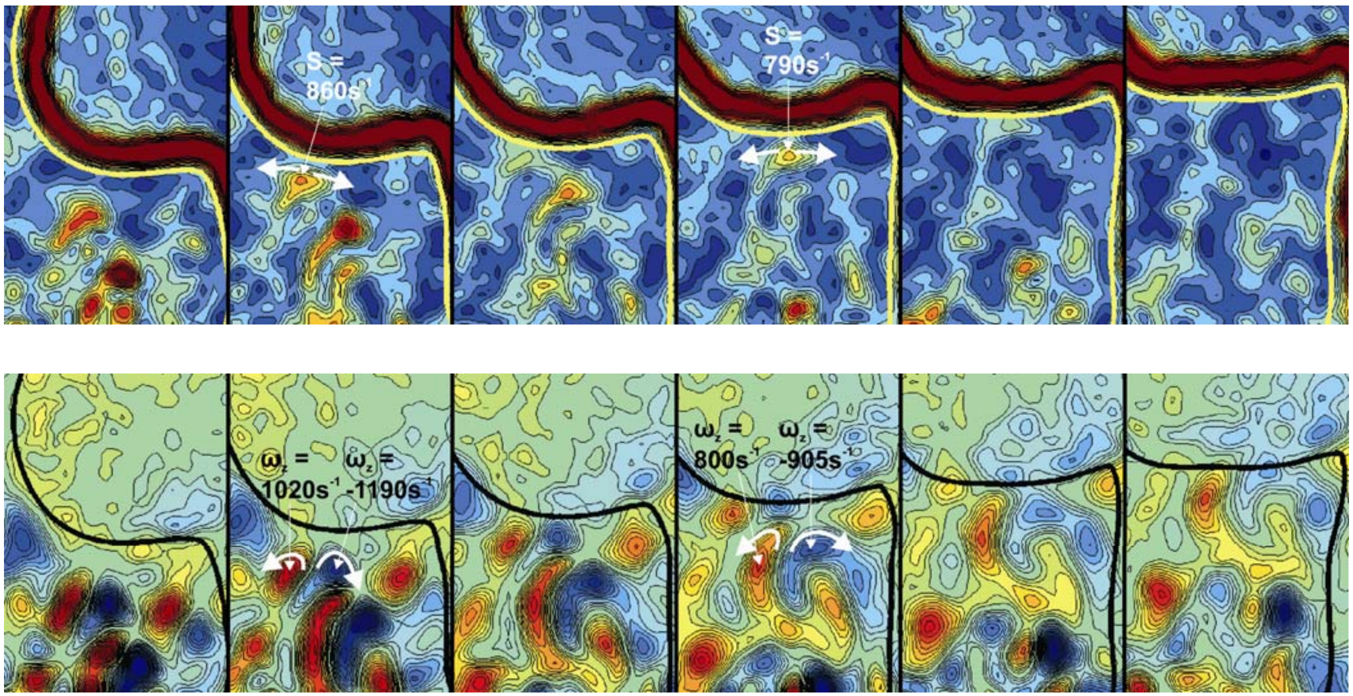


Strain-rate structures describe location and pattern of strain rate on the flame

Results

Interaction 4

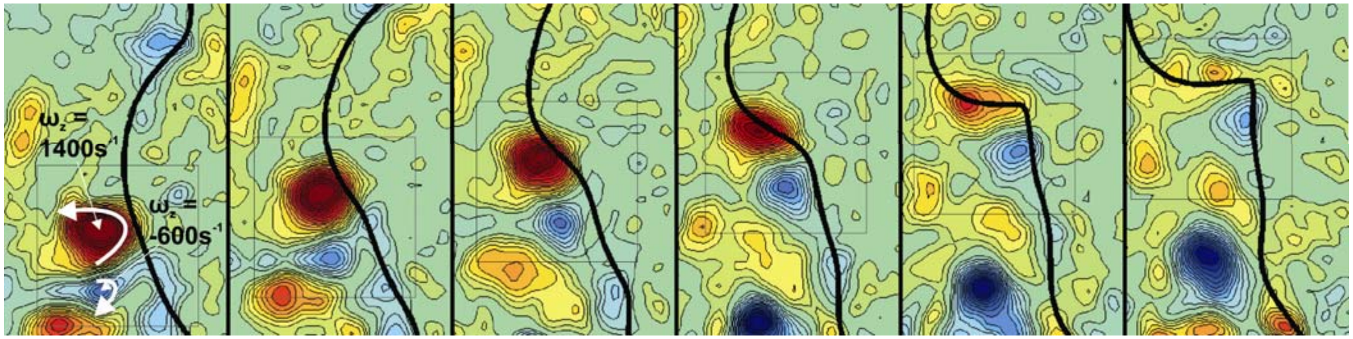
- Two successive pulses of extensive strain rate
- Create a longer flat flame segment

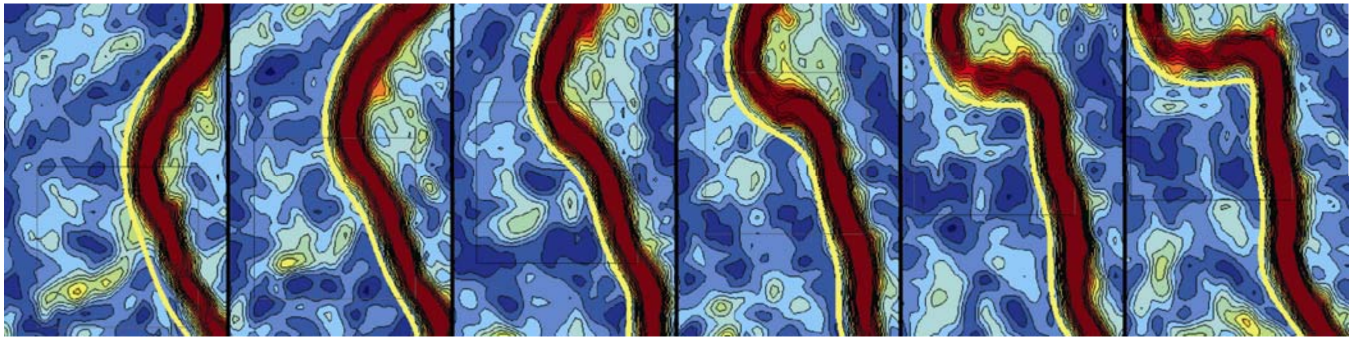


Results

Interaction 5

- Strong positive vorticity
- Flame wrapped around with little strain





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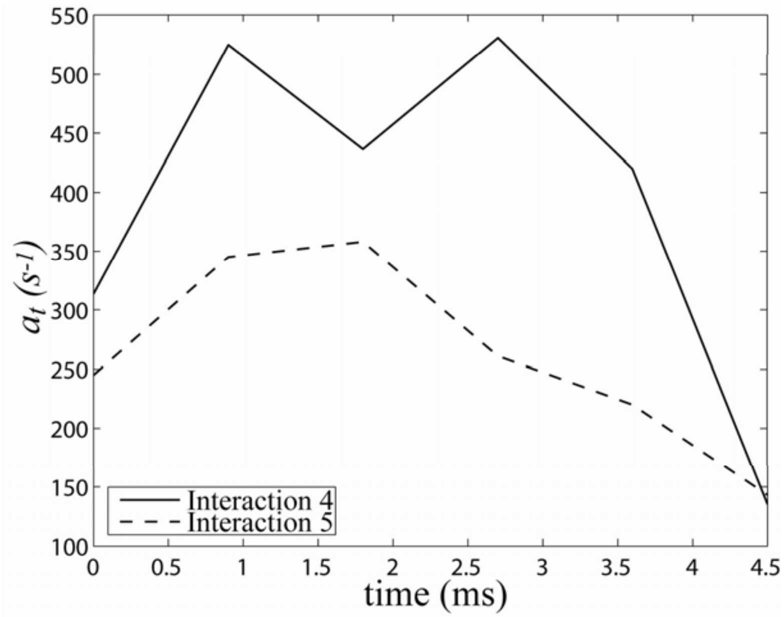
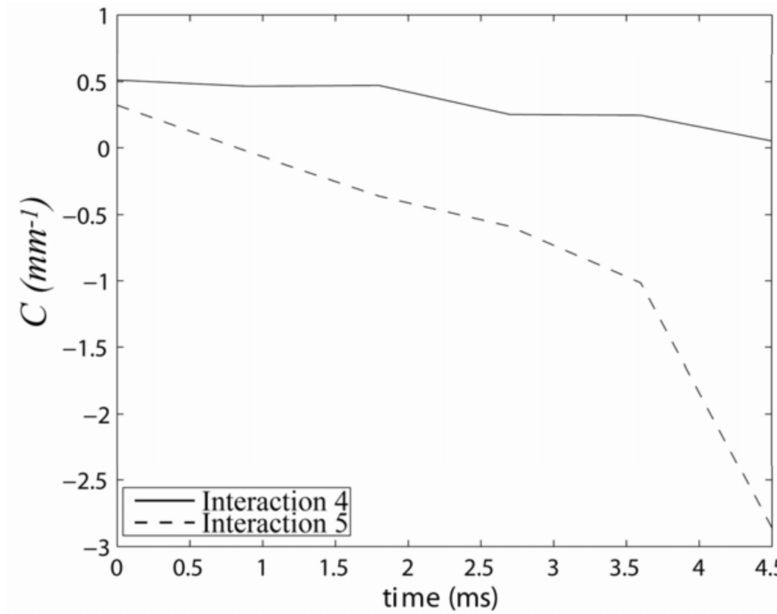
Results

Strain rate and curvature on the flame surface





Strain-rate rate and curvature not necessarily correlated

Conclusions

- Dynamics of turbulence-flame interactions and hydrodynamic instability measured using Cinema-Stereoscopic PIV
- Generation of flame surface area from each source observed
- Hydrodynamic instability can cause significant strain and generation of flame surface in moderately turbulent flames
- Vorticity field does not properly characterize strain rate on flame front
- New mechanism for turbulence-flame interaction proposed
    - Straining of flame by turbulent strain-rate structures
    - Wrinkling of flame by turbulent vortical structures
- Interpretation confirmed from measurements

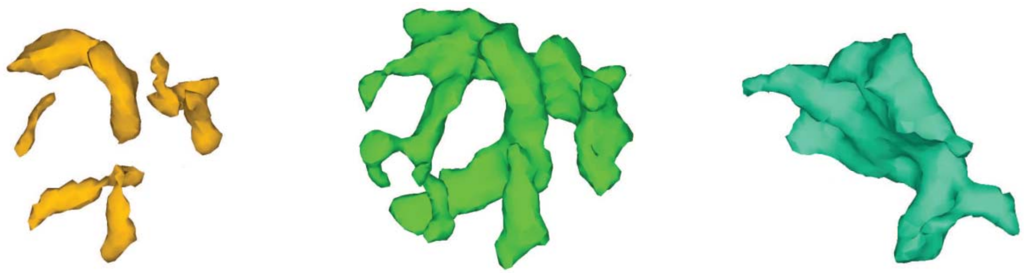
Questions

?

Future work

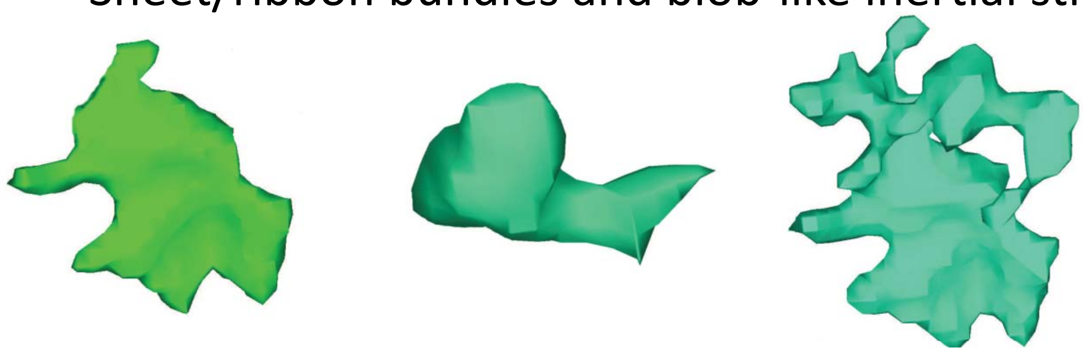
Vortical Structures

- Tube-like dissipative structures
- Tube-bundle and sheet-like inertial structures



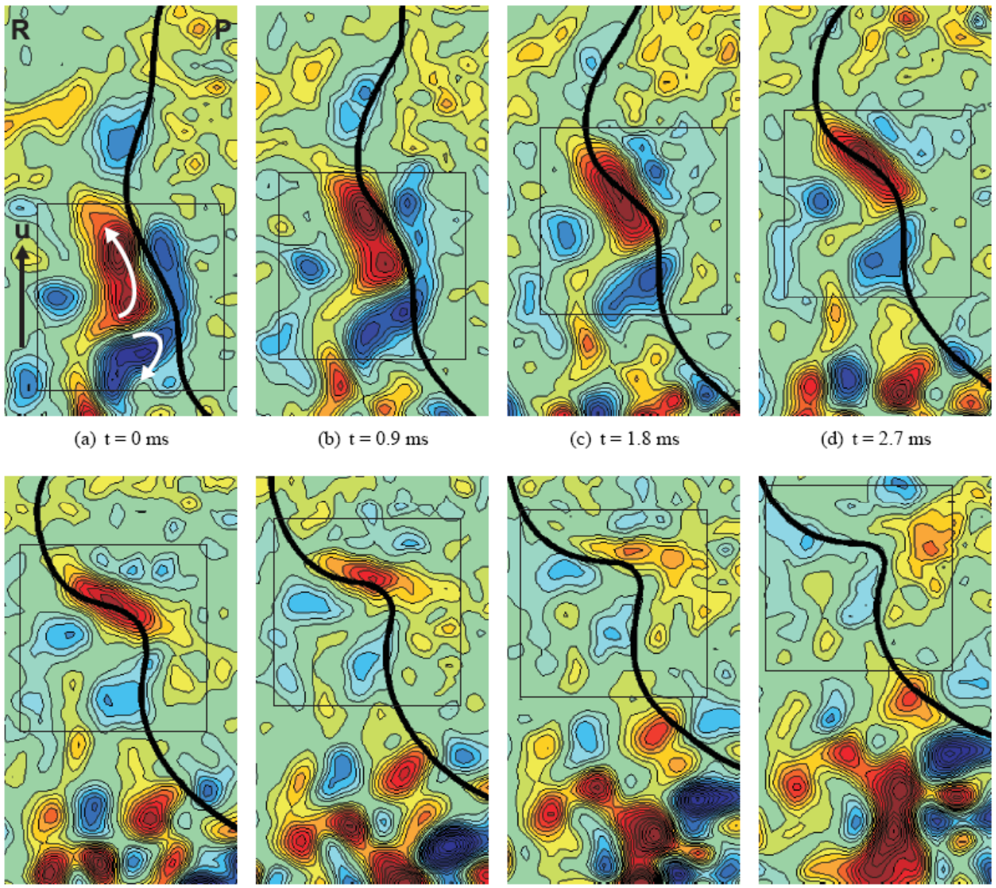
Strain-Rate Structures

- Sheet-, ribbon-, and blob-like dissipative structures
- Sheet/ribbon bundles and blob-like inertial structures



Results

Turbulence-Flame Interaction



(a) t = 0 ms (b) t = 0.9 ms (c) t = 1.8 ms (d) t = 2.7 ms

(e) t = 3.6 ms (f) t = 4.5 ms (g) t = 5.4 ms (h) t = 6.3 ms

Turbulence strains flame and wraps flame surface into wrinkle

Vorticity attenuated, some flame generated vorticity in products

Outline

- Motivation
- Sources of strain rate
- Diagnostics and Experiment
- Results
    - Strain due to turbulence and the hydrodynamic instability
    - Roles of coherent turbulent structures
- Conclusions
- Future work

Motivation

Strain rate $a_t = -\hat{n} \cdot (\hat{n} \cdot \nabla)\, \vec{u} + \nabla \cdot \vec{u}$

- Describes generation of flame area from velocity gradients pulling and pushing on the surface

Curvature stretch rate $\kappa_c = (\nabla \cdot \hat{n})\, S_L$

- A wrinkled flame propagating normally to itself changes area
  - Wrinkles initiated by velocity gradients

Velocity gradients associated with

- Turbulence
- Hydrodynamic instability

Turbulence-Flame Interactions

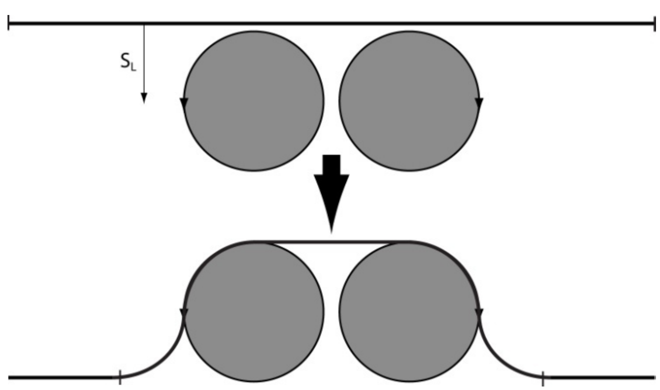
Thought experiment:

- What are the effects of a purely vortical or strain-rate flow field
- Flame is an infinitely long freely propagating surface

<u>Vorticity (no strain-rate)</u>

Solid body rotation

Configure in canonical manner



<u>Strain-rate (no vorticity)</u>

Counter-flow geometry

Laminar flamelet concepts