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Simultaneous Tomographic Particle Image Velocimetry and Laser-Induced Fluorescence Imaging in Turbulent Flames

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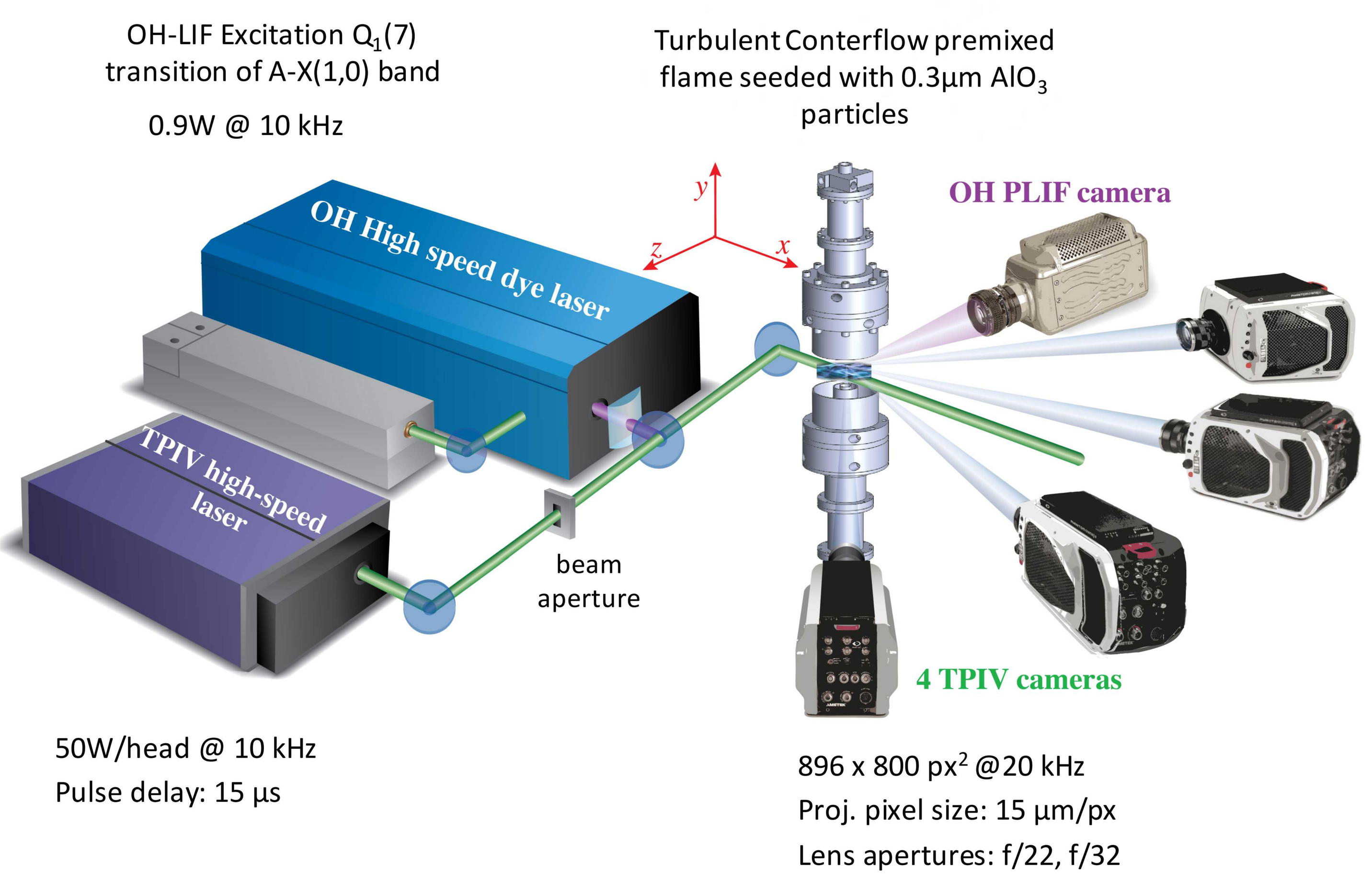
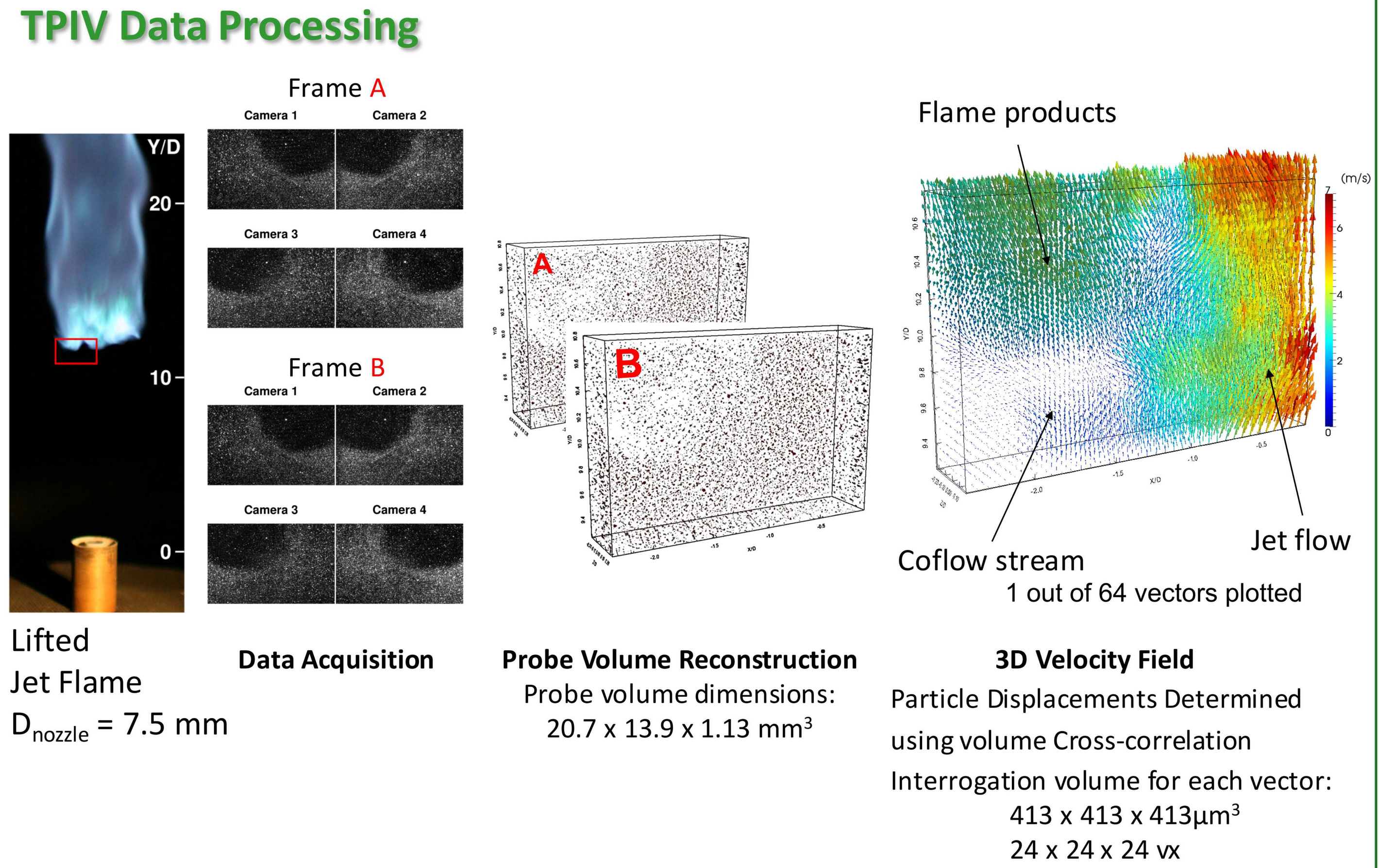
Turbulent combustion involves complex nonlinear interactions between fluid dynamics, molecular transport, and flame chemistry that span a broad range of length and time scales, posing a formidable challenge to imaging diagnostics. Advances in diode-pumped pulsed lasers and high-speed CMOS cameras are providing new opportunities for measuring these interactions. In present work, we use simultaneous Tomo-PIV and 2D-LIF imaging of the hydroxyl radical (OH) at 10 kHz to study the effects of flame heat release on preferential alignment of fluid dynamic strain with the normal direction to the local flame front in turbulent premixed counterflow flames as well as a turbulent premixed Bunsen flame. The existence of large bulk strain rate in the counterflow flames sets a distinct difference from that of the Bunsen flames, and its influence is studied by comparing the alignment statistics in both flames.

Tomographic PIV and 2D OH-LIF Imaging



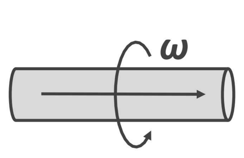
TPIV Data Processing



3-Component, 3D Velocity Measurements Enable Determination of Vorticity Vector and Full Strain Rate Tensor

Vorticity

$$\boldsymbol{\omega} = \nabla \times \boldsymbol{v}$$

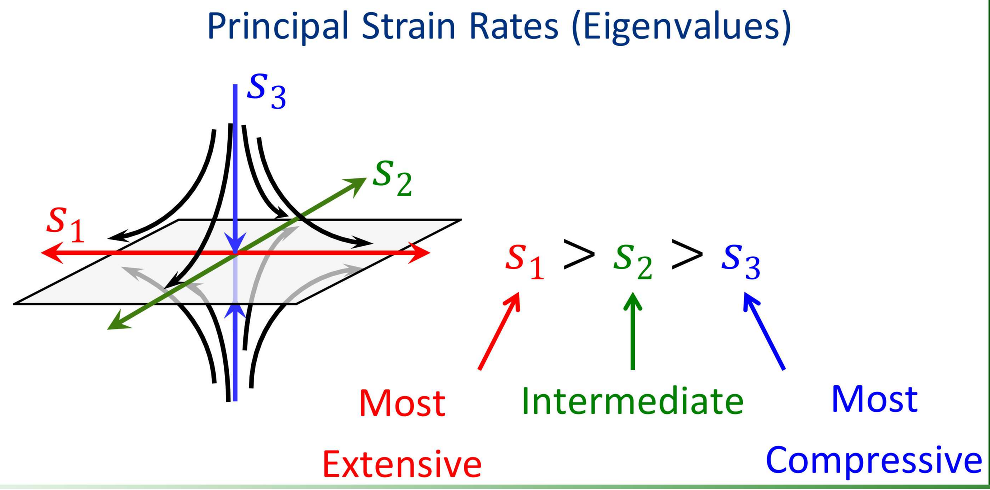


Strain rate tensor

$$S = \begin{bmatrix} s_{11} & s_{12} & s_{13} \\ s_{21} & s_{22} & s_{23} \\ s_{31} & s_{32} & s_{33} \end{bmatrix}$$

$$S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

Principal Strain Rates (Eigenvalues)



Alignment of Strain with Flame Normal

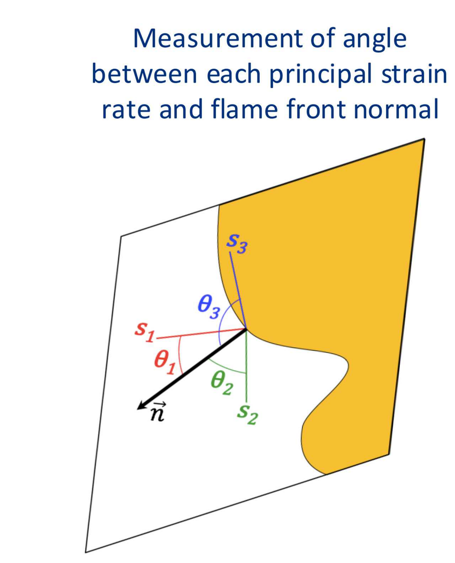
- Fluid dynamic strain plays central role in turbulence-chemistry coupling.
- Over what length scale is the strain rate orientation affected by flame heat release?
- To what extent does dilatation from heat release dominate over turbulence in determining the orientation of extensive and compressive strain rates?
- To what extent does the existence of bulk strain rate affect the alignment statistics.
- Approach: Measure statistics of angle between flame front normal direction and strain rate eigenvectors as a function of distance from flame front.

Transport Equation for Scalar Dissipation ($N_c = D|\nabla c|^2$)

Diffusive Flux — Dissipation of Scalar Gradient — Dilatation + Turbulence-Scalar Interaction — Production by Chemical Reaction

$$\rho\frac{DN_c}{Dt} = \frac{\partial}{\partial x_j}\left(\rho D\frac{\partial N_c}{\partial x_j}\right) - 2\rho D^2\left[\frac{\partial}{\partial x_j}\left(\frac{\partial c}{\partial x_i}\right)\right]^2 + 2\rho N_c\left[(\delta_{ij} - n_i n_j)s_{ij}\right] + 2D\frac{\partial c}{\partial x_i}\frac{\partial \dot{\omega}}{\partial x_i}$$

Measurement of angle between each principal strain rate and flame front normal



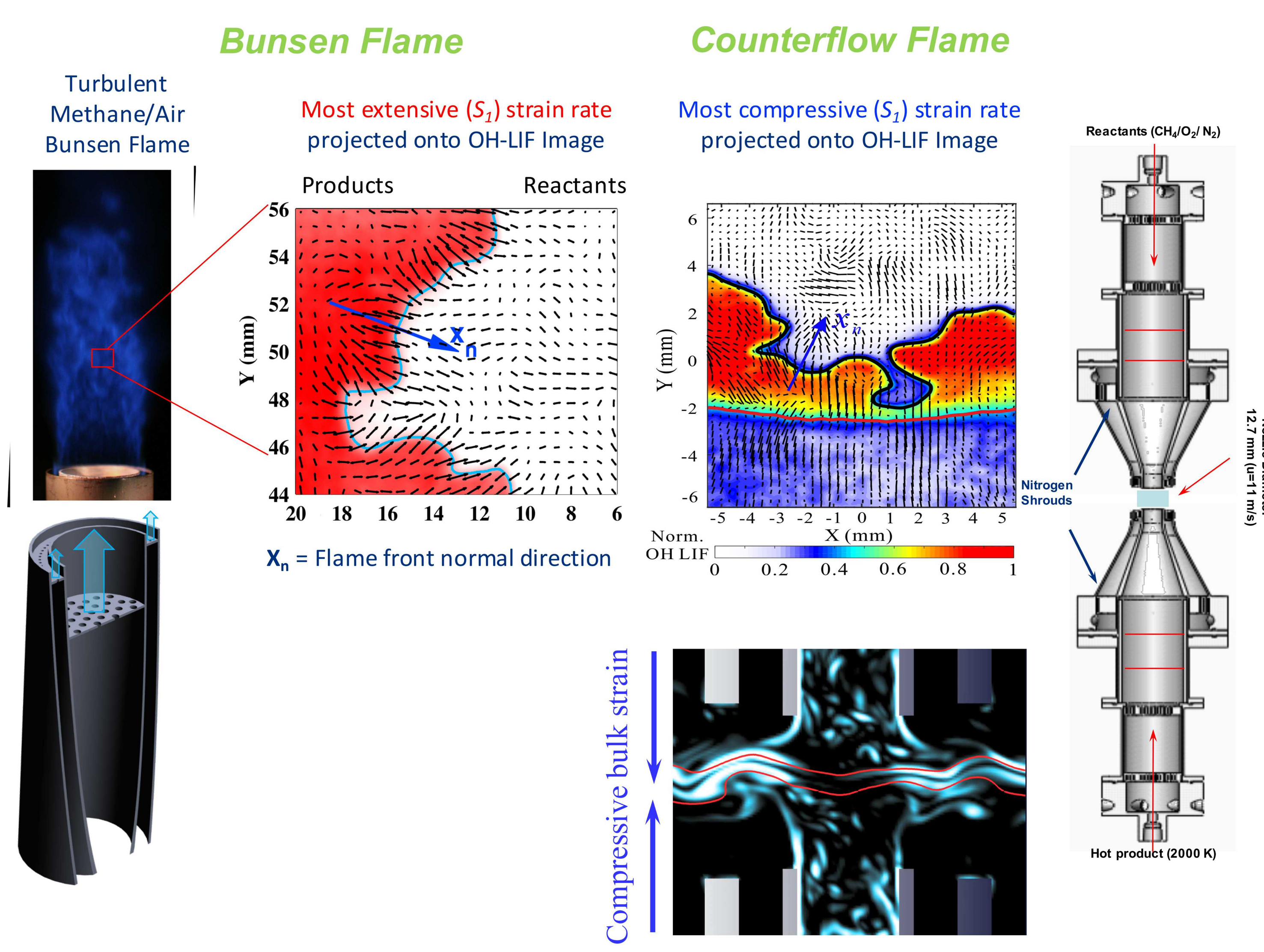
Flame Tangential Strain

$$S_t = \left[(\delta_{ij} - n_i n_j)s_{ij}\right] = \Delta - S_n$$

Flame Normal Strain

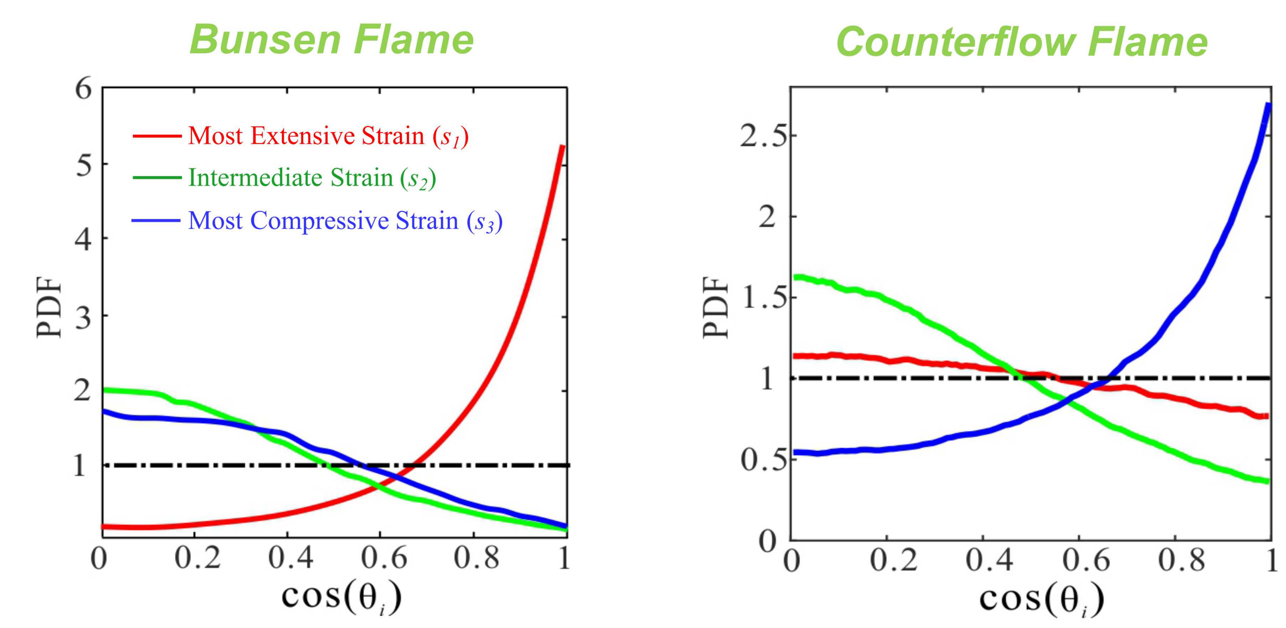
$$S_n = s_1 cos^2(\theta_1) + s_2 cos^2(\theta_2) + s_3 cos^2(\theta_3)$$

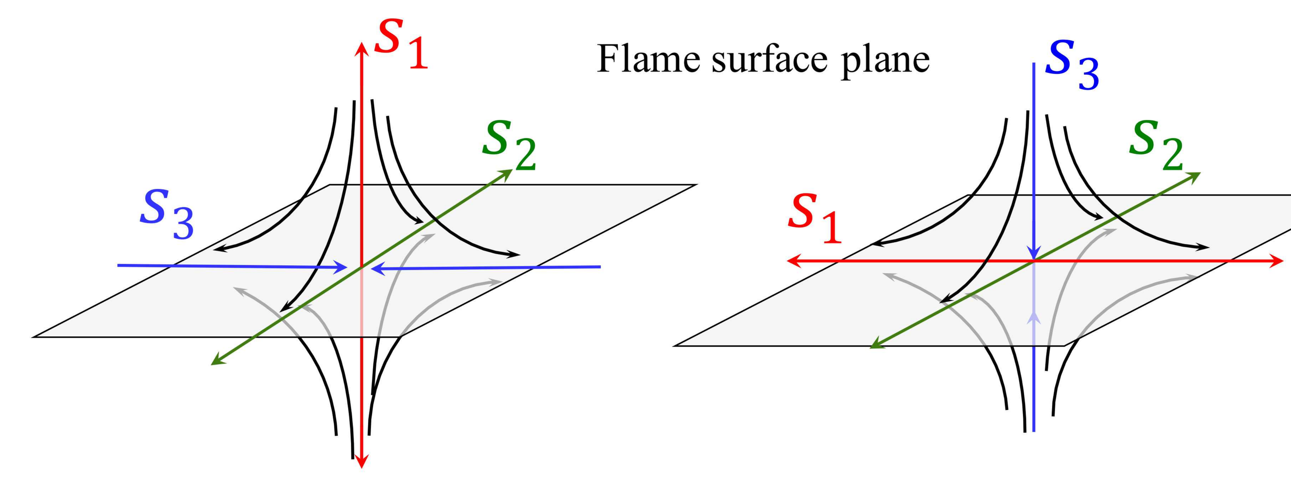
Different Flow Patterns with two Burner Geometries



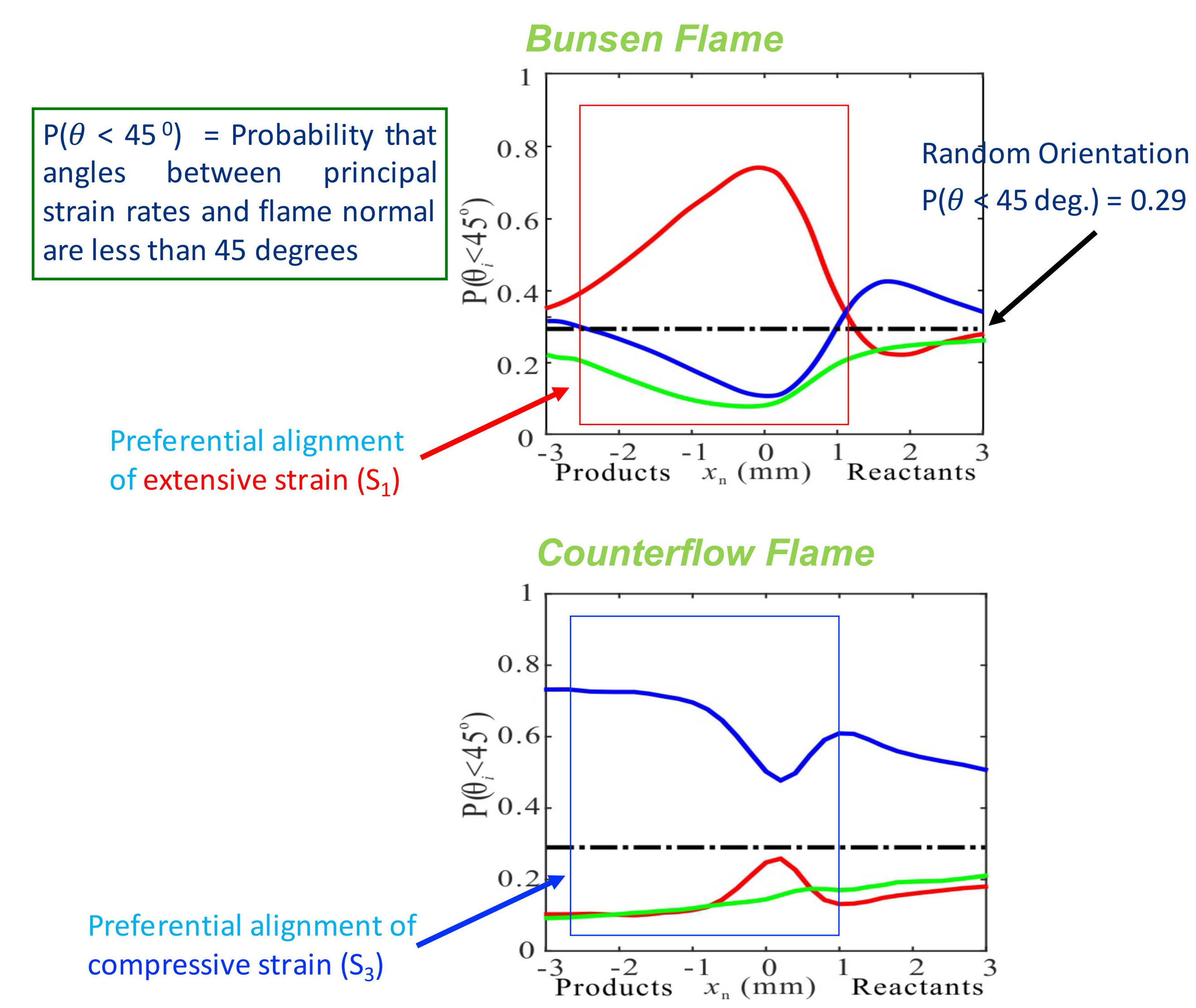
Strain Rate Alignment Statistics In Bunsen and Counterflow Flames

Flames	Mixture	ϕ	Re_t	Heat release para.	u'/S_L	Ka
Bunsen	CH_4/Air	1.0	250	6.5	1.8	0.79
Counterflow	$CH_4/O_2/N_2$-vs-Product	1.0	470	7.6	2.8	1.3





P(θ < 45°) as a function of distance from flame front (x_n)



Summary

- Tomographic particle image velocimetry and 2D LIF imaging of OH provide insights into local impact of flame front on strain rate alignment.
- At 3-mm from the flame front on both reactant and product sides, alignment is nearly random in the Bunsen flame while preferential alignment with compressive strain rate was shown in the counterflow flame due to large compressive bulk strain rate.
- Near the flame front, preferential alignment of flame normal with most extensive strain and with most compressive strain was observed in the Bunsen flame and the counterflow flame, respectively.
- Existence of large compressive bulk strain rate suppress physic space in which heat release affects the alignment statistics.

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