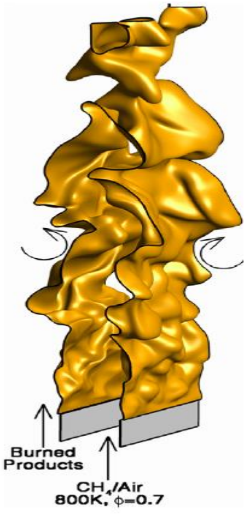
Tuesday: Kilohertz PLIF, PIV measurements

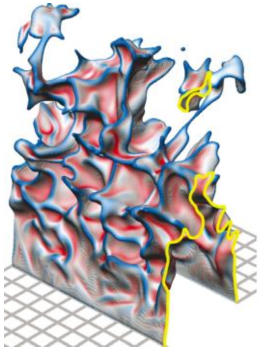
Turbulent Combustion

Experiments and Fundamental Models

J. F. Driscoll, University of Michigan



R. Sankaran,
E. Hawkes,
Jackie Chen,
T. Lu, C. K. Law
premixed



Bell, Day,
Driscoll
"corrugated"
premixed

Outline for the week

Mon: **Physical concepts** faster mixing, faster propagation, optimize liftoff, flame surface density, reaction rate, PDF

Tues**:** **Kilohertz PLIF, PIV measurements of flame structure** - to assess models

Wed: **Non-Premixed and Premixed flames** - measurements, models
gas turbine example

Thurs: **Partially premixed flames -** and some examples

Fri: **Future challenges:** Combustion Instabilities (Growl) , Extinction

Outline for Tuesday

1. **Canonical experiments**
2. **PLIF and KHz PLIF - of reaction layer structure** – Borghi regime diagram
3. **Kilohertz PIV movies of vorticity** - flame-eddy interactions
4. **Kilohertz PLIF -** movies of flame surface density to assess models of combustion instabilities, spectra, phase angles

Canonical Non-premixed flames

1. Turbulent Jet flame   (Sandia Flame D)

2. Jet in Co-Flow (Cabra burner)

3. Jet in Cross flow (JICF)

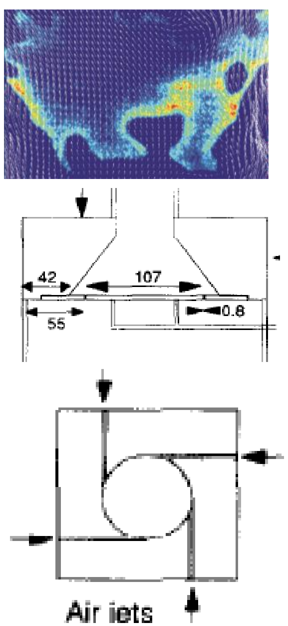
4. Gaseous Fuel Jet Surrounded by Swirling Air = Gas Turbine-Like

5. Spray flame – surrounded by swirling air = Gas Turbine-Like

Canonical premixed turbulent flames

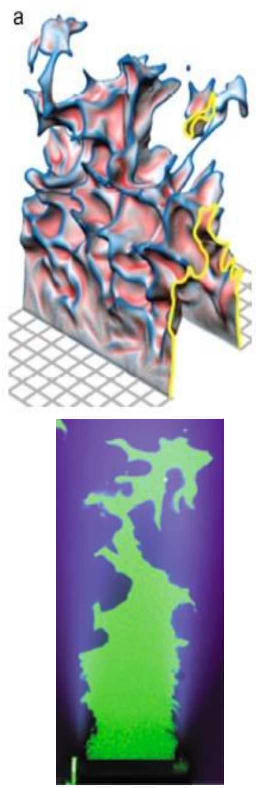
Low swirl

RK Cheng
PROCI 31
3155



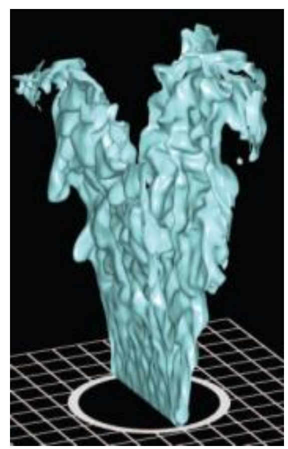
Slot Bunsen

Driscoll, Bell
PROCI 31, 1299



V-Flame

Gulder
Comb Flame
162, 1422

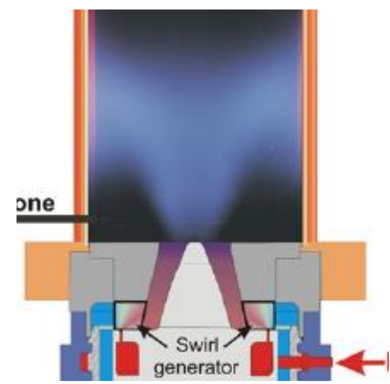


Piloted jet flame

Dunn, Masri
Flow Turb Comb
85, 621

Premixed Gas Turbine-like Swirl flame

Meier, DLR
Precinsta burner
Comb Flame
150, 2

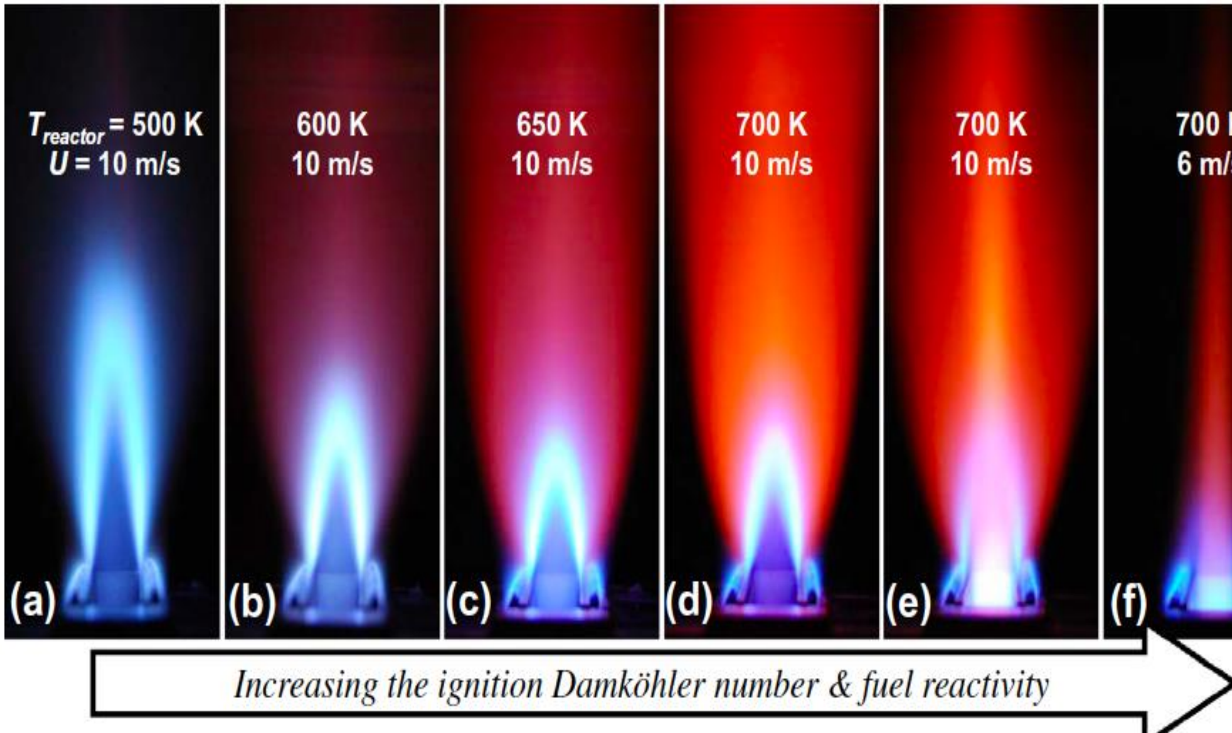


“Canonical premixed flames” - have been modeled

	type	experiments			DNS	LES	
1	low swirl	Berkeley	Cheng Shepherd	PIV, OH		Strakey, Pitsch	ThckFlm, G-eqn
2	low swirl	Lund	Alden Dreizler	PIV, T		Bai, Fureby	G-eqn, PaSR
3	2-D Slot Bunsen	Michigan	Driscoll Steinberg	PIV, CH	Grcar, Day		
4	2-D Slot Bunsen	none	(highly preheated)	none	JH Chen		
5	V-flame	Berkeley	Cheng Shepherd	PIV, T	Grcar, Day	Duwig	flamelet
6	V-flame	Hannover	Dinkelacker	PIV, T	Swamin.		
7	Bluff Body	FOI/Volvo	Volvo/Fureby	OH		Fureby	PaSR
8	jet, shear	Sydney	Dunn Masri	Raman,q			
9	jet, shear	Lund	Alden	CH, OH		Bai, Fureby	G-eqn, PaSR
10	jet, shear	Aachen	YC Chen, Peters	LDV,Raman		Pitsch	G-eqn
11	high swirl, gas t.	Darmstadt	Dreizler	PIV, Raman		Janicka	G-eqn
12	high swirl, gas t.	Karlsruhe	Siemens, PPC	LDV		Poinsot	ThickFlm
13	high swirl, gas t.	GE LM6000	Mongia, PPC			Menon, Fureby	LEM, PaSR

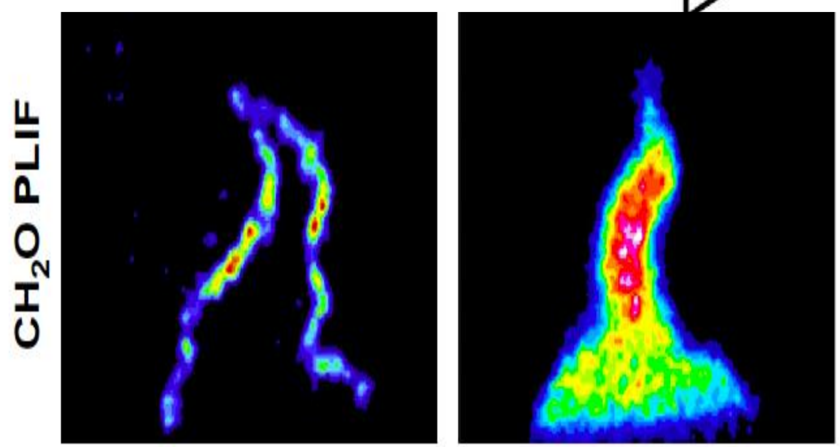
Ex.: Bunsen with Preheated reactants:

Yiguang Ju, SH Won, B Windom, B Jiang, Princeton U.



four regimes:

- chemically-frozen-flow,
- low-temperature-ignition,
- transitional, and
- high-temperature-ignition



Diagnostics: Laser sheet imaging - of flame structure

Mie scattering – oil drops are in reactants but not products

Rayleigh scattering – temperature field = cold in reactants, hot in products

PIV – velocity field imaging – abrupt change at flame front

OH PLIF - uniform OH in products, no OH in reactants

CH PLIF - thin layer marks chemical reaction layer

Formaldehyde PLIF - marks preheat zone

OH-Formaldehyde overlap – thin layer that marks reaction layer

Raman scattering - primarily a point measurement, will work along a 2 mm line but not for imaging

CARS - primarily a point measurement will work along a 2 mm line, but not for imaging

Mie and Rayleigh scattering

Mie – commercial kerosene oil drop atomizer adds 10 micron drops that evaporate at flame boundary, illuminate with any color laser sheet

Rayleigh - any color laser sheet, record with intensified camera light scattered from molecules

- must eliminate any dust or soot
- must eliminate any scattering off walls, windows

$$S_{Rayleigh} = [n_{N2}\,\sigma_{N2} + n_{fuel}\,\sigma_{fuel} + n_{O2}\,\sigma_{O2} + n_{CO2}\,\sigma_{CO2} + n_{H2O}\,\sigma_{H2O}]\;\; I_{laser}\, constant$$

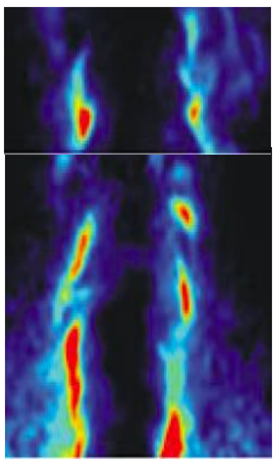
where S = signal, n is number density and σ is Rayleigh scattering cross section. If a fuel is chosen that has the same cross section as N_2, then, approximately, all cross sections are nearly equal so:

$$S_{Rayleigh} = n\;\; \sigma_{N2}\, I_{laser} = \left[\frac{p}{RT}\right] \sigma_{N2}\;\; I_{laser}$$

Rayleigh signal is a measure of gas temperature

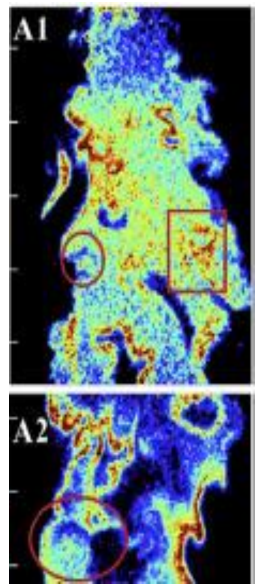
Challenge - two ways to image reaction zones

OH and formal-
dehyde overlap



Dunn, Masri
Bilger, Barlow
Flow, Turb. 85
(broken)

CH PLIF



Alden, Bai,
Bo Zhou, Lund
PROCI 35
(distributed)

CH PLIF

Mastorakos, Meier,
Gas Turbine
Model Combustor
(flamelet)

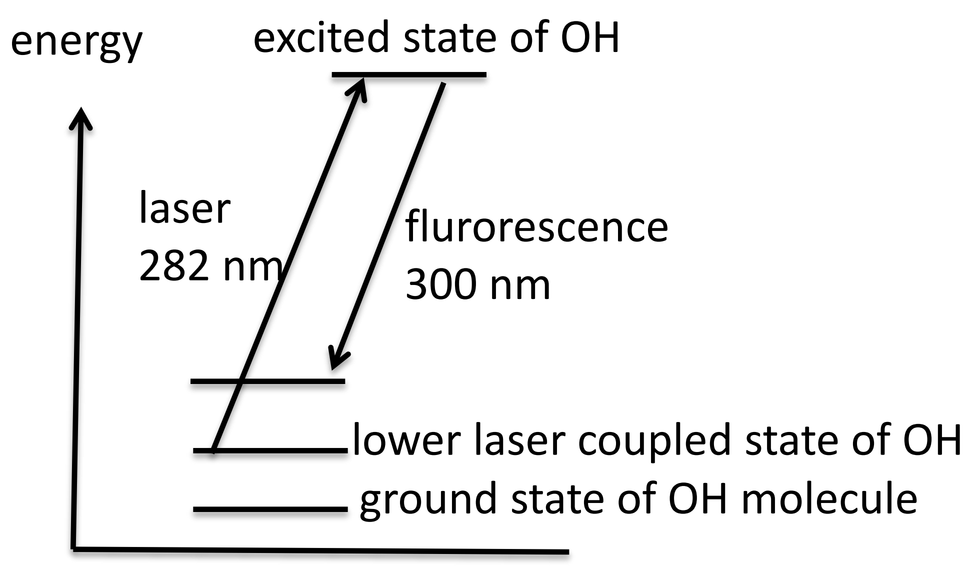
PLIF = planar laser induced fluorescence

Fluorescence = (absorption of laser light) + (spontaneous emission of light at a longer wavelength than the laser light)

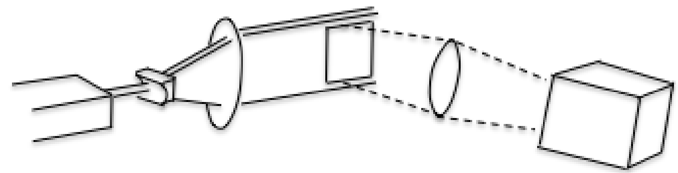
OH absorbs laser light at 282 nm (in UV), emits fluorescence at 300-400 nm

<u>Species that fluoresce</u>

OH 282 nm
CH 390 nm
Formaldehyde 355 nm
NO 226 nm
NO_2 430 nm
Acetone 266 nm
Gasoline 270 nm
CO 230 nm
Iodine 514 nm
Ammonia 2000 nm
O 113 nm



PLIF = planar laser induced fluorescence



Rate of molecules Excited to excited State by absorption = Rate of molecules Lost from excited state by spontaneous emission + Rate of molecules lost from excited state by collisional quenching

$$I_\nu \; n_{OH} \; f \, B_{12} \;=\; n^*_{OH} \;\; A_{21} + n^*_{OH} \, Q \quad (1)$$

Define signal from OH as:

$$S_{OH} \;=\; n^*_{OH} \;\; A_{21} \, c_1 \quad (2)$$

Solve Eq. (1) for n_{OH}* and plug into Eq. (2) to get:

n_{OH} = number density OH
B_{12} = absorption const.
A_{21} = emission const.
Q = quenching factor
c_1 = a constant
I_ν = laser intensity

$$S_{OH} \;=\; I_\nu \;\; [n_{OH} \, f] \; V \;\; B_{12} \, c_1 \, A_{21} \, (A_{21} + Q)^{-1}$$

Signal = laser intensity * number density of OH molecules
in lower laser coupled state
f = Boltzmann fraction

PLIF signal

Mole fraction of OH: $X_{OH} = n_{OH} / n$ total number density: $n = p/(k\,T)$

Laser volume $V = \Delta x^2 \; \delta_{laser}$

$$S_{OH} = X_{OH} * \left[\frac{p}{T} \;\; E_L \;\; \frac{(\Delta x)^2}{H}\right]\left[\frac{f\,A_{21}}{Q+A_{21}}\right] \frac{const}{(FN)^2}$$

OH PLIF signal per camera pixel

OH mole fraction

laser energy per pulse

pixel size^2/ height of field of view

lens f-number^2

To maximize fluorescence signal S_{OH}, you can:

bin the pixels and make pixel size Δx larger, but you lose spatial resolution
reduce the height (H) of the field of view – more energy/volume of laser sheet
use small FN lens = larger diameter lens, FN = lens focal length / diameter of lens
increase laser energy per pulse E_L
increase gas pressure p

Some limitations to PLIF diagnostics

The molecule of interest must absorb at a frequency of an available laser

(Water, CO_2, O_2, N_2, H_2 do not fluoresce, H and O are very difficult to fluoresce)

Molecule must emit fluorescence in visible or near UV or near IR where we have cameras

Fluorescence wavelength must be separated from fluorescence from other species

Difficult to get quantitative values of mole fraction – must measure quenching factor Q

Flame or soot radiation may create excessive background noise, esp. at high pressure

Must have sufficiently large windows to collect sufficient emitted light

Window glass can fluoresce and cause background noise

Good references on fluorescence diagnostics

Hanson, RK, J. M. Seitzman, P. Paul, Planar Laser-Fluorescence Imaging of Combustion Gases, Appl. Phys. B 50, 441454 (1990)

Ekbreth, A., Laser Diagnostics for Combustion Temperature and Species, Combustion Science & Technology Pub.

Johnson, Raynor Carey. An introduction to molecular spectra

Herzberg, G. Spectra of Diatomic Molecules, Van Nostrand, 1950.

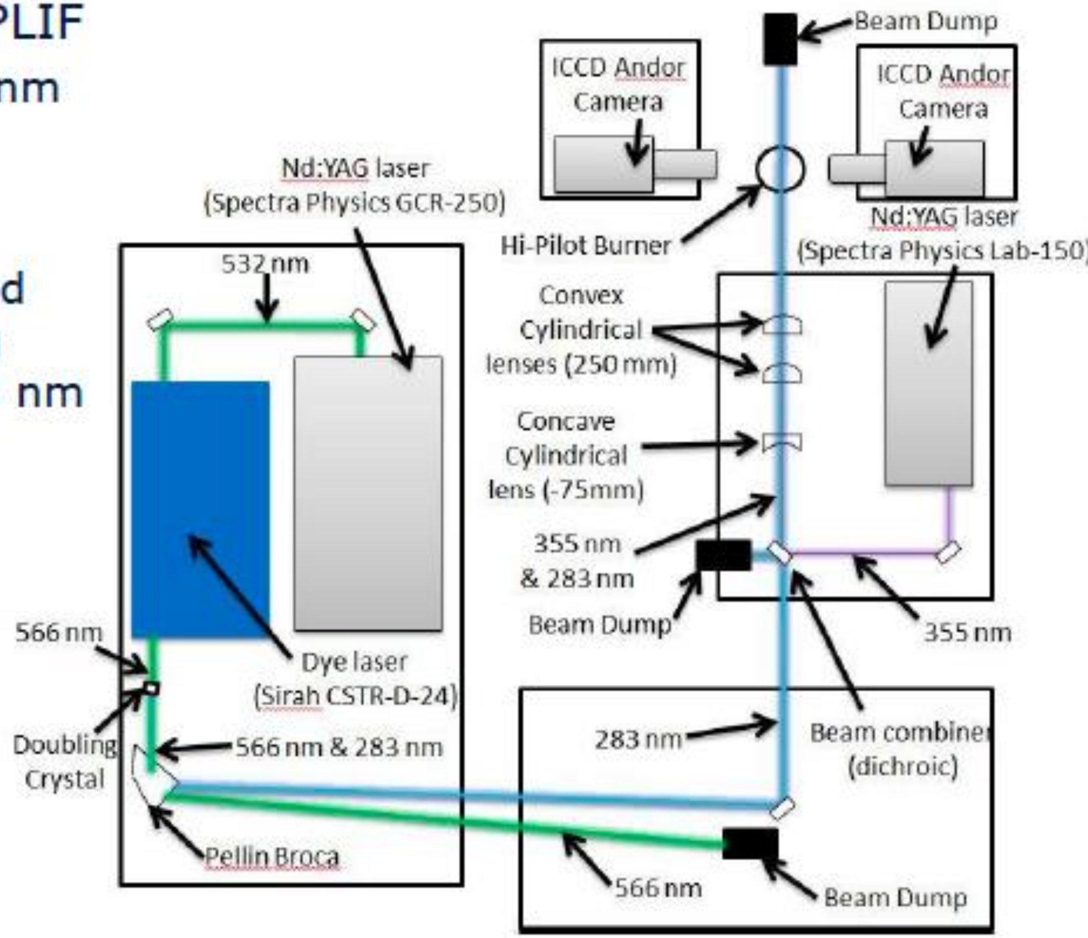
Ayoola B, Balachandran R, Frank J, Mastorakos E. Spatially resolved heat release measurements in turbulent flames. Comb. Flame 2006; 144: 1-16.

Marcus Alden, Xue-Song, Bai, Bo Zhou, Lund U., Comb. Flame 162, 2937, 2015

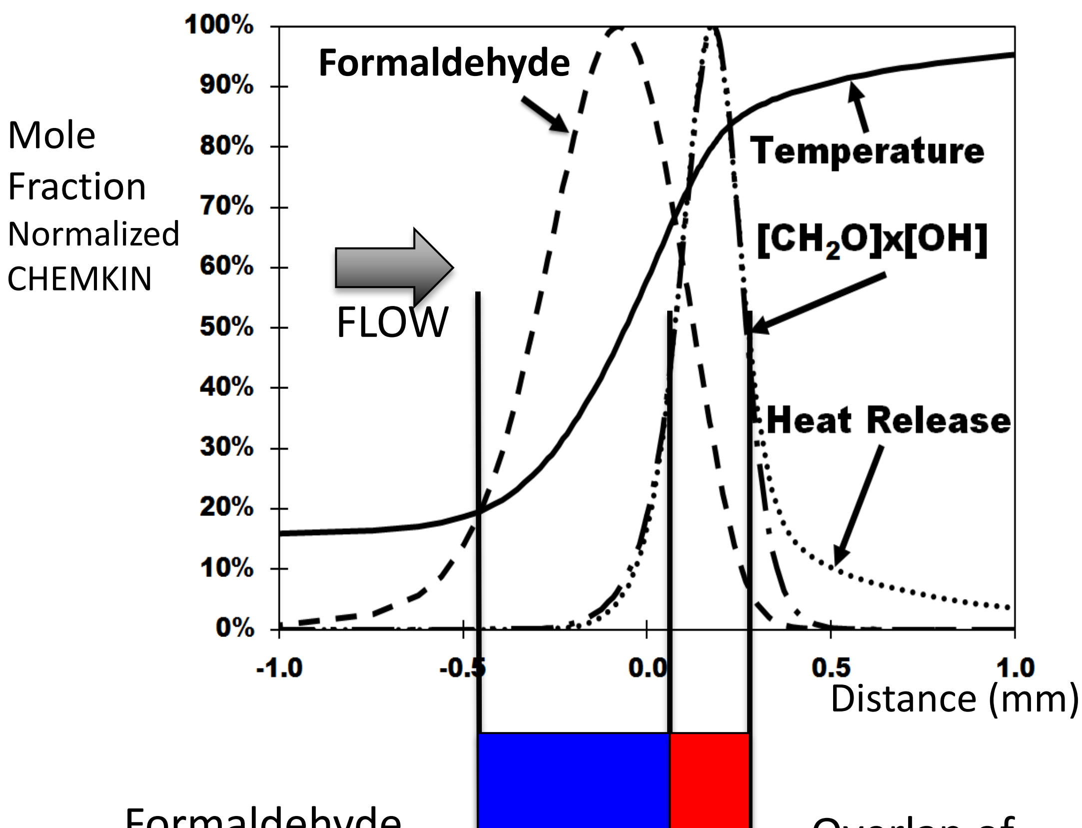
Wolfgang Meier, Adam Steinberg, et al. (kilohertz), Comb. Flame 157, 2250

OH, Formaldehyde and CH PLIF diagnostics

- Formaldehyde (CH_2O) PLIF
  - Nd:YAG outputs 355 nm
- OH PLIF
  - Sirah dye laser pumped with 532 nm, doubling crystal produces ~283 nm
- Andor intensified CCD cameras
  - 100 ns gate times
  - 200 ns delay
  - 27 x 36 mm and 13 x 20 mm FOV

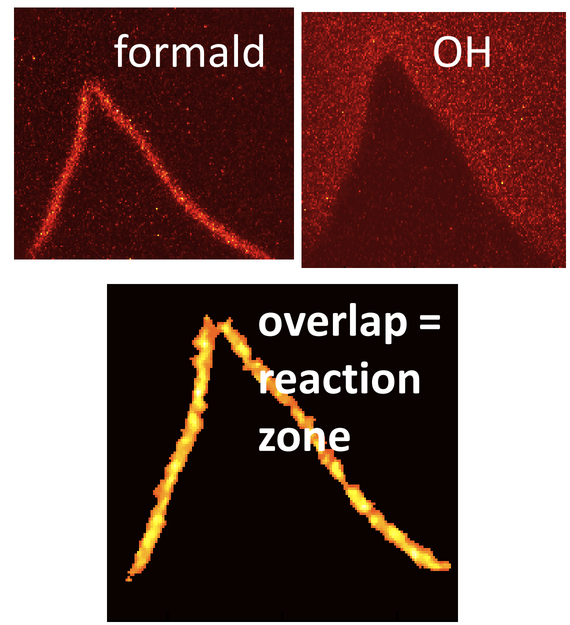


Reaction zone imaged with formaldehyde-OH overlap



Formaldehyde marks the preheat zone

Overlap of formaldehyde- OH marks reaction zone



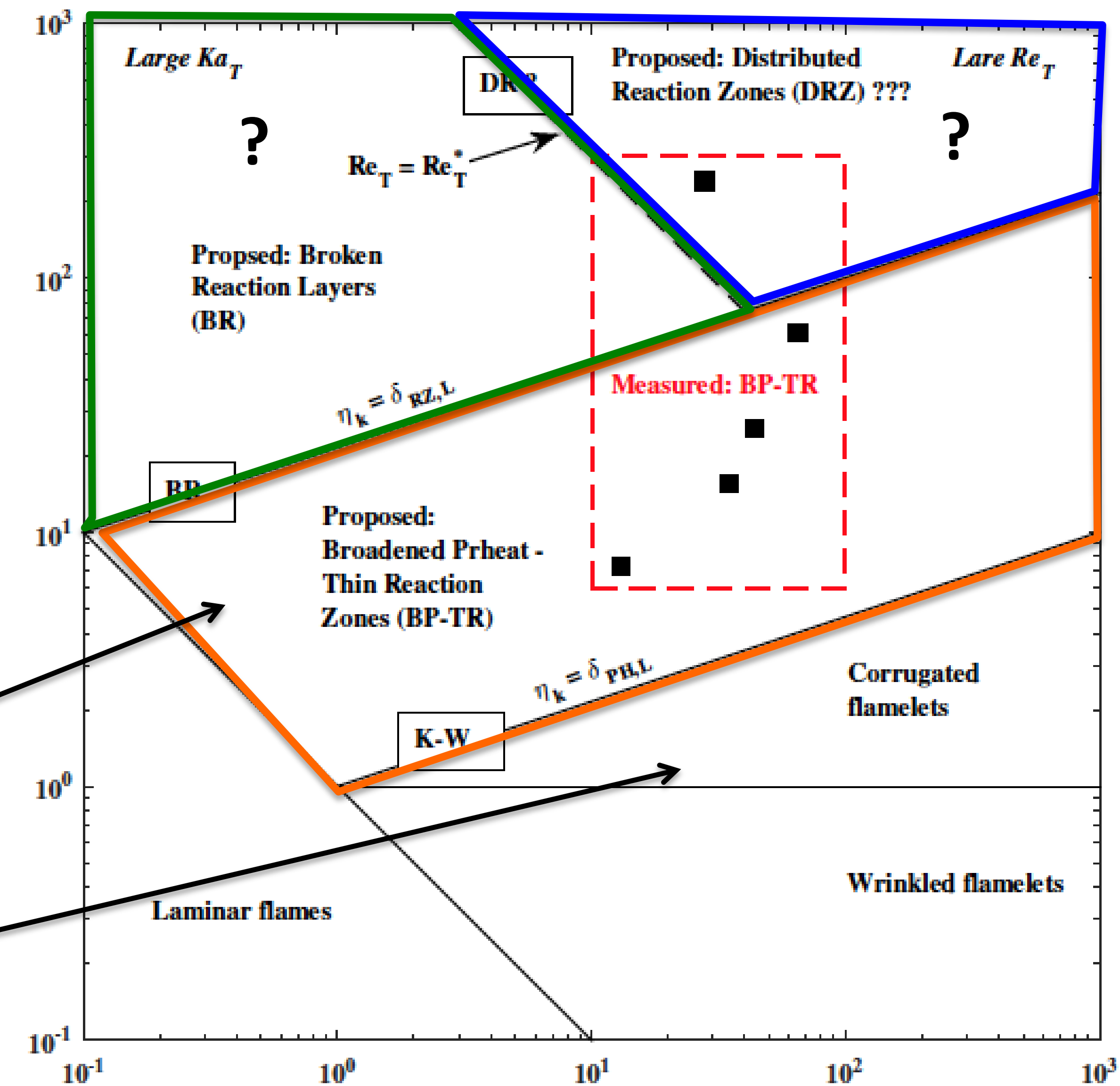
Laminar bunsen flame

Regimes of Premixed Turbulent Combustion (Borghi diagram)

Turbulence Level u'/S_L

Damkohler's second concept

Damkohler's first concept



Integral scale, normalized by flame thickness

Regime boundaries

Klimov-Williams boundary is where $\delta_{PH} = \eta_K$

= where Kolmogorov eddies of size (η_K) fit inside the PREHEAT layer (δ_{PH}) of the flame

They predict: **"BP-TR" = Broadened preheat, thin reaction layers**

Define: Ka = Karlovitz number (Peters) = $(\delta_{RZ} / \eta_K)^2$

so if Ka > 1, Kolmogorov eddies of size (η_K) fit inside reaction zone (δ_{RZ}) of the flame

Peter's predicts Ka > 1 causes **"broken reaction layers"**

Are tiny Kolmogorov eddies strong enough to cause broken layers ? (NO)

We need to know these boundaries because:

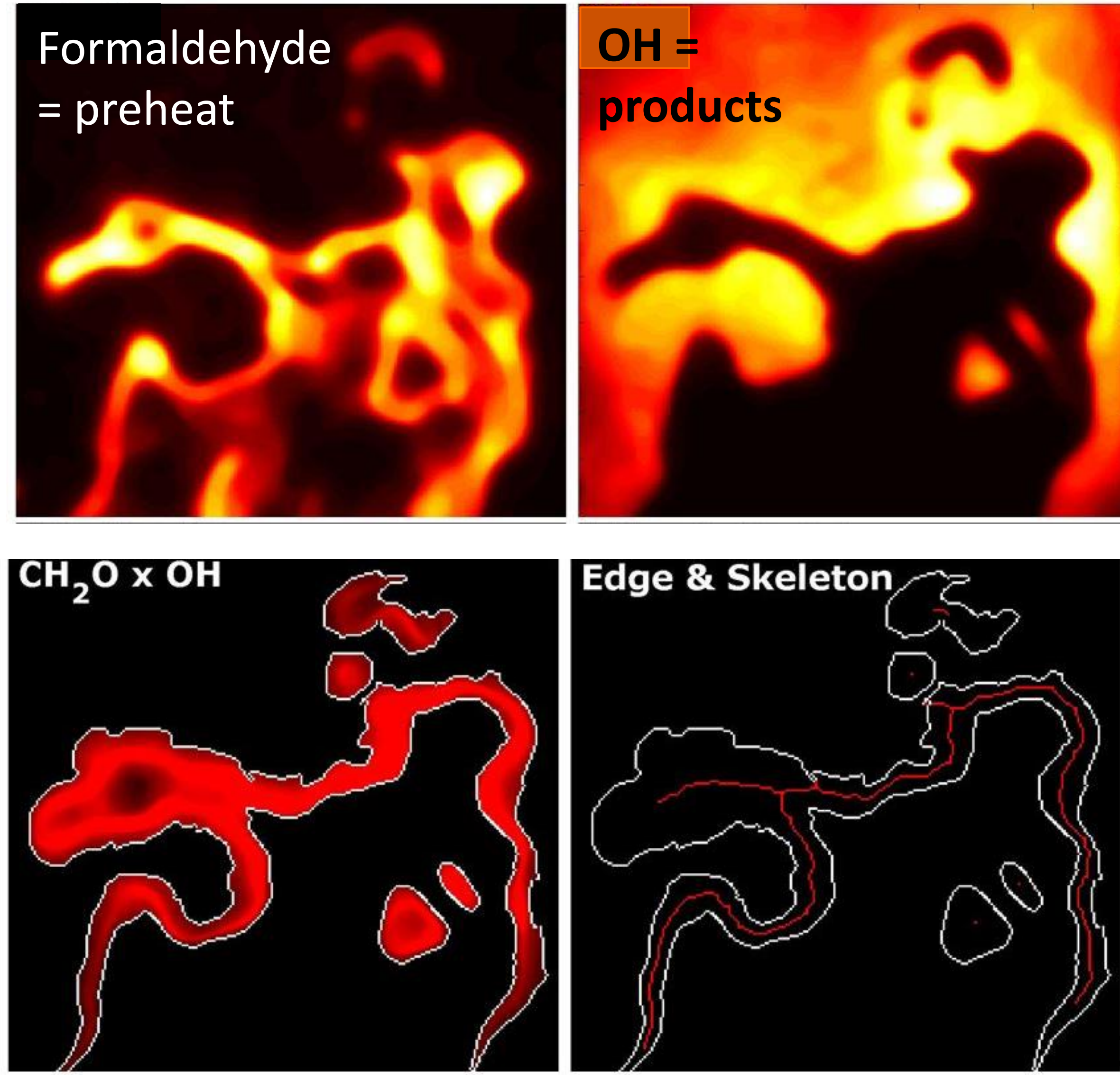
they tell us conditions when the following models are valid or not: the FSD/ thin flamelet model,the TM = thickened flamelet model, DM = distributed reaction models

Reaction layers, Method #1: formaldehyde - OH overlap

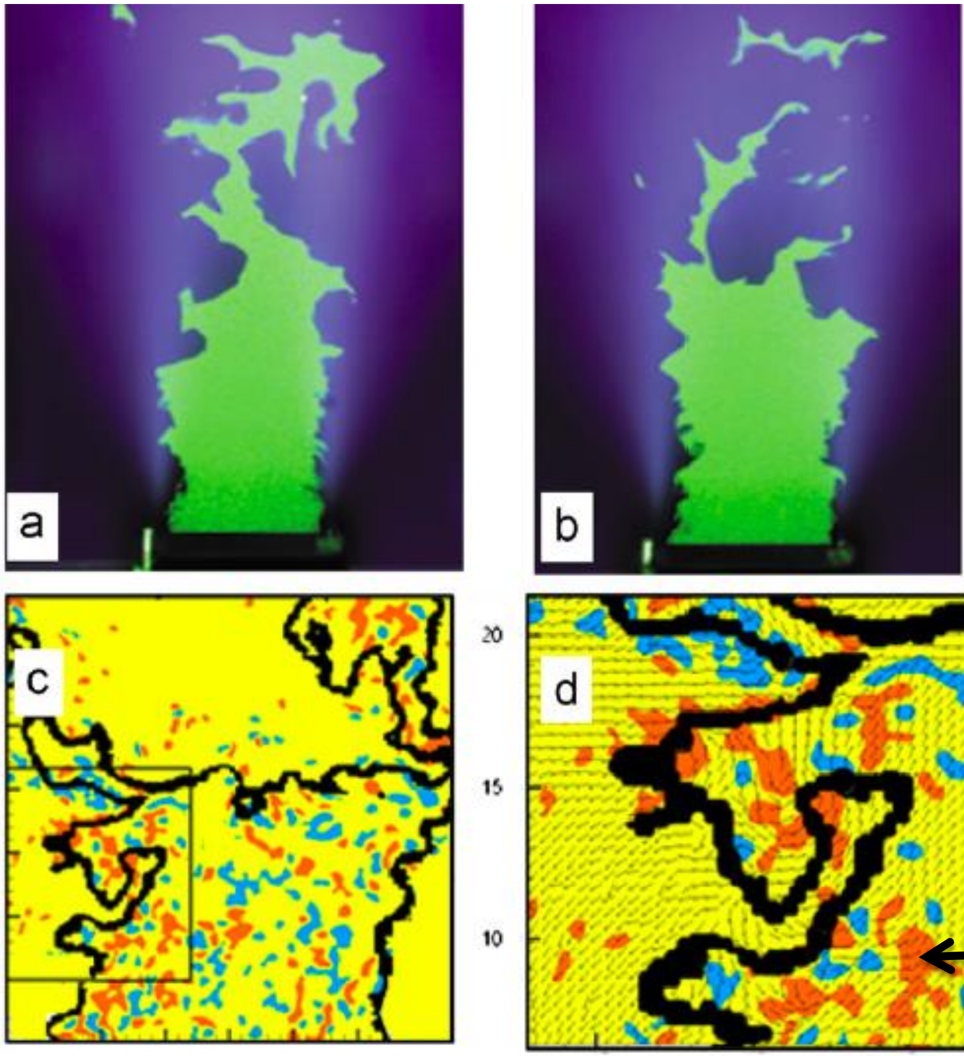
Overlap = reaction zone

distributed

broadened flamelets



Reaction layers, Method #2: CH PLIF



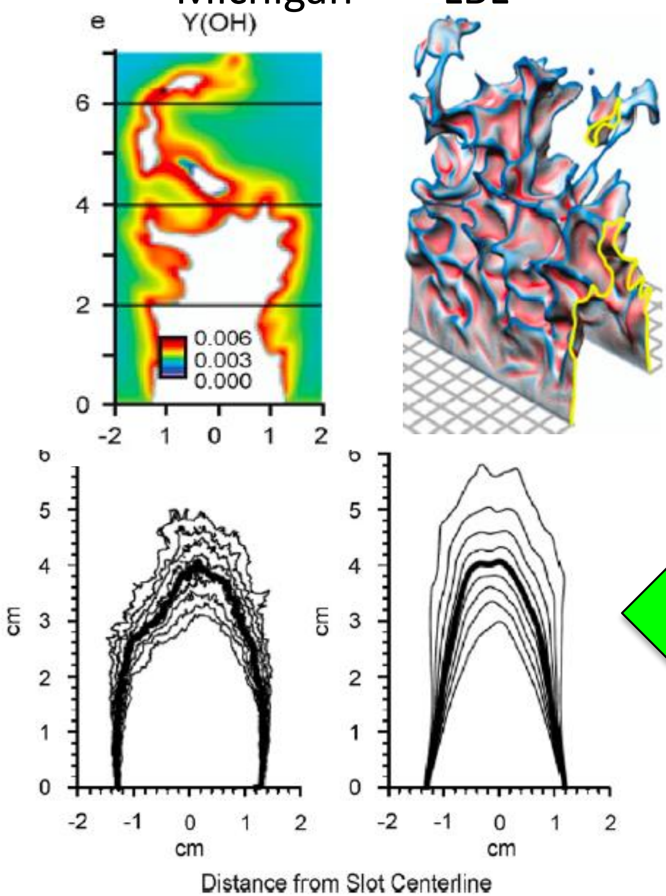
Simultaneous CH – PIV
Carter and Driscoll
Comb Flame

Reaction Layer
= CH PLIF

Vorticity =
eddies

Assess DNS - of Bell (LBL) with experiment of Driscoll, Carter

Experiment	**DNS**
Driscoll, Michigan	Bell, LBL

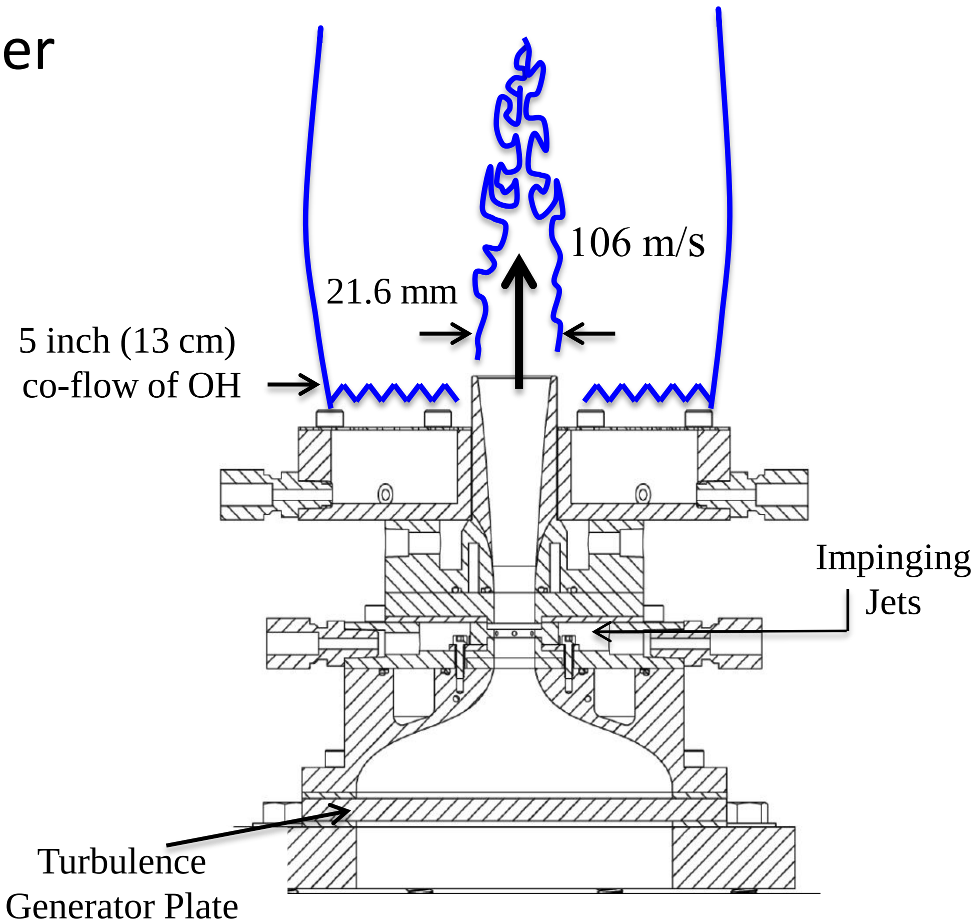


DNS of Bell predicts a height of slot bunsen flam, that agrees with the experiment of Driscoll and Carter, thus DNS yields the measured value of turbulent burning velocity

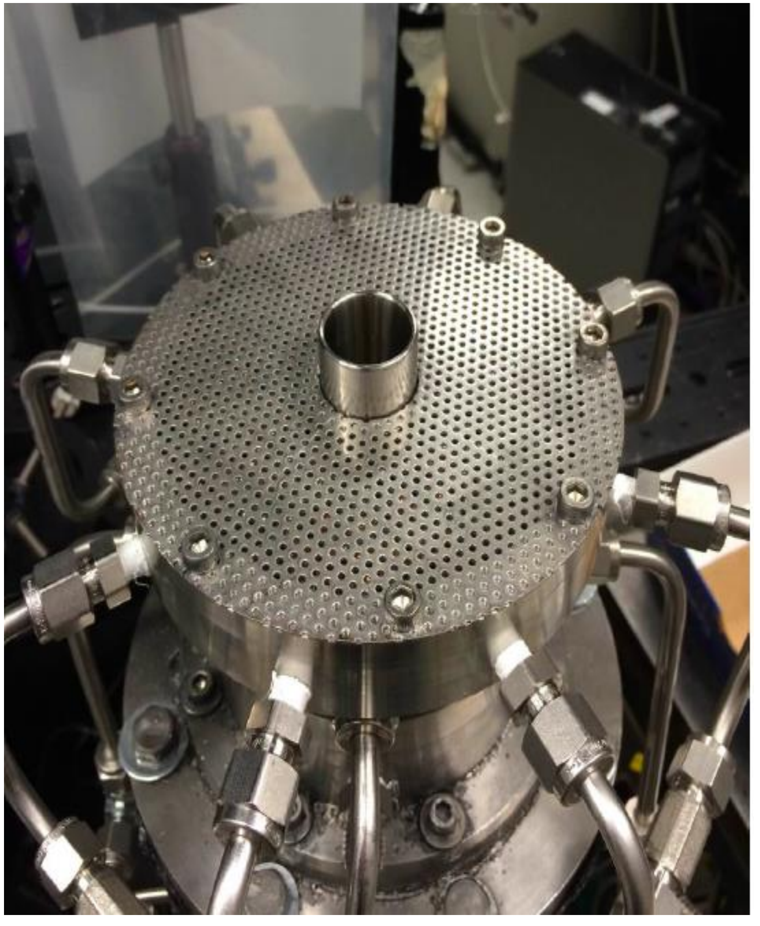
What happens as turbulence level is greatly increased ?
Do reaction layers become broadened, broken, distributed ?

Michigan Hi-Pilot Burner

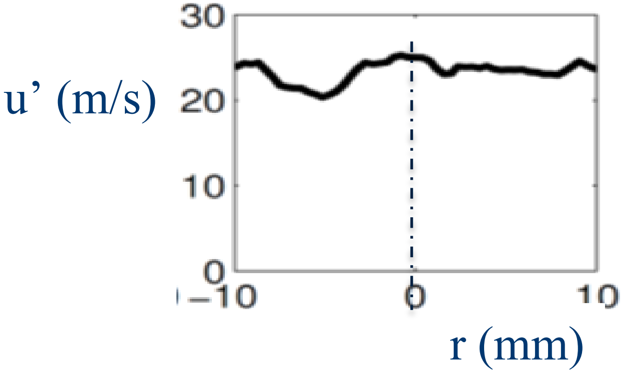
- u'/S_L up to 243
- mean velocity to 78 m/s
- Re_t up to 100,000
- (preheat up to 1000 K)
- Methane, Butane, JP-8 at
  ER = 0.75, 1.05



Hot co-flow of combustion products –
prevents outside air from being entrained

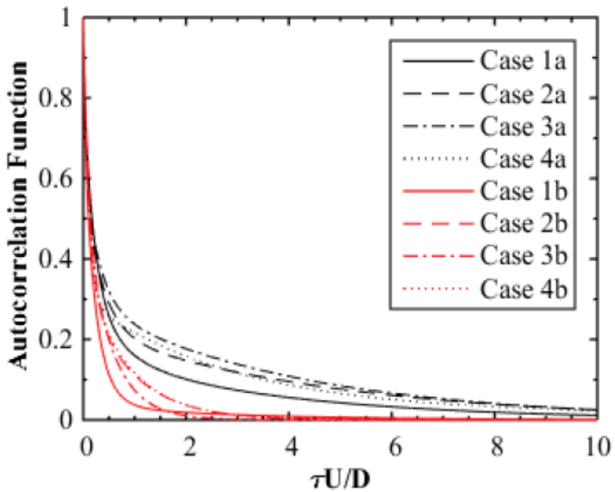


Turbulence is uniform across burner exit

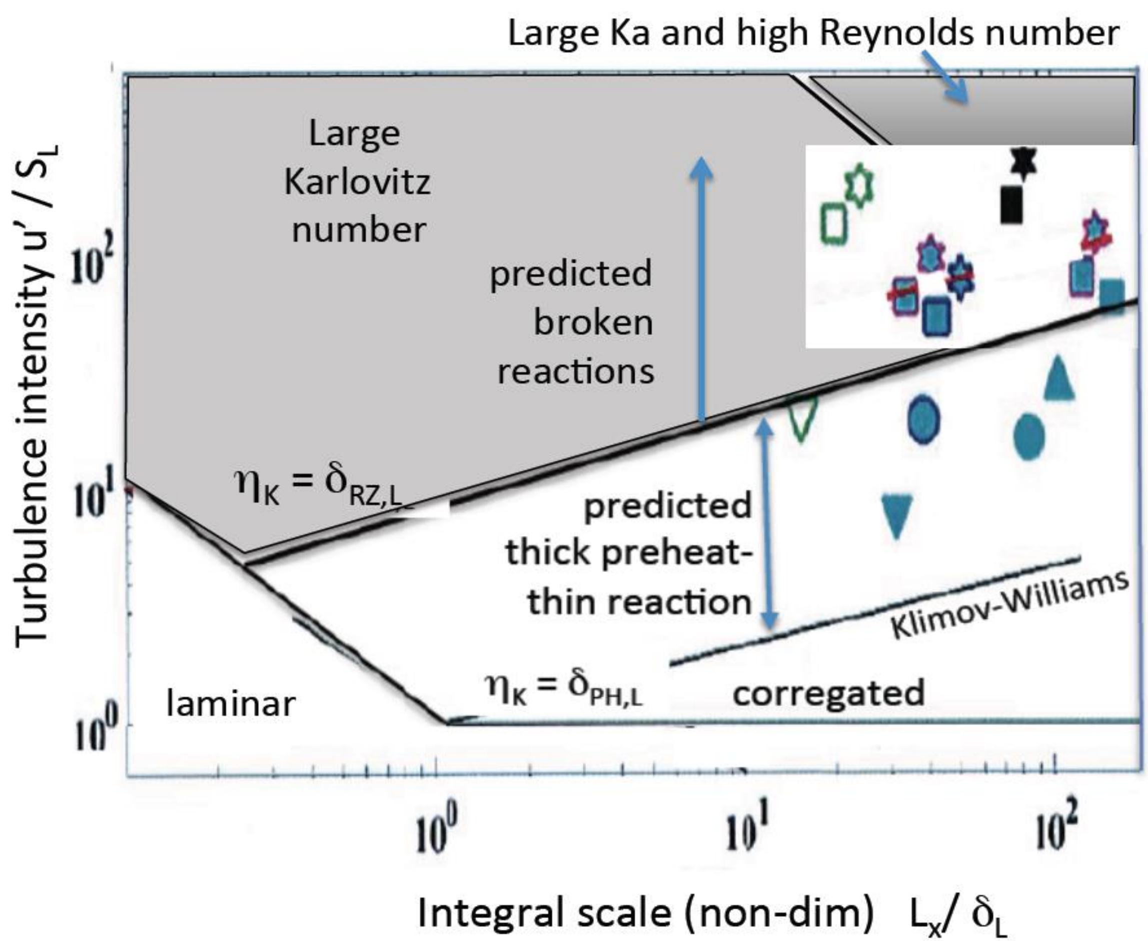


Turbulence levels and integral scales are large

Case	ϕ	U_0 (m/s)	u' (m/s)	λ_I (mm)	Re_T	Da_T	Ka_T	u'/S_L	$\lambda/\delta_{PH,L}$
2a	1.05	14	2.9	7.5	1,400	25.4	4.7	7.5	31
3a	1.05	32	6.0	20	7,900	33.1	8.5	15	84
4a	1.05	44	10	25	17,000	24.6	16.5	26	105
5a	1.05	64	24	37	58,000	15.1	50.4	62	154
6a	0.65	78	37	41	99,000	1.7	503	243	83



Hi-Pilot Conditions on Borghi Plot



Hi-Pilot Burner

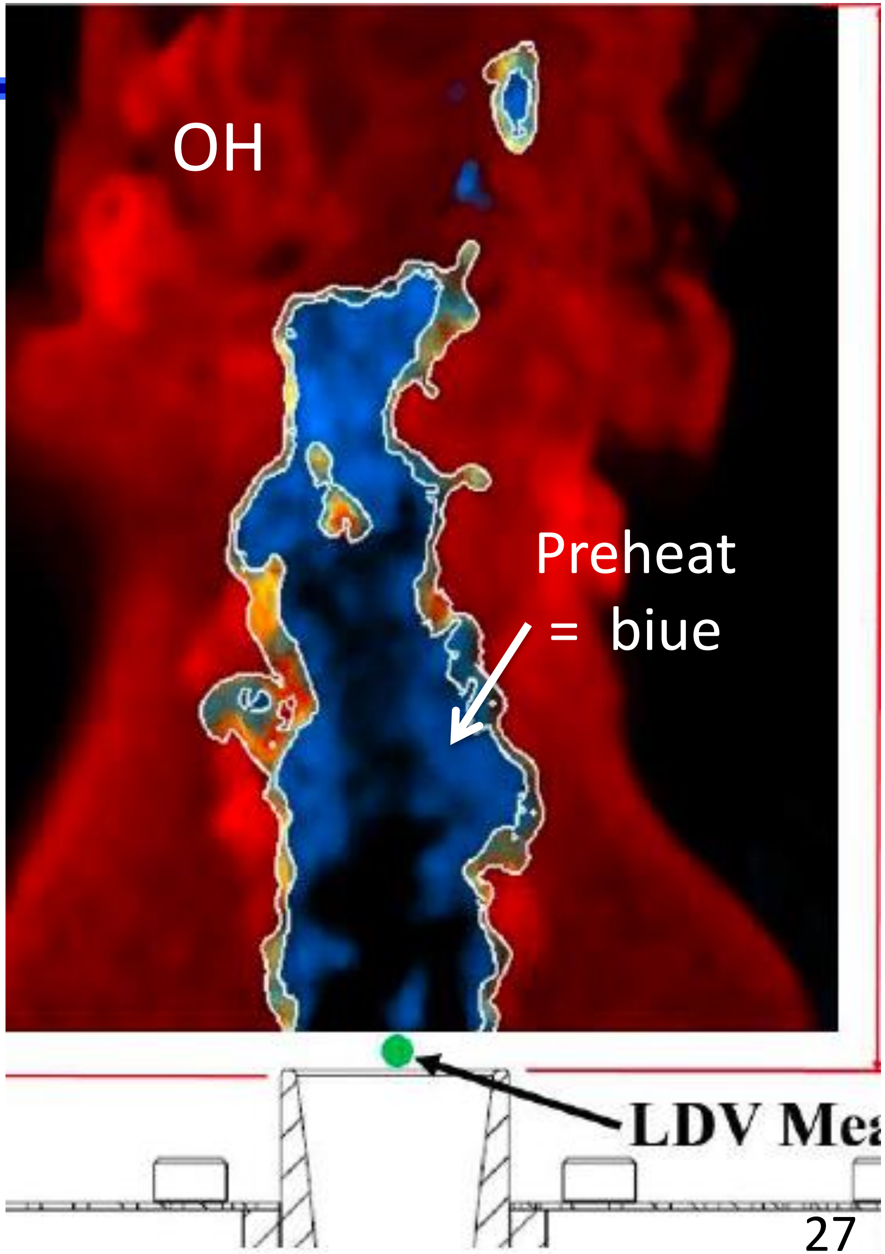
Thickness of Reaction zone

Thickness of Preheat zone

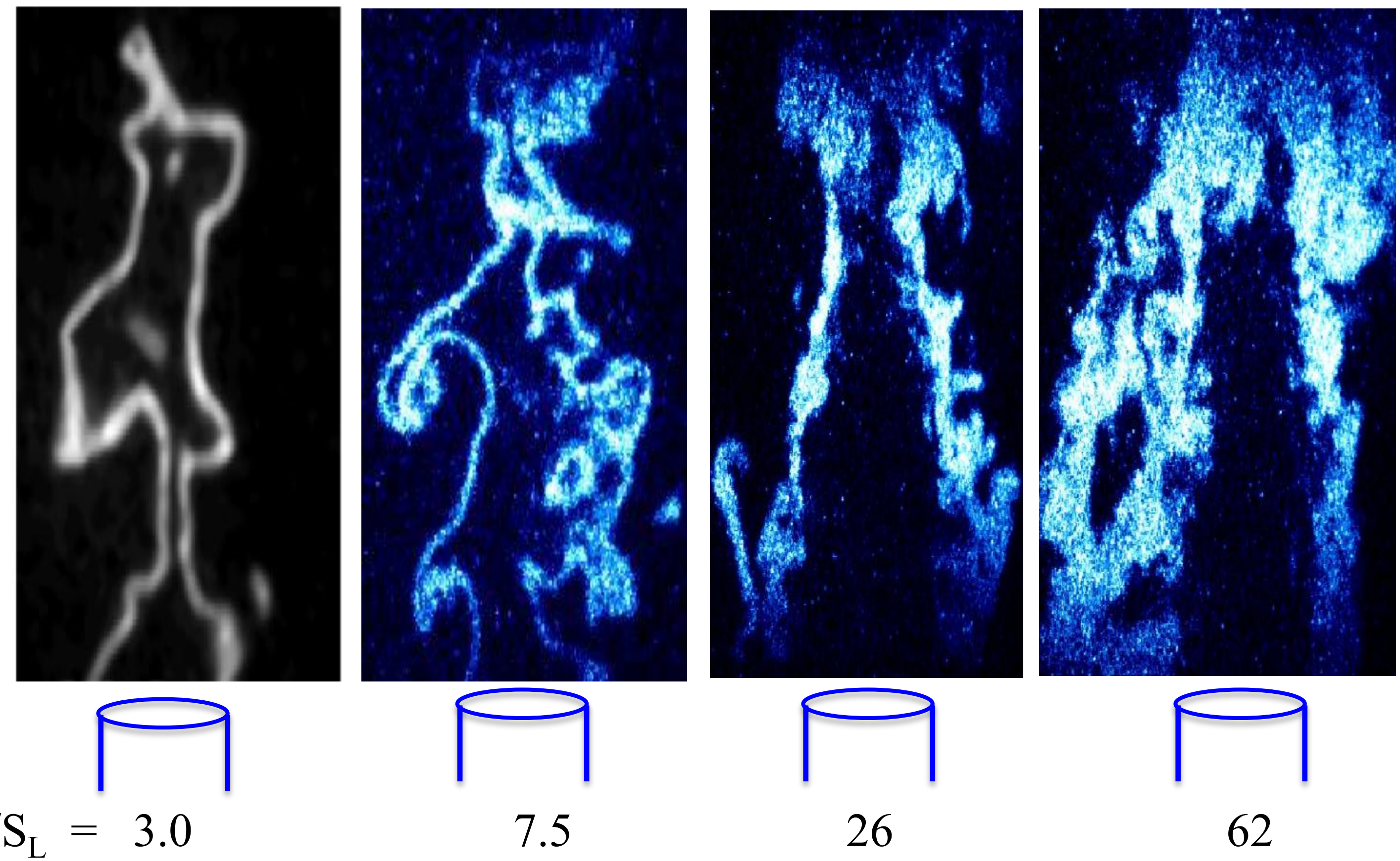
Fraction that is distributed

Fraction of local extinction

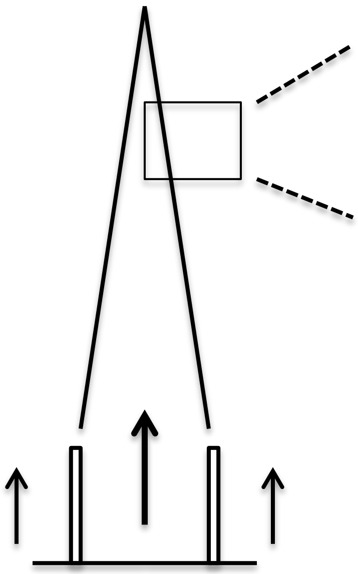
Boundaries of regimes

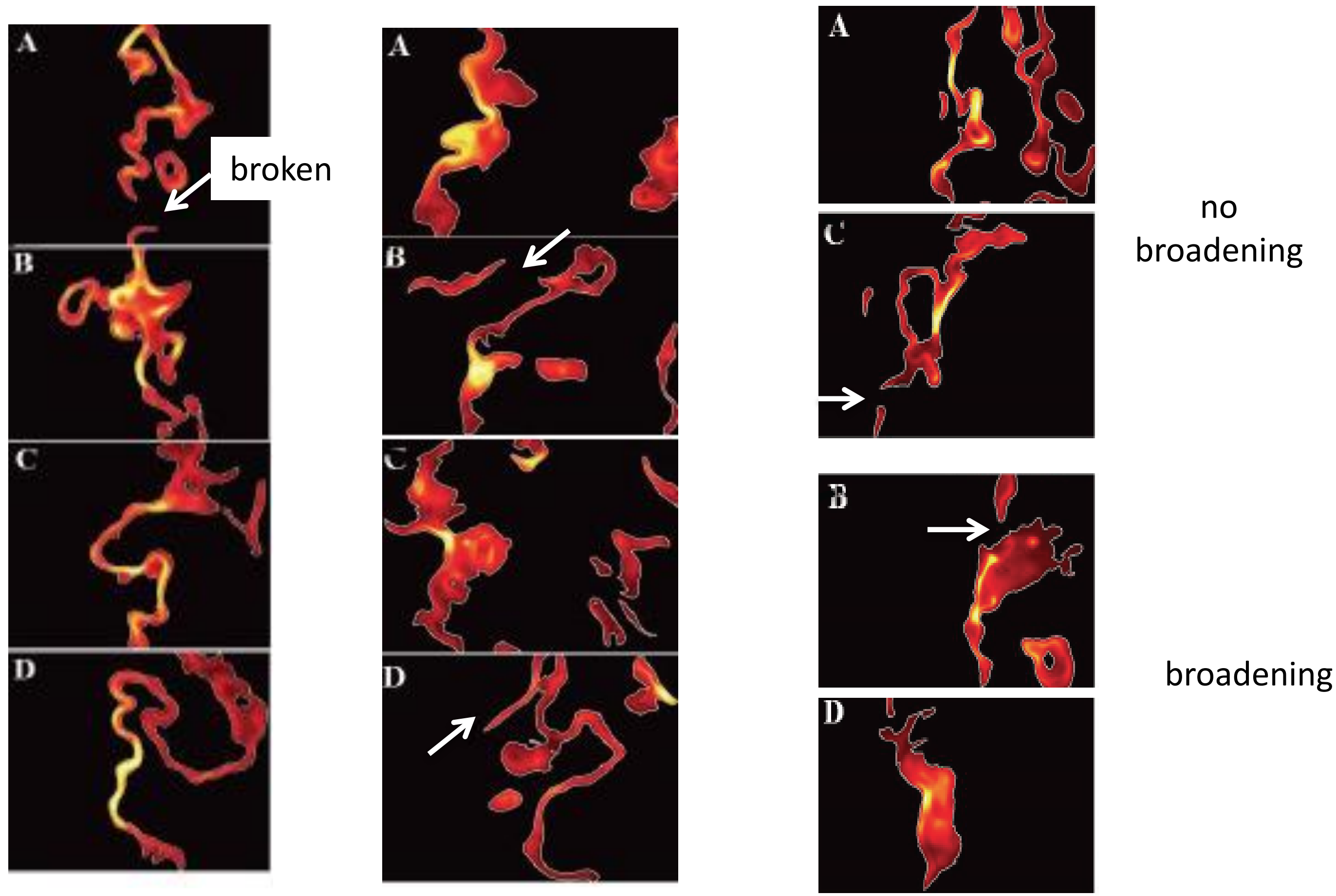


Preheat zone – what does it look like ? formaldehyde



Reaction Layers (from overlap method)



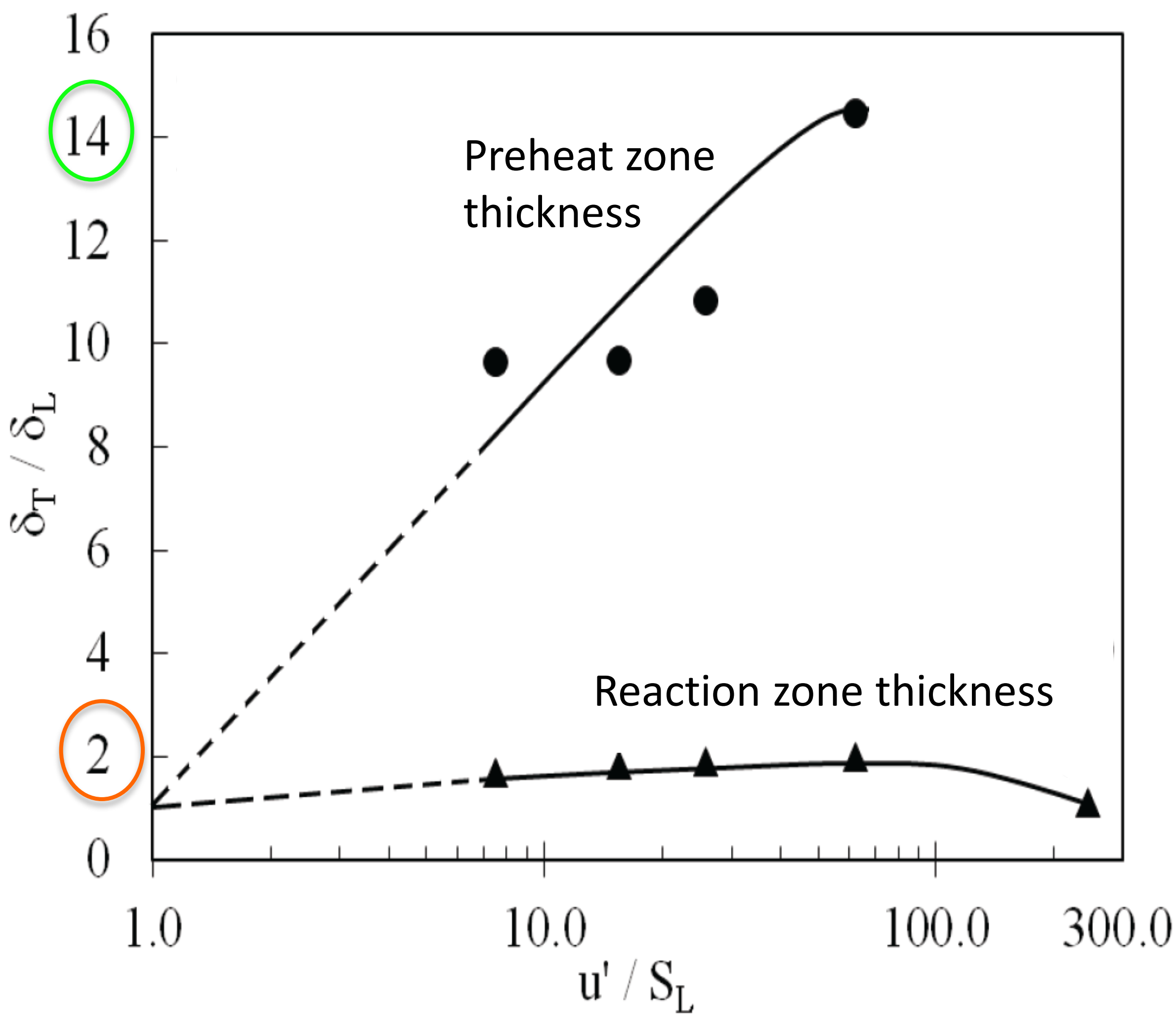


Case 2 $u'/S_L = 7.5$

Case 3 $u'/S_L = 15$

Case 4 $u'/S_L = 26$

Preheat Zone is Thickened - Reaction Zone is not

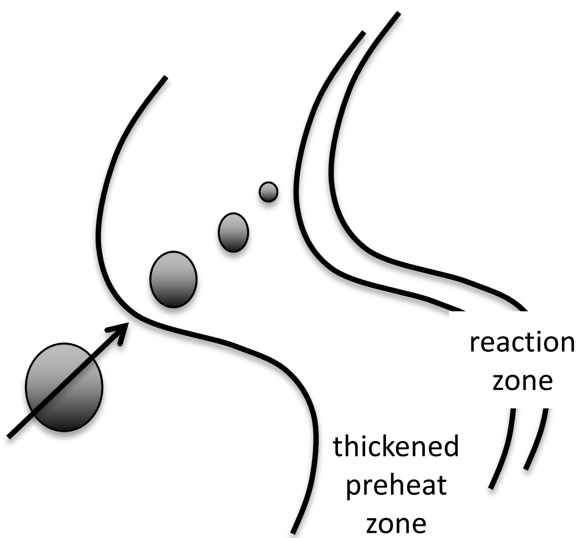


$\delta_{PH,L}$ = 0.35 mm
$\delta_{RZ,L}$ = 0.18 mm

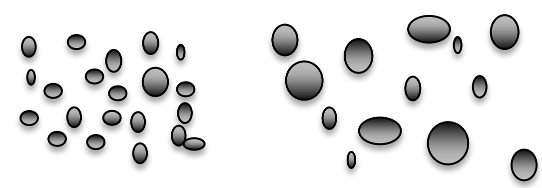
Preheat is 14 X broader, reaction zone only 2 X broader

thickening of preheat zones → eddies travel long distance through hot, viscous, preheat gases → eddies too weak to thicken reaction zone ↓

do larger integral scale eddies survive passage ?



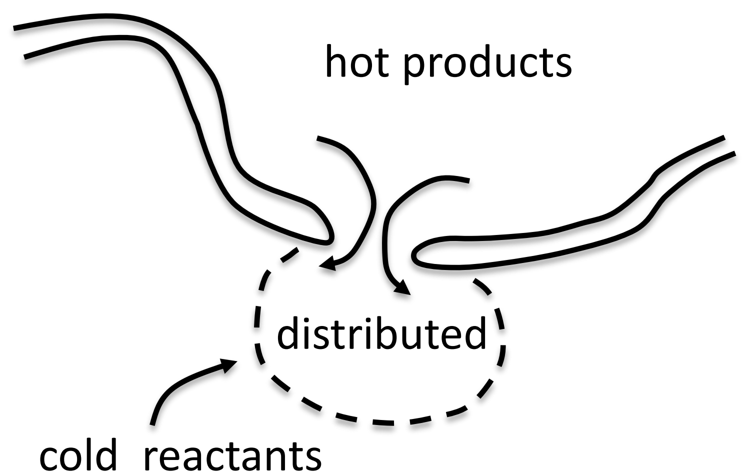
Stretch Efficiency Function - Poinsot



Are "broken" and "distributed" regimes related ?

broken - flamelets allows reactants to mix with products, promotes:

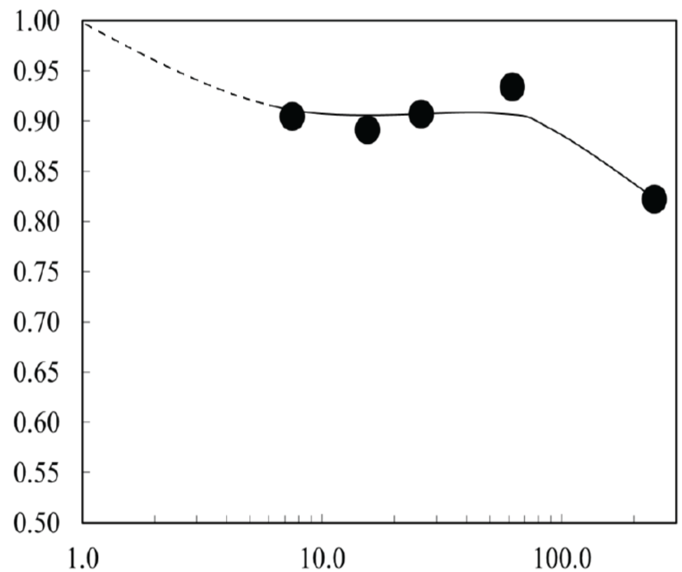
distributed - reactions ?



Burning fraction - always above 82% for homogeneous products

Burning Fraction

fraction of OH boundary that has reaction



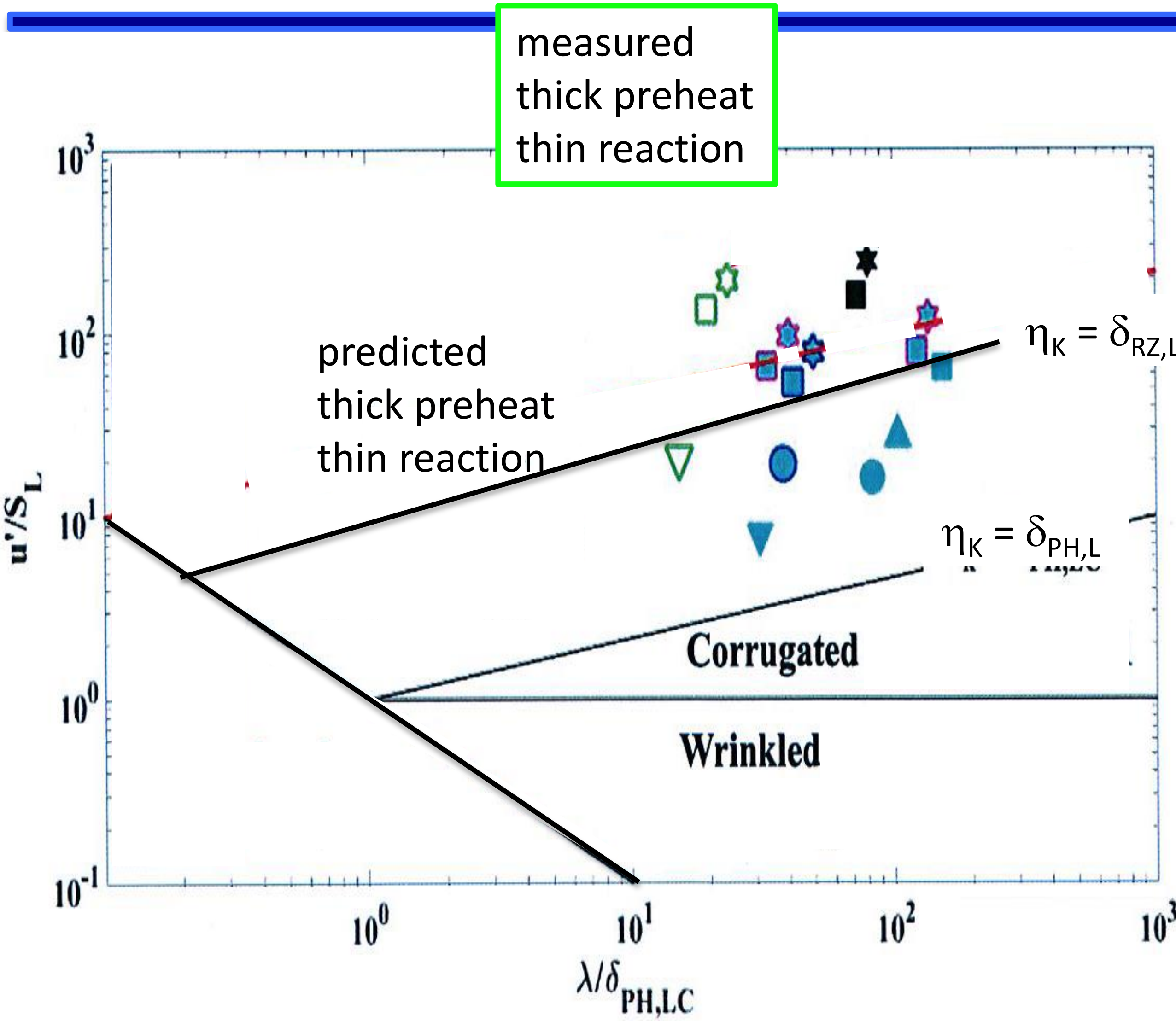
u' / S_L

Ten times the turbulence level of previous studies of this type

→ "broken regime" - is not possible if products are kept homogeneous and hot

"broken regime" IS possible if products are stratified (for this expt.)

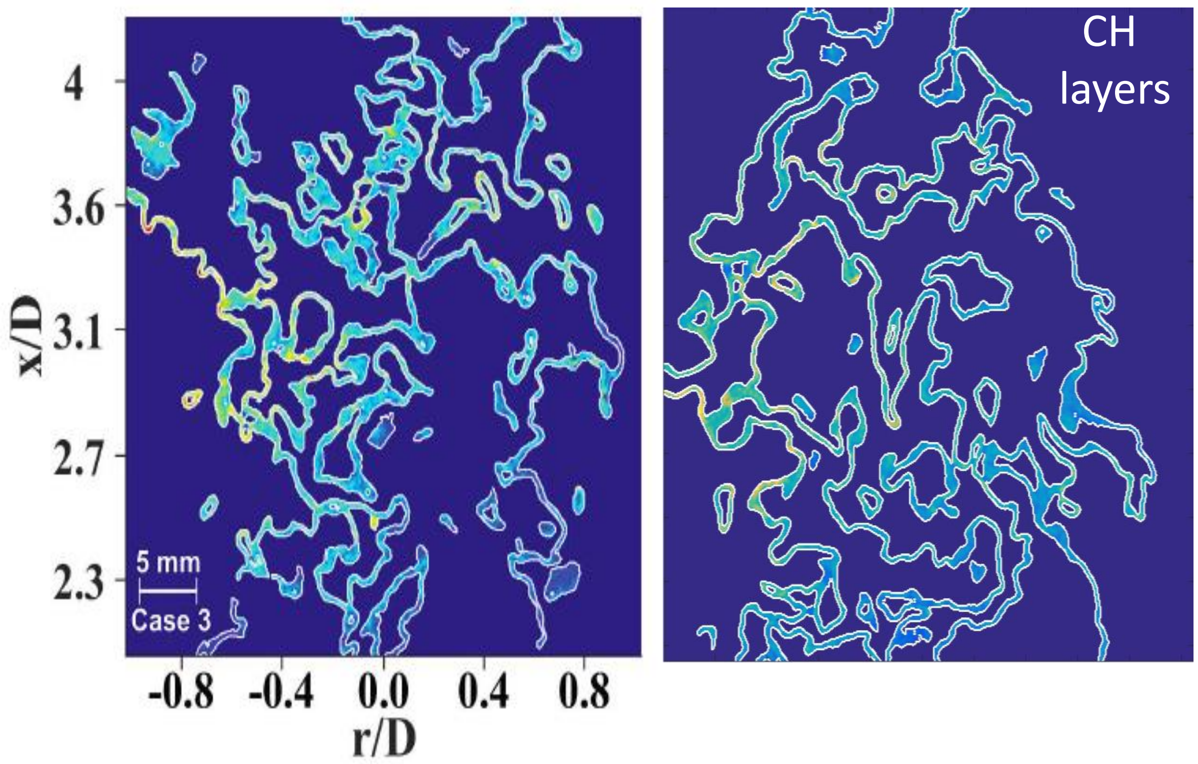
Measured thick preheat/thin reaction zone is larger than predicted



predicted to be broken but are not broken

Peters boundary does not agree with our measurements

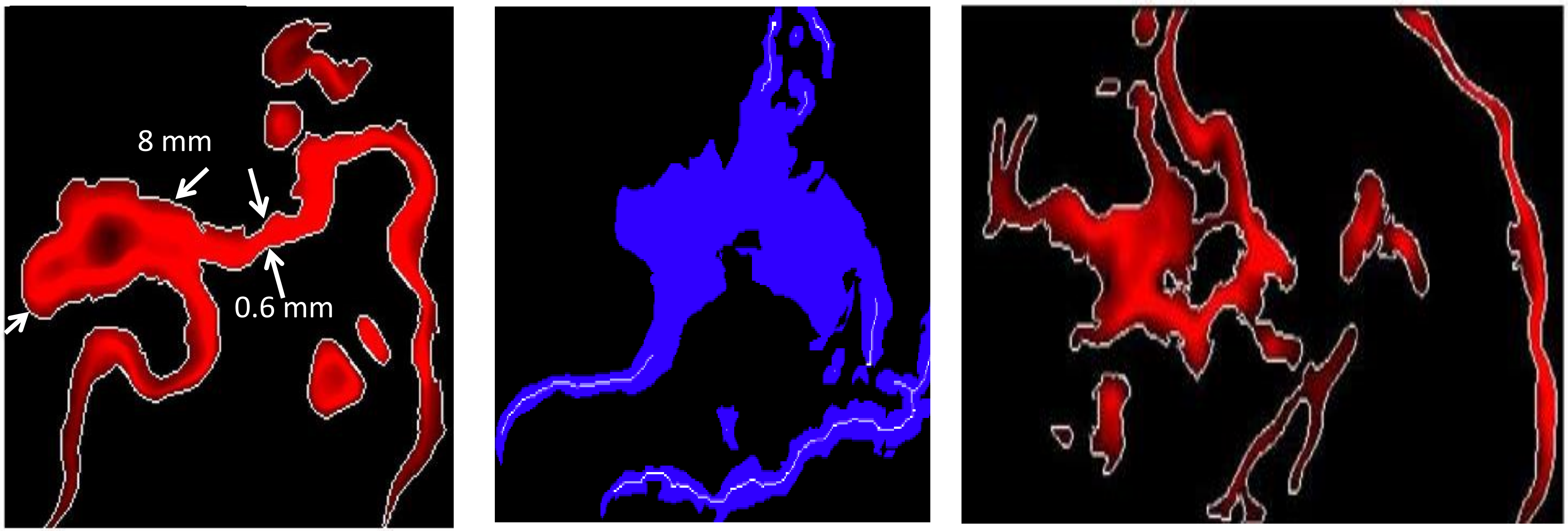
Densely Packed Flamelets - Regime



If flamelets are this densely-packed – can we model them as “distributed reactions” ?

“Partially-distributed” regime

10 % of OH boundary has distributed reactions for highest turbulence



see: “blobs of chicken in a noodle soup”

How to achieve broken reactions ? - stratified products

simultaneous CH-OH PLIF (Carter, Driscoll, Skiba, Wabel):

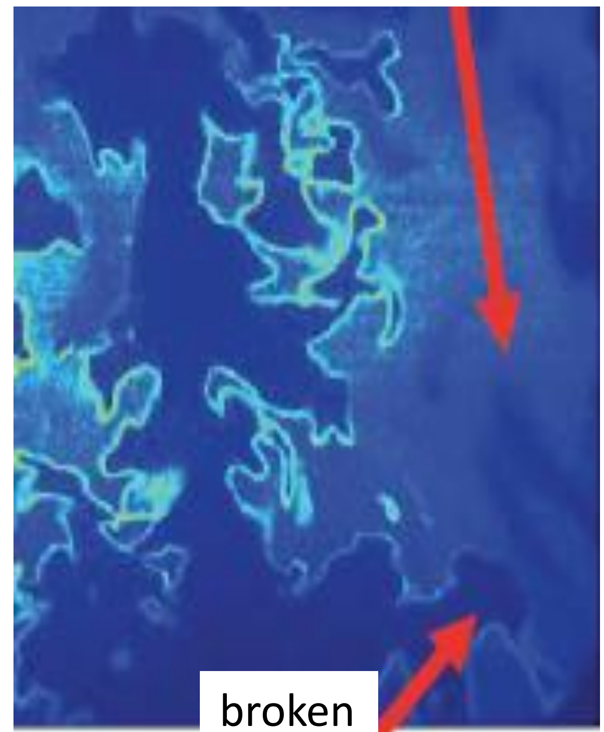
CH reaction layer = thin bright blue line

OH products = broad light blue

Stratified products

Broken Reactions = Bright line is discontinuous

Stratified products



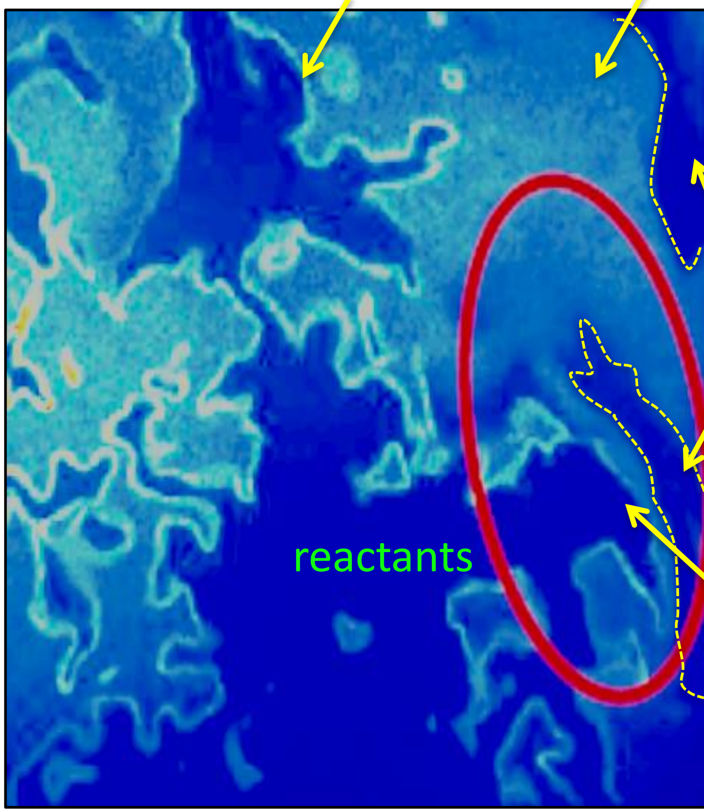
→ keep products hot to avoid broken reactions

Stratified Products - lead to broken reactions

CH reaction layer =
thin bright blue line

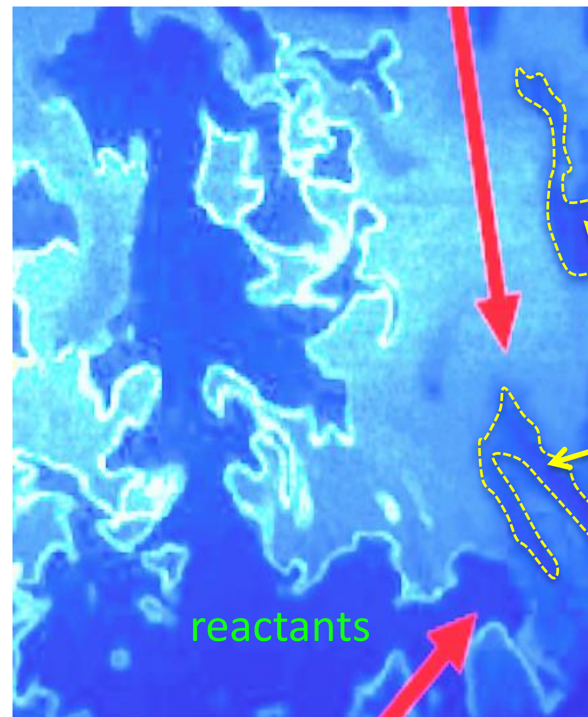
OH products =
broad light blue

CH-OH method of Cam Carter



dark blue =
stratified
products

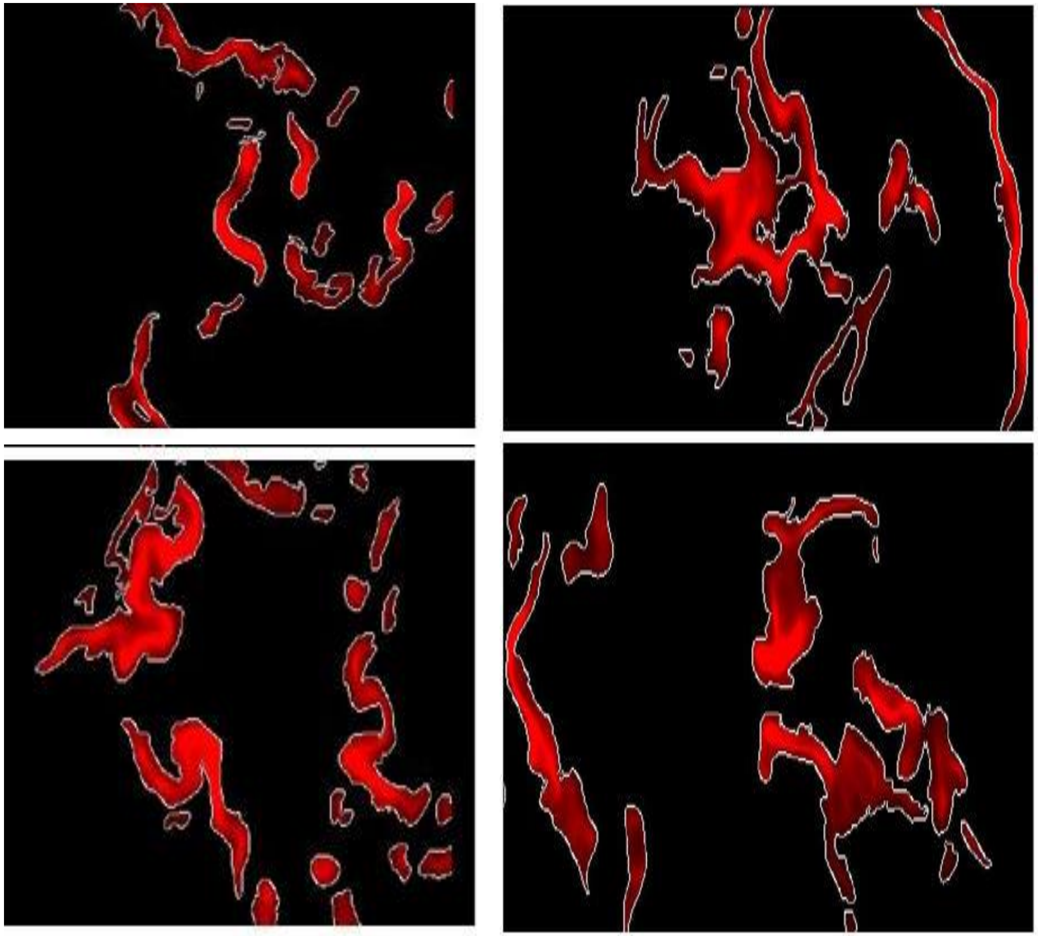
Broken
reactions



dark blue=
stratified
products

Broken reactions

Broken reaction layers - with stratified products



What happens at “extreme” levels of turbulence ?

Wabel, Skiba, Driscoll, to PROCI 36

- As u’/SL is increased to “extreme” values of 240, preheat zone gets very thick = 16 times the laminar thickness
- The reaction layers do not become thick, and remain at 1-2 times their laminar thickness
- Extreme turbulence is predicted to cause “broken” reactions, but no broken reactions were seen, even when turbulence was 10 times the predicted limit As long as the product gas were kept hot – no stratification of products because of No outside air entrainment
- If some outside air was entrained to cause stratification of product, then some Broken reactions were observed
- Distributed reactions were not observed in the Bunsen flame, even for extreme Turbulence levels. Distributed requires preheating of reactants and internal Hot gas recirculation, such as in a gas turbine combustor

Additional axes needed on the Borgi regime diagram

Da_2 = residence time of eddies in flame (x/U) / chemical time

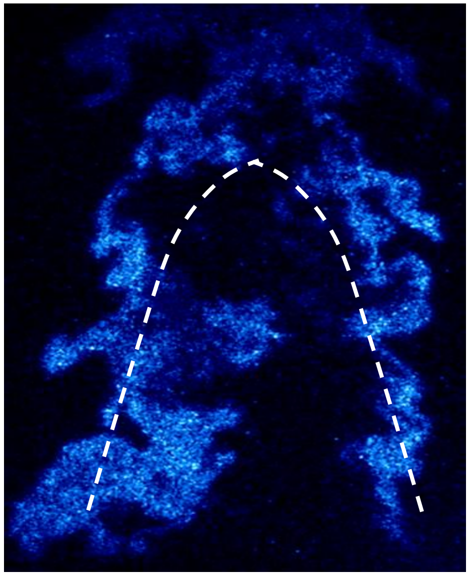
Reactivity (Y. Ju) = Initial temperature of reactants / ignition temp. (T_R / T_{ig})

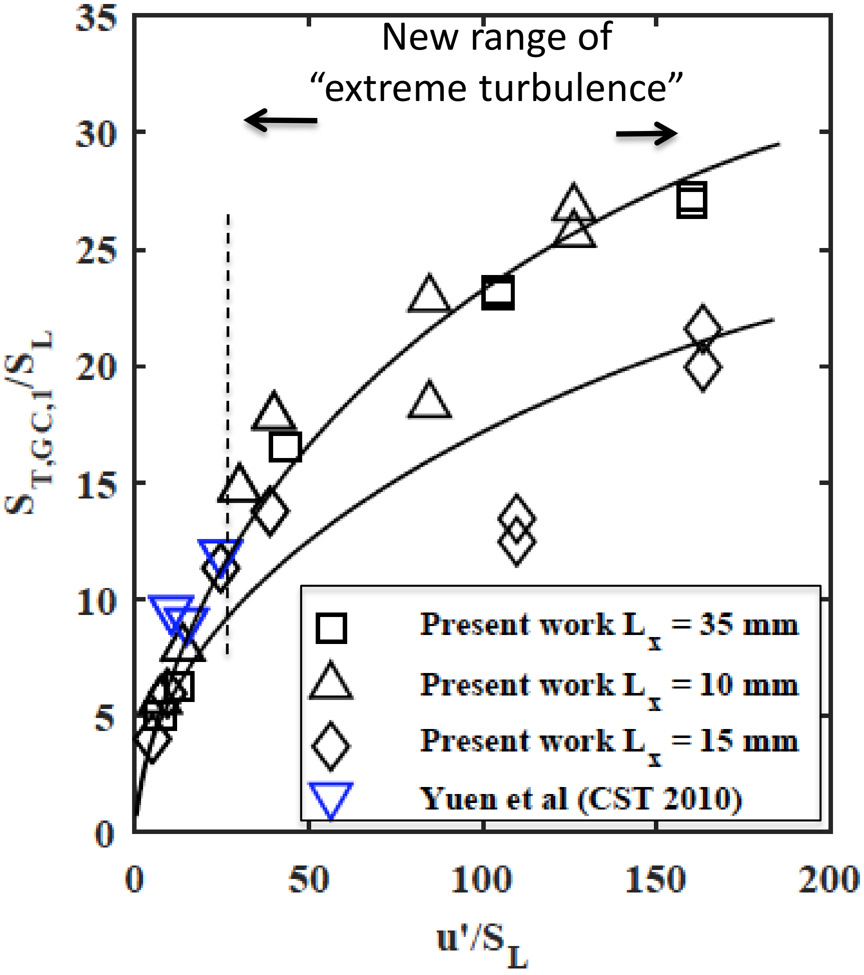
Degree of stratification = "DS" = $[\, T'_{rms} / T \,]_{products}$

controls "broken" regime boundary

Turbulent Burning Velocity

$$S_T = \frac{\dot{m}_R}{\rho_R \; A_T}$$

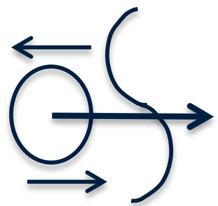




Wabel, Driscoll, PROCI 36, 2016

Turbulent Burning Velocity – what happens at extremely large turbulence levels ?

correlations are different for each "canonical geometry"



$$\frac{S_T}{S_L} = \frac{A_T}{A_L} = \underbrace{\left[1 + C_1 \left(\frac{u'}{S_L}\right)^2\right]^{1/2}}_{\text{Schelkin theory}} - \underbrace{\left[C_2 \left(\frac{u'}{S_L}\right)^2\right]}_{\text{Bending term}}$$

Bending term = due to ? Eddies destroyed traversing preheat layer ?
Geometric effects
Strain causes local extinction ?

Function C_1 and C_2 = ? Depend on integral scale ? Residence time due to mean velocity ?

Extend Burning velocity curve to "extremely" high turbulence levels (10X)

What do all these measurements mean ? Implications for models

Turbulent Burning Velocity S_T increases if
Thermal diffusivity α_T increases, or
Reaction rate $\widetilde{\dot{\omega}_P}$ increases

$$\bar{\rho}\, S_T \frac{d\tilde{c}}{dx} = \bar{\rho}\, \alpha_T \frac{d^2\, \tilde{c}}{dx^2} + \widetilde{\dot{\omega}_P}$$

Diffusivity: model $\alpha_T = \nu_T$ = related to resolved scale velocity gradients (Smagorinsky)

$$c = \frac{T - T_R}{T_P - T_R}$$

How to model reaction rate $\overline{\dot{\omega}_P}$? Depends on <u>probability</u> that flamelet is at a point

i) $\overline{\dot{\omega}_P} = \rho_R\, S_L\, \Sigma$ + flame surface density (Σ) transport eqn (Bray, F-TacLES, Fureby)

ii) Or Set

$$\overline{\dot{\omega}_P}\left(\bar{c}, \overline{c'^2}\right) = \int_0^1 \dot{\omega}_P(c)\; P(c, \bar{c}, \overline{c'^2})\, dc$$

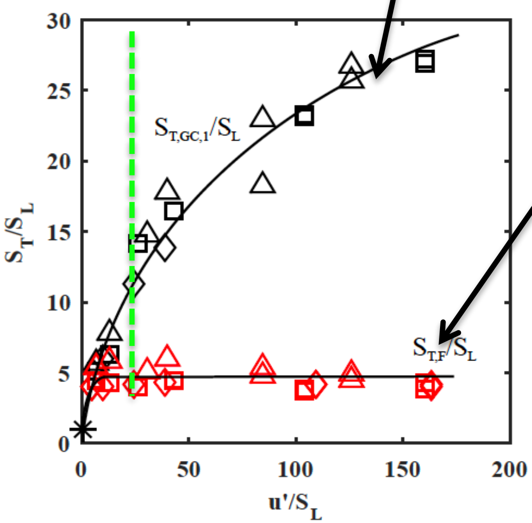
+ need PDF shape near c = 0.5
FPV (Moin, Pitsch, Ihme)

Implications for modeling

1. Provide modelers → measured PDF and flame surface density → to correctly model reaction rate, for methane and JP-8 at high Re

2. Provide modelers → measured Consumption Speed ($S_{T,G}$) for "extreme" turbulence = mass flow rate of reactants / density reactants / area for methane, JP-8 at high Re
   Models also should compute correct flame brush thickness

3. Model should predict "bending" at high Re



Wabel, Skiba, Driscoll, Seoul Symp.

4. Model should predict Thin Flamelet Component (FC) of burning velocity

$$(S_{T,F}) = S_L\,(A_T/A_L) \quad \text{where}$$

$A_T \approx$ integral of flame surface density

Model should explain why Flamelet Component curve is flat ?
= flame cannot wrinkle any more, but propagates faster

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Implications for modeling , continued

5. Model should account for **"Differential Broadening"** – Preheat layer is broadened by 16X but reaction layer broadened by only by 2X

6. Model should explain **Variation of turbulence** across flame brush

7. Model should predict that
   - **Stratified** flames become broken & distributed but
   - non-stratified flames do not

8. Model should explain why **Geometries** of Bunsen, spherical, gas turbine / swirl flames lead to → different turbulent burning velocities

9. Model should predict - measured effect of **Preheating** the reactants (Y. Ju)

10. Model should predict differences due to JP-8 **Pyrolysis layer**

What global metrics MUST a model predict correctly ?

before attempting to measure individual terms ?

<u>Premixed turbulent flames:</u>

Global Consumption Speed vs u' Model first must demonstrate it can predict measured height of a bunsen flame, angle of a V flame, dR/dt of spherical flame

Flame Brush thickness - as function of distance (Bunsen) or time (spherical)

Carbon Monoxide Emission Index - g CO / kg fuel

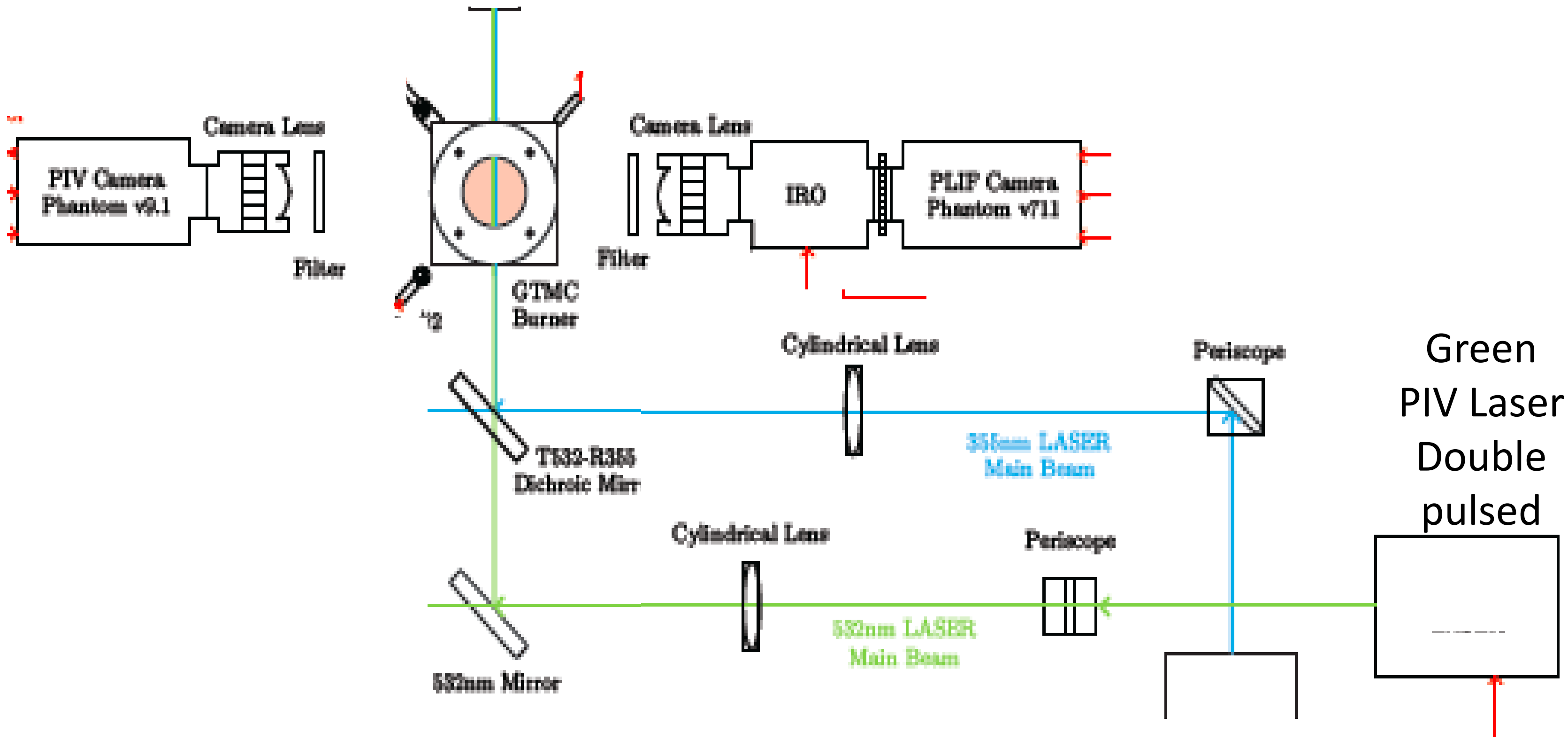
<u>Non-premixed turbulent flames</u> (jet, jet in coflow, jet in crossflow)

Flame Length (properly defined) as function of U_F, U_A, etc.

Carbon Monoxide Emission Index - g CO / kg fuel

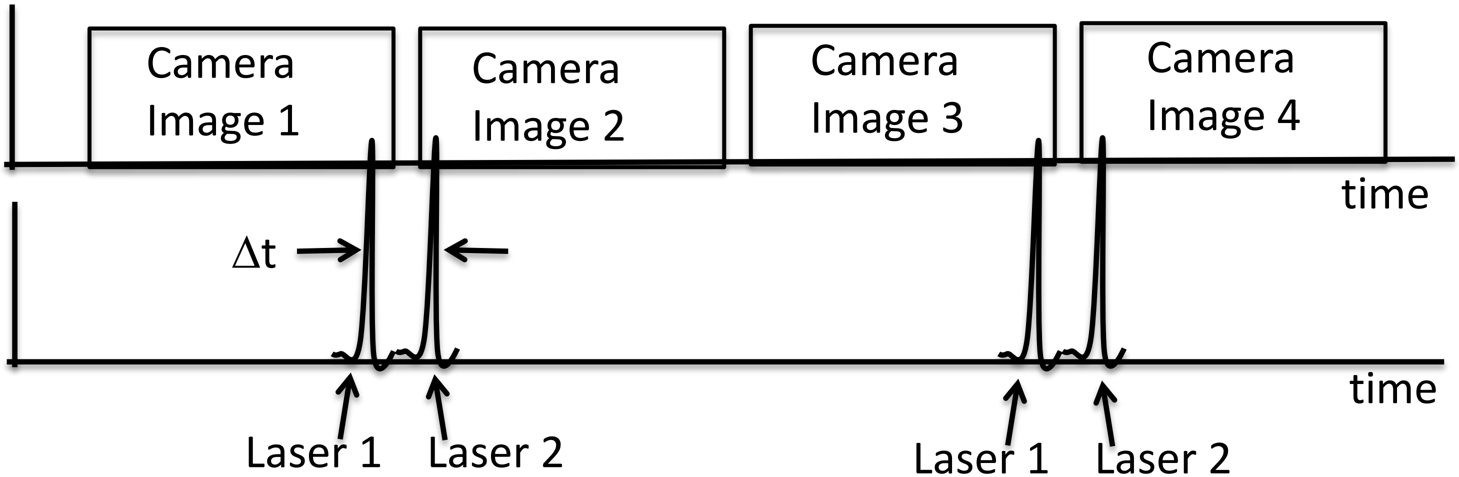
Kilohertz simultaneous PLIF and PIV

Quantronix kilohertz lasers - US made
Edgewave kilohertz lasers – German made



"Frame straddling" - with kHz PIV

One PIV camera operating at 20,000 images/sec
Two lasers – each operating at 10,000 pulses /sec



$\Delta t = \Delta x / U$ want Δx = distance particle moves = 1/3 interrogation box size

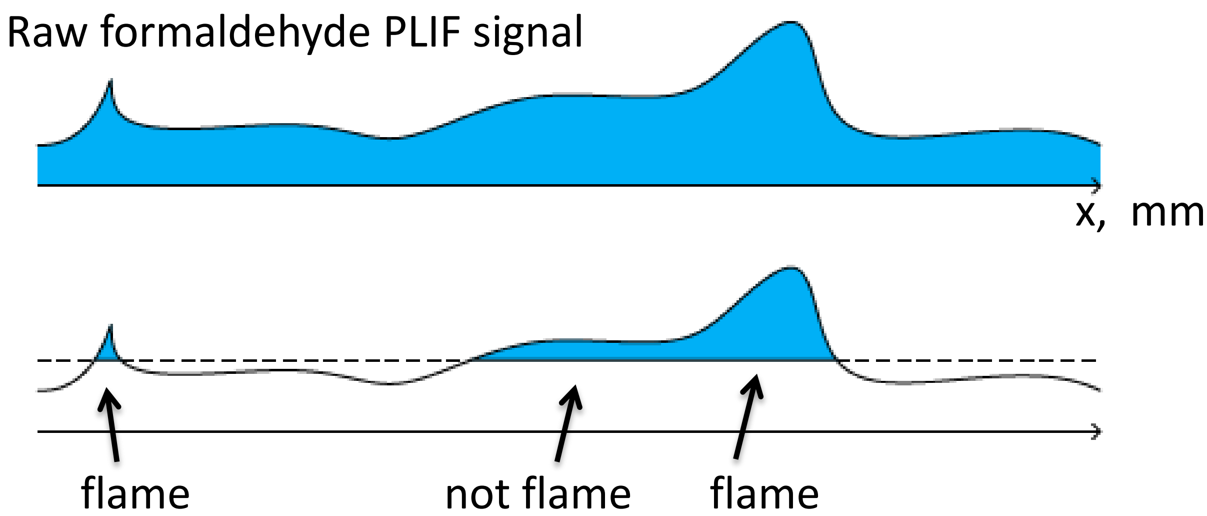
Interrogation box = one PIV velocity vector = 0.3 mm

so $\Delta x = 0.1$ mm

If U = 50 m/s, then $\Delta t = 2\ \mu s$

camera must turn off, then turn on - in less than 2 μs

Edge detection - to identify flame - from formaldehyde PLIF



Flame is at the sharp edge of the formaldehyde PLIF signal

Perform: thresholding for background subtraction

Spatial smoothing to remove noise, Canny edge detection algorithm

Check that flame is nearly continuous

CH Reaction layer

Cam Carter (AFRL)
Tonghun Lee UIUC
Driscoll (UM)
Not yet published

10 kilohertz

314.4 nm C-X band

Case 5, $u'/S_L = 62$

Highly corregated

Highly wrinkled

Merging

Excite CH at new wavelength 314 nm

Cam Carter, Tonghun Lee Appl. Phys. B 116:515

$C^2\Sigma^+ – X^2\Pi(0,0)$ Band

Previously CH excited $A^2\Delta – X^2\Pi(0,0)$ band at 431 nm

and $B^2\Sigma$-$X^2\Pi(0,0)$ at 390 nm

New method is best for kHz lasers: developed by Cam Carter, Tonghun Lee

$C^2\Sigma^+ – X^2\Pi(0,0)$ Band at 314 nm

10 kHz diode-pumped, Q-switched Nd:YAG laser

(Edge-Wave Innoslab IS12II-E)

532-nm pumps a dye laser (Sirah CREDO with DCM dye)

628 nm into a BBO frequency doubling crystal to 314 nm

Linewidth is 0.1 cm^{-1}, duration 7 ns, energy is 0.22 mJ at 10 kHz

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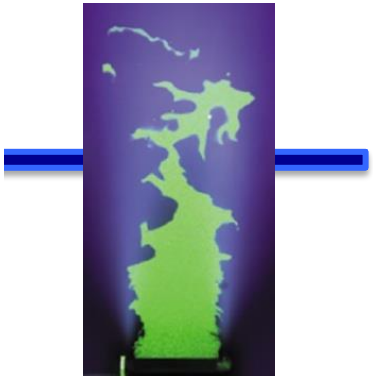
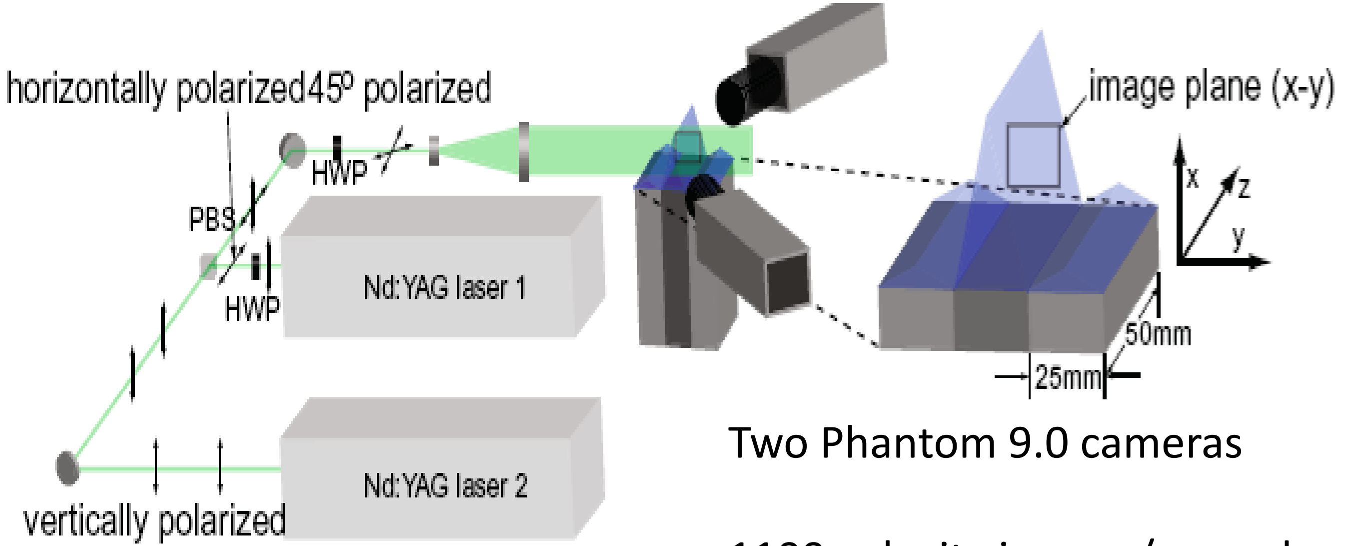
Steinberg, Driscoll Michigan 2-D Slot burner



measure stretch efficiency function for LES
complete velocity, flame surface data base
Cinema-stereo PIV



Two Clark OMB YAG lasers
Pulsed at 1100 pulses/sec

"fully-turbulent" $u'/S_L = 3.0$
$S_T/S_L = 2.5$

Two Phantom 9.0 cameras

1100 velocity images/second
Scheimpflug stereo PIV optics

Small field of view 8 x 11 mm
Spatial resolution = 140 microns
Time resolution 0.9 ms

Kilohertz PIV

Steinberg, Driscoll
Comb. Flame 156, 2285
Michigan kHz PIV
eddies passing through flame

Sheet thickness = 200 microns
spatial resolution =200 microns
temporal resolution =4,000 Hz

Lasers:
Quantronix Hawk: 4,000 Hz, 355 nm,
for CH_2O PLIF
Quantronix Hawk PIV laser: 4,000 Hz,
for PIV

Cameras:
Phantom v711 +LaVision high speed
Intensifier
Phantom 9.1

Observe eddy pairs –consistent with Damköhler, Schelkin

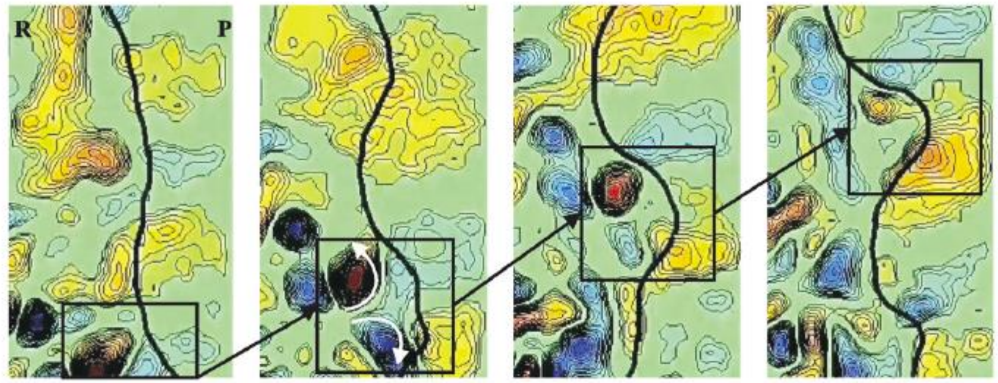
Colors = Vorticity (ω_z) ; -700 s^{-1} (blue)
and 700 s^{-1} (red)

Field of view = 6 mm x 10.5 mm,
Δt = 0.9 ms

1. **Initial Vortex Pair**
2. **Vortex Pair Disappears**
3. **Wrinkle in Flame Appears**

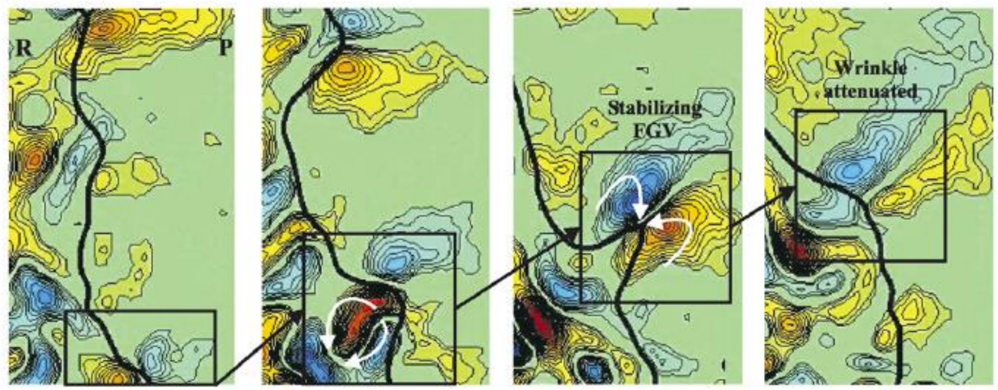
Reactants

Products



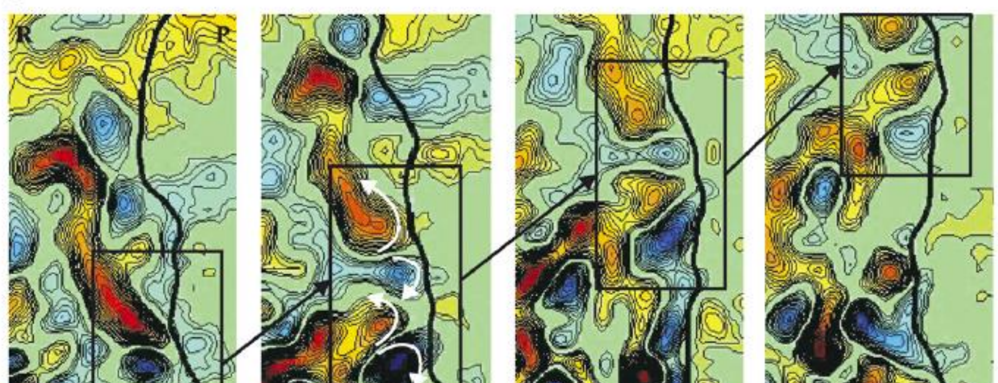
Wrinkle caused by single counter-rotating eddy pair

b



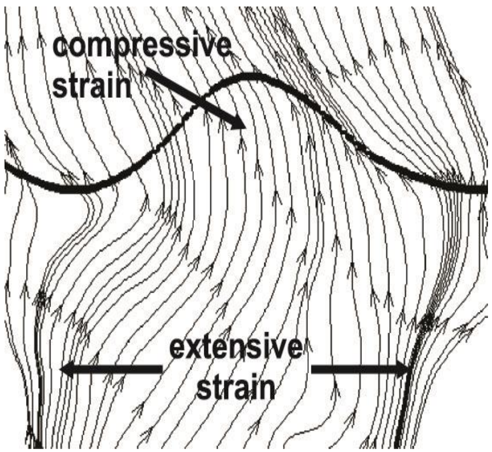
Flame generated vorticity observed

c

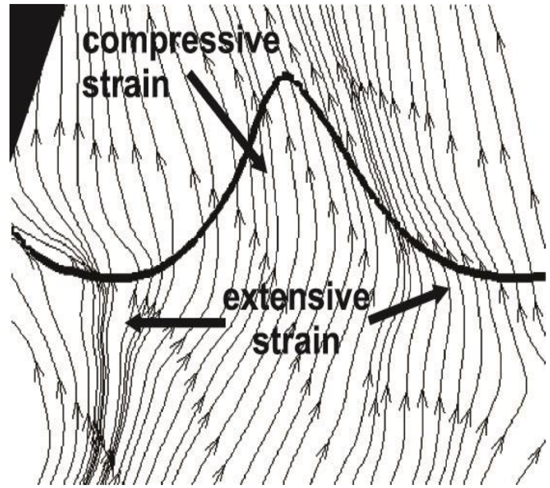


What do kHz diagnostics tell us ? Hydrodynamic Instability observed

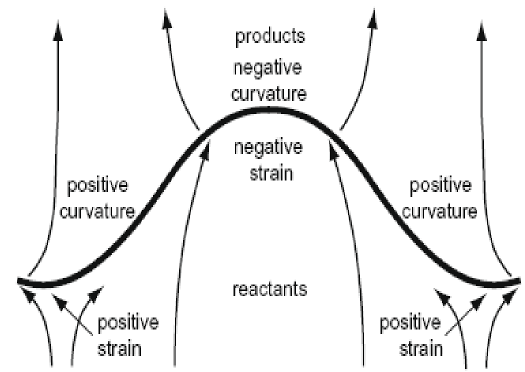
t = 6.3 ms



t = 12.6 ms

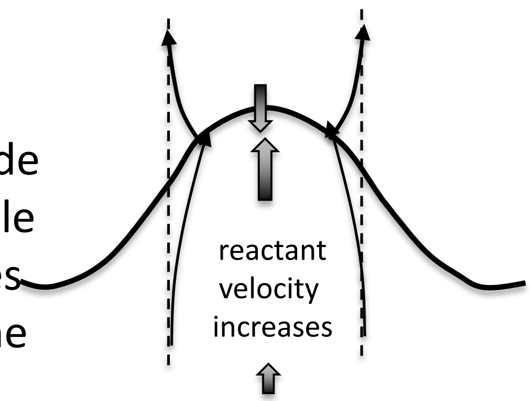


Landau instability



Measured streaklines

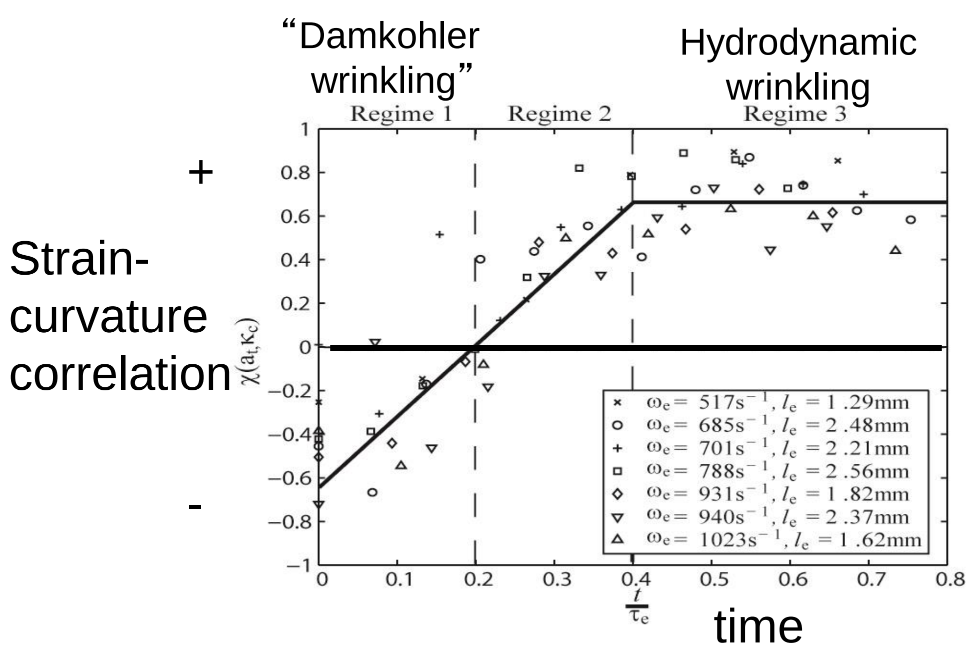
amplitude of wrinkle increases with time



- Eddy first creates a small wrinkle
- Measured diverging streaklines agree with theory
- Strain and curvature are <u>positively</u> correlated
- Wrinkle forms cusp due to hydrodynamic instabilility

KHz diagnostics tell us - the Time History of the Eddy-Flame Interactions

- **Early times: observe "Damkohler-like "**wrinkling sometimes
  Strain & curvature are <u>negatively</u> correlated as predicted
- Later times: vortex is destroyed by flame passage
- **Later times: observe Landau hydrodynamic instability**
  causes additional wrinkling
  Then strain & curvature are <u>positively</u> correlated



Goal: provide LES submodels with stretch rate efficiency function

Flame surface density models use the following equation for

Σ = subgrid flame surface density = flame area/volume

$$\frac{\partial \Sigma}{\partial t} + \tilde{U}\frac{\partial \Sigma}{\partial x} + \tilde{V}\frac{\partial \Sigma}{\partial y} = \nu_{\mathrm{T}}\frac{\partial^2 \Sigma}{\partial y^2} + \bar{K}\Sigma - \bar{M} - \bar{Q}$$

flame area increase per second
(per unit volume)

K = Subgrid stretch rate
of flame area

= (1/A) dA/dt
= area increase per second
(per unit area)

$K\,\Sigma$ = (1/A) (dA/dt) (area/volume)

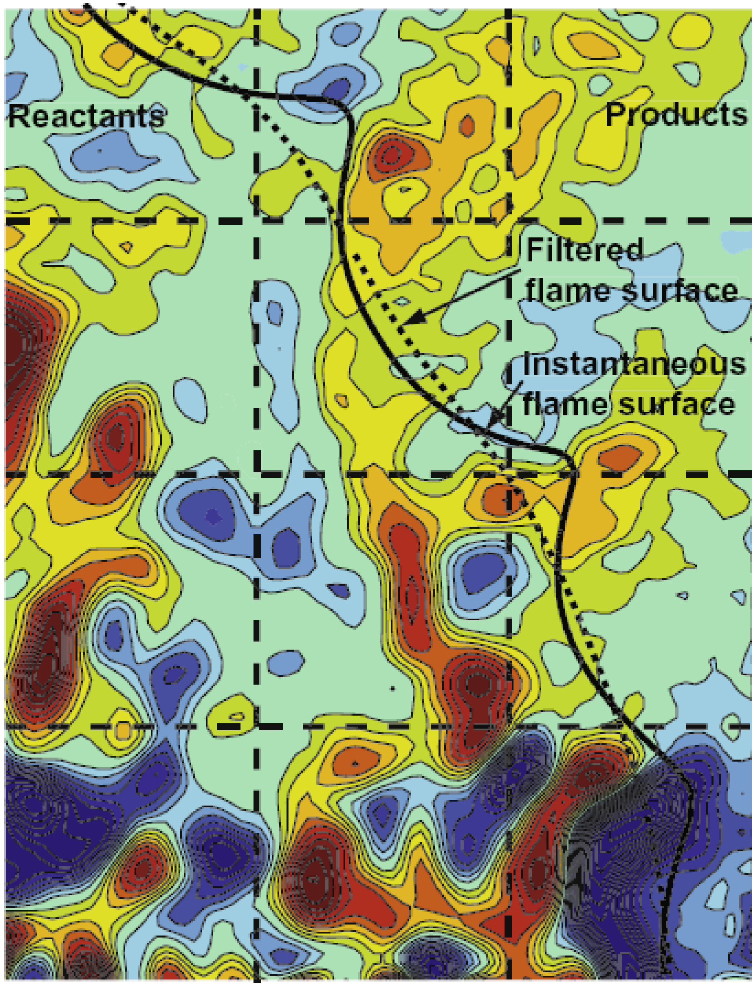
Steinberg measured subgrid stretch rates

1. Break up the experimental field into **“cells”**

2. **Track eddy motions** in a Lagrangian manner

3. **Perform “filtering”** - both spatial and time averaging over each cell

4. **Correlate** the cell-averaged flame stretch rate with either the cell-averaged (u’/L) (Poinsot) or the fluid strain rate S



How to measure K = (subgrid) stretch rate on flame surface

Why ? To predict correct degree of wrinkling, flame area
To predict local flame speed
To predict local extinction, overall blowout

$$K = \frac{1}{A}\frac{dA}{dt} = -\hat{n}\cdot(\hat{n}\cdot\nabla)\vec{u} + \underbrace{\nabla\cdot\vec{u}}_{0} + (\nabla\cdot\hat{n})\,S_L$$

Stretch Rate of the
Flame Surface Area A

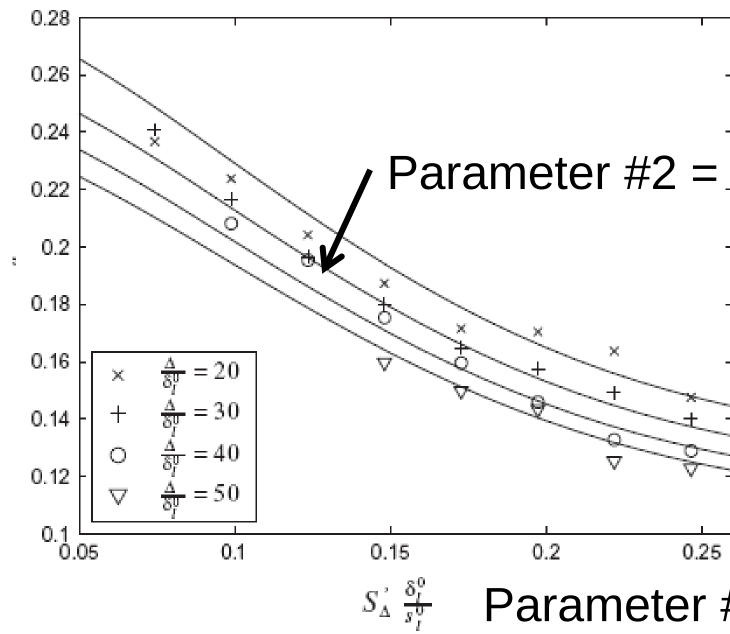
Strain Rate of Flame Surface

Curvature of Flame Surface

Measurements relate subgrid stretch *K* to the resolved-scale strain rate S_{ij}

Measured Stretch Efficiency function Γ_s

needed for LES



Parameter #2 = Δ / δ_{L0}

Parameter #1 $= S_\Delta / (S_{L0} / \delta_{L0})$

S_Δ = subgrid strain rate, related to resolved-scale velocity gradients

such as $\dfrac{\partial \tilde{u}}{\partial x}$

LES Closure - requires three steps

Step 1. Compute subgrid fluid strain rate from energy dissipation balance

$$\frac{\nu}{2}\,(S_\Delta^{\prime})^2 = \varepsilon = -\overline{u_i^{\prime} u_j^{\prime}}\ \widehat{S_{ij}}$$

Subgrid resolved

Step 2. Compute subgrid Reynolds stress using Smagorinsky:

$$-\overline{u_i^{\prime} u_j^{\prime}} = 2\,C\,\Delta^2\,\widehat{S_{ij}}\,\left|\widehat{S_{ij}}\right|$$

Step 3. Use our measurements to compute:

K = fcn (S'_Δ, Δ)

K = subgrid flame stretch rate (on the flame surface)

S'_Δ = subgrid fluid strain rate in reactants

What does kHz PIV tell us ?

1. **Stretch rate measurements** needed to model correct area, speeds

2. **Eddy-flame interaction measurements** are needed to assess physics of DNS and LES

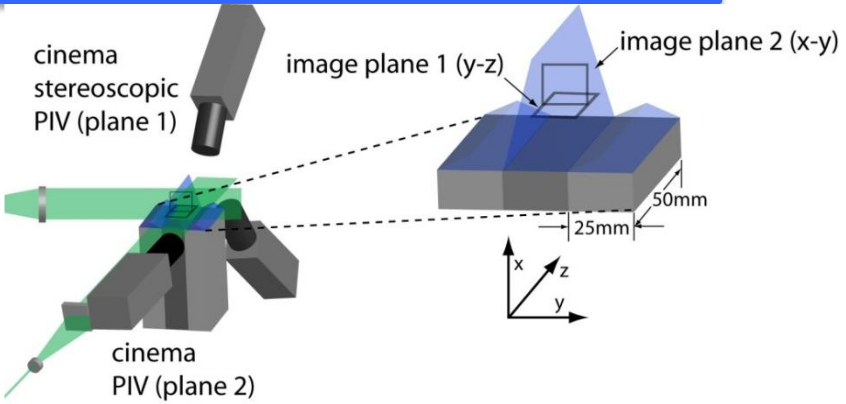
3. **A method was developed** to make high-speed movies of eddy – flame interactions and to measure stretch rates

4. “**Damkohler wrinkling**” increases flame area at early times

5. “**Landau hydrodynamic instability**” increases area after eddy gone

6. **Subgrid stretch rate correlation with resolved strain rate** was measured to improve LES models

"3-D" eddy-flame imaging



Lay the kilohertz laser sheet horizontal

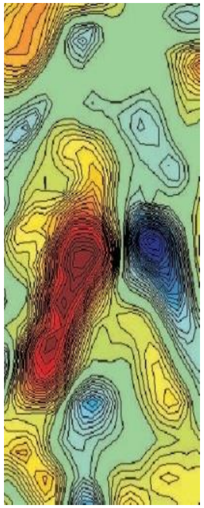
As eddies pass vertically upward through sheet:

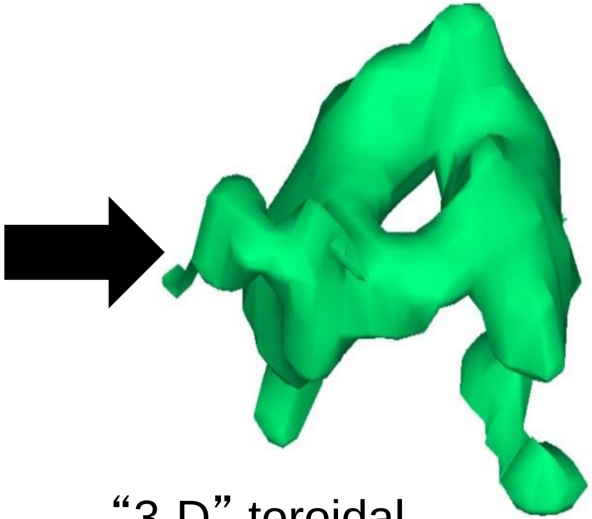
Rapidly image eddies in the horizontal plane

Apply Taylor's hypothesis

$$\frac{\partial}{\partial x} = \frac{1}{U}\frac{\partial}{\partial t}$$

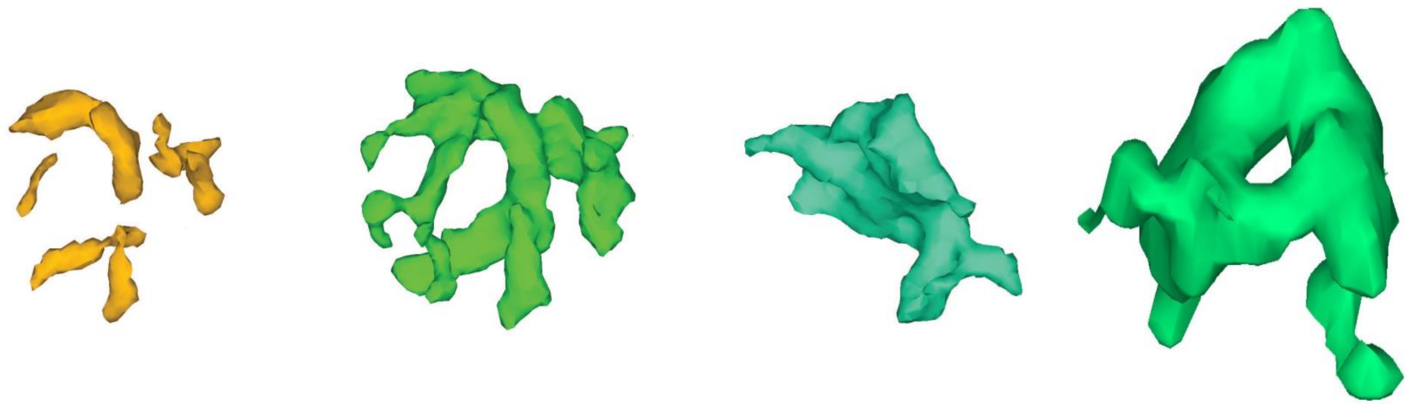
Check Taylor's hypothesis using one vertical sheet



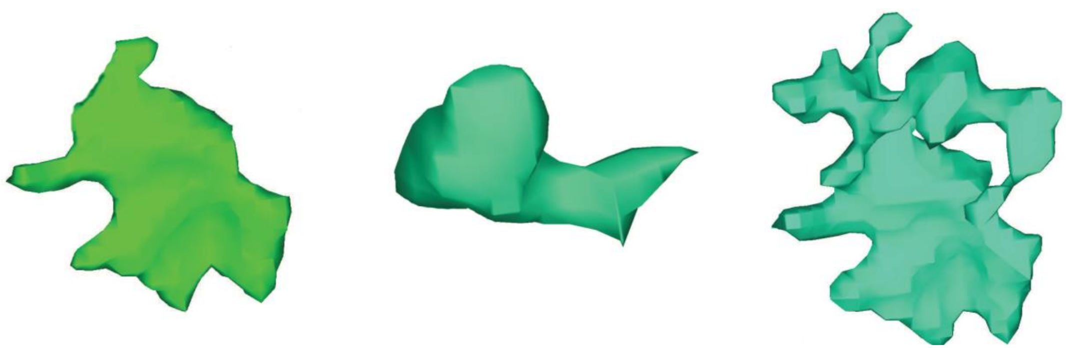


"3-D" toroidal vortex ring

KHz PIV images 3-D Vortical Structures = bundles of tubes



Observe Strain-Rate Structures - Sheets and Blobs



Kilo Hertz PIV movie of eddies entering a lifted flame base

Upatniek, Driscoll PROCI 29, p. 1867 (2002)