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Comparison between Flame-Flame Interactions in Hydrogen and Hydrocarbon Flames

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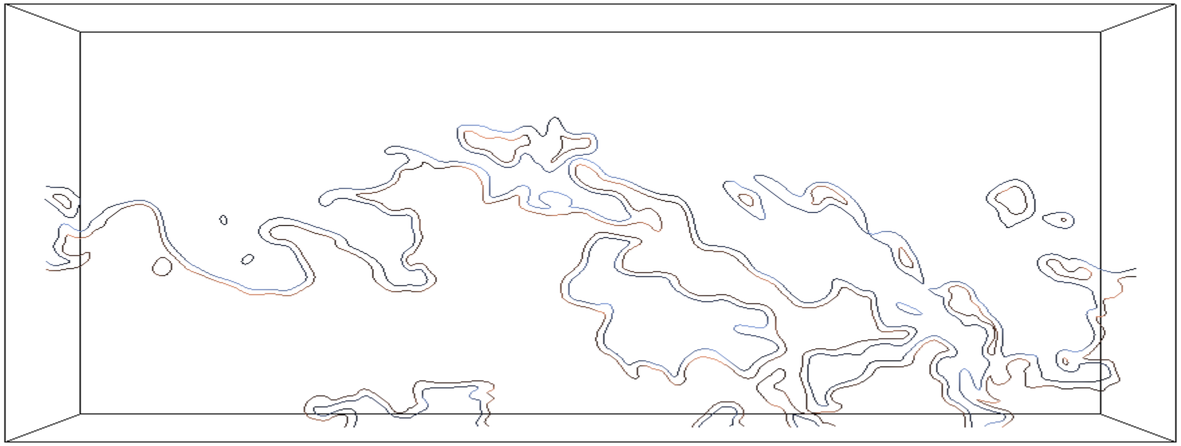
Introduction

- Turbulence wrinkles the flame and increases its surface area. In high intensity turbulence, the flame front begins to interact with itself.
- Flame self-interactions may lead to flame-area destruction.
- Griffiths et al. quantified flame-flame interactions using Morse theory of critical points for counter-flowing H_2 flames using the DNS datasets of Hawkes et al.



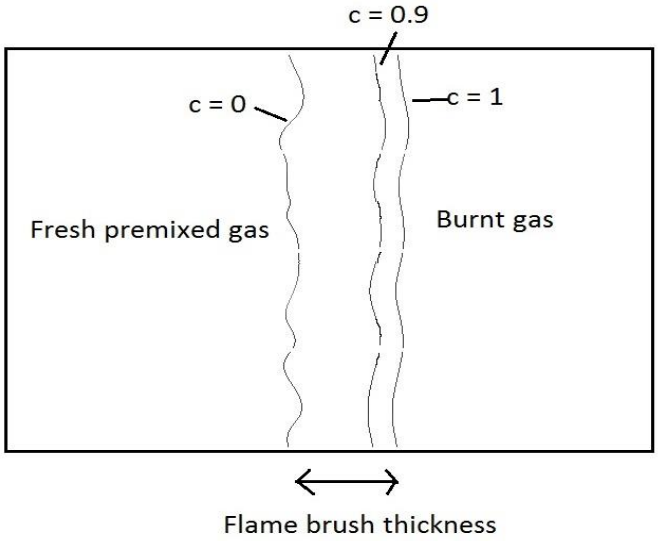
R.A.C. Griffiths, J.H. Chen, H. Kolla, R.S. Cant, W. Kollman: Three-dimensional topology of turbulent premixed flame interaction. Proceedings of the Combustion Institute, 35 pp. 1341-1348(2014)
E.R. Hawkes, O. Chatakonda, H. Kolla, A.R. Kerstein, J.H. Chen: Combust. Flame 159 (2012) 2690-2703

Critical points definition

- Critical point is defined as a point on a surface where the gradient of the scalar is either zero or does not exist.
- For a flame, the scalar to define a surface is progress variable *c*

$$c = \frac{Y_{\alpha} - Y_{\alpha R}}{Y_{\alpha P} - Y_{\alpha R}}$$

- When flames interact, they mutually annihilate each other, ∇c does not exist at this point, therefore, it is a critical point.



Hessian function

- Taylor expansion at critical points is: $\mathrm{c}(\mathrm{a}+\mathrm{x}) = \mathrm{c}(\mathrm{a}) + \frac{\mathrm{x}^{\mathrm{T}}}{2} H\big(\mathrm{c}(\mathrm{a})\big)\mathrm{x} + \cdots$
- *H* is called the Hessian function with eigenvalues (λ_1, λ_2, λ_3) give the curvature along the three orthogonal principal axes.
- These eigenvalues fully define the local topology to second order.

J. Milnor, Analysis of Math. Studies, Princeton University Press (1963) p. 51.

R.A.C. Griffiths, J.H. Chen, H. Kolla, R.S. Cant, W. Kollman: Three-dimensional topology of turbulent premixed flame interaction. Proceedings of the Combustion Institute, 35 pp. 1341-1348(2014)

Normalised shape factors

- Normalised shape factors can be evaluated from these eigen values, given as:

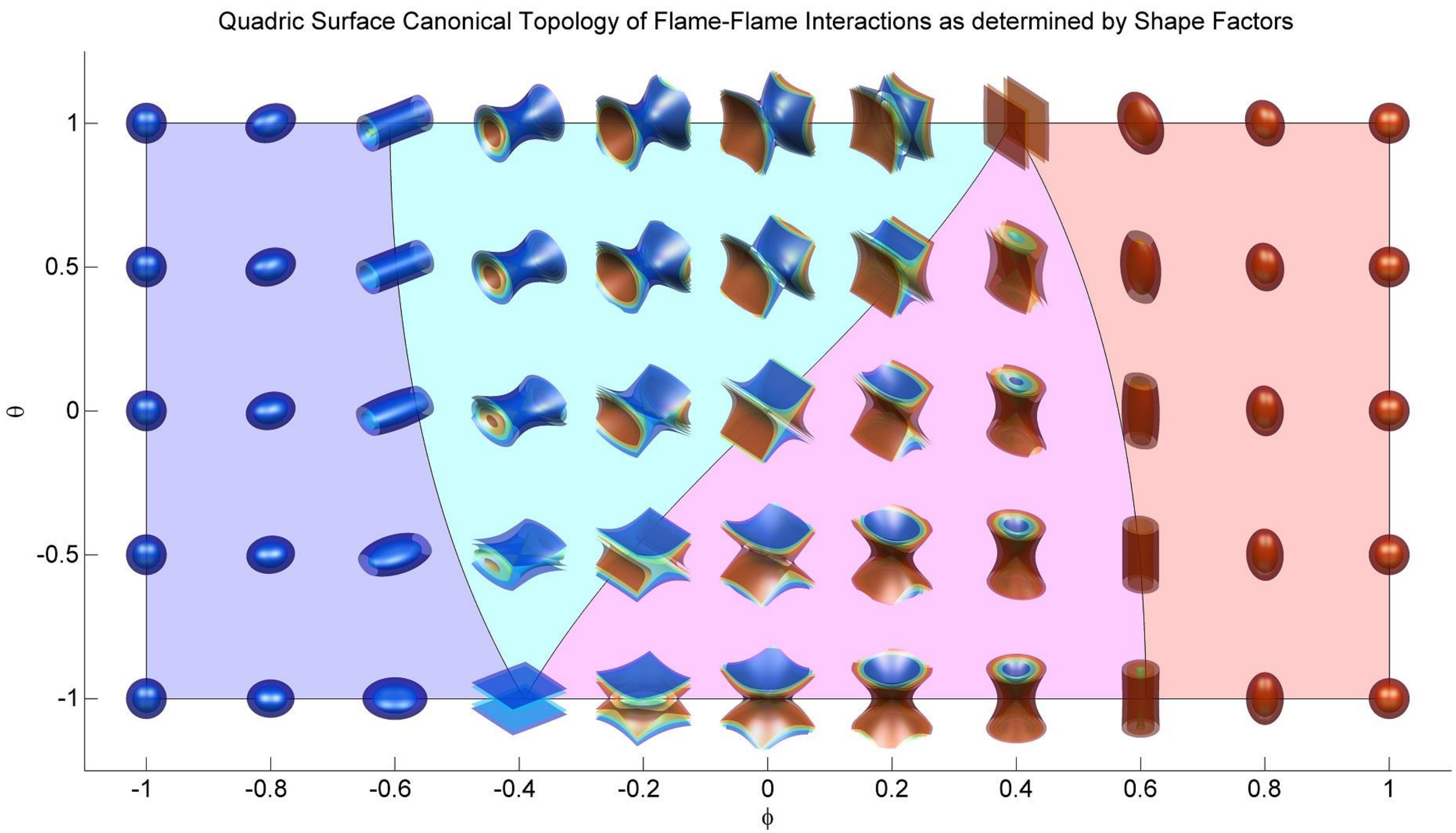
$$\phi = \frac{2}{\pi}\arctan \frac{(\lambda_1 + \lambda_2 + \lambda_3)\cos(\theta\pi/6)\,/3^{1/2}}{(\lambda_1 - \lambda_3)/2^{1/2}}$$

$$\theta = \frac{6}{\pi}\arctan \frac{(\lambda_1 - 2\lambda_2 + \lambda_3)/6^{1/2}}{(\lambda_1 - \lambda_3)/2^{1/2}}$$

- Also, the mean curvature can be evaluated as:

$$\kappa = \left(\lambda_1^2 + \lambda_2^2 + \lambda_3^2\right)^{1/2}$$

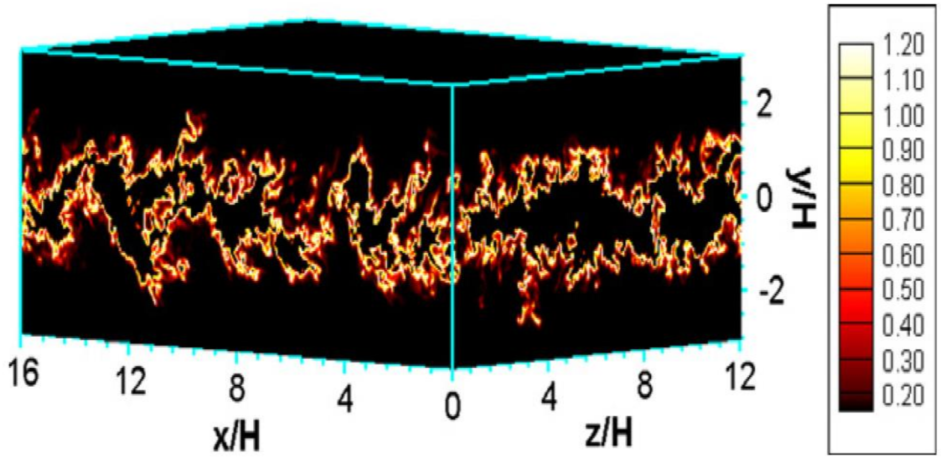
All possible topologies in 3-D



R.A.C. Griffiths, J.H. Chen, H. Kolla, R.S. Cant, W. Kollman: Three-dimensional topology of turbulent premixed flame interaction. Proceedings of the Combustion Institute, 35 pp. 1341-1348(2014)

Dataset description – Hydrogen

- DNS data of Hawkes et al. used for the hydrogen-air results, generated using the code S3D.
- 19-step Li et al. mechanism for hydrogen-air combustion.
- Two cases Da+ (Da=0.54) and Da- (Da=0.13) analysed.

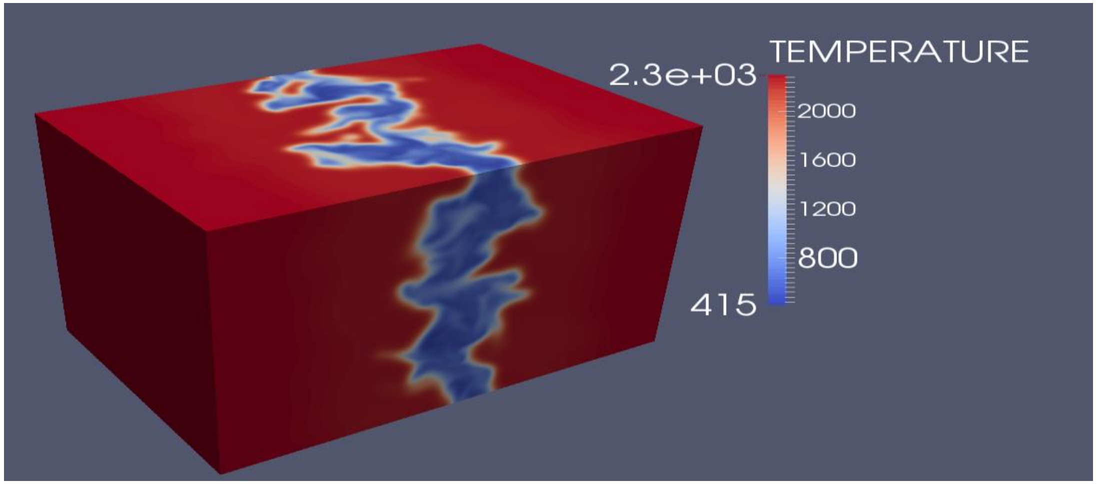


E.R. Hawkes, O. Chatakonda, H. Kolla, A.R. Kerstein, J.H. Chen: Combust. Flame 159 (2012) 2690-2703

J. Li, Z. Zhao, A. Kazakov, F.L. Dryer, Int. J. Chem. Kinet. 36 (2004) 566–575.

Dataset description - Hydrocarbon

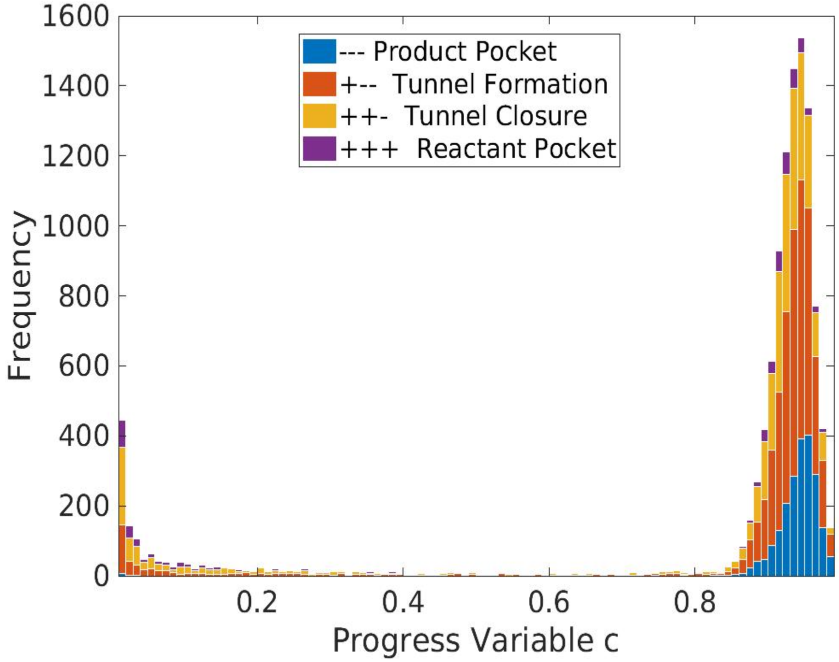
- DNS code Senga2 based on tenth-order finite-difference scheme for spatial discretisation and fourth order five-stage Range-Kutta algorithm for time-stepping
- 1-step reaction mechanism, $u'/s_L = 10$, 20, 40.



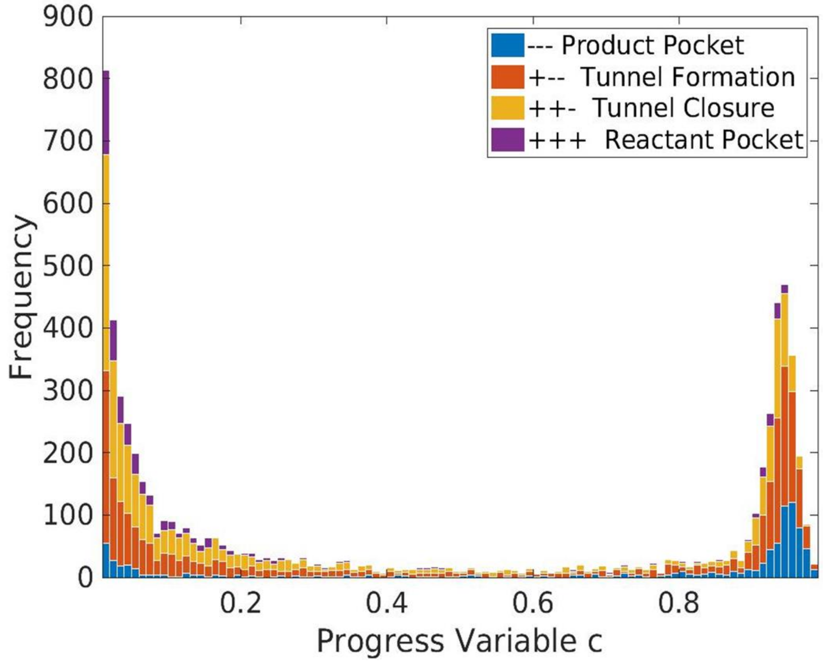
Hydrogen flame results

- Many more trailing edge interactions were found in hydrogen-air flames, consistent with the findings of Griffiths et al.

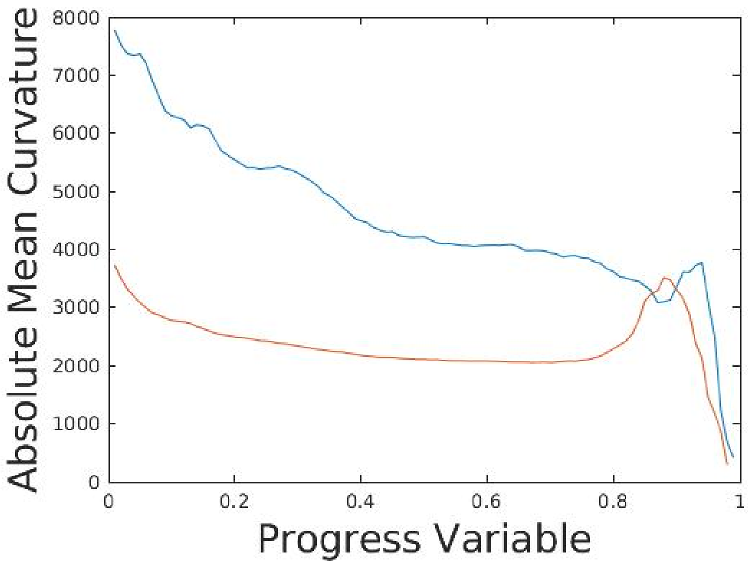
Da+ case

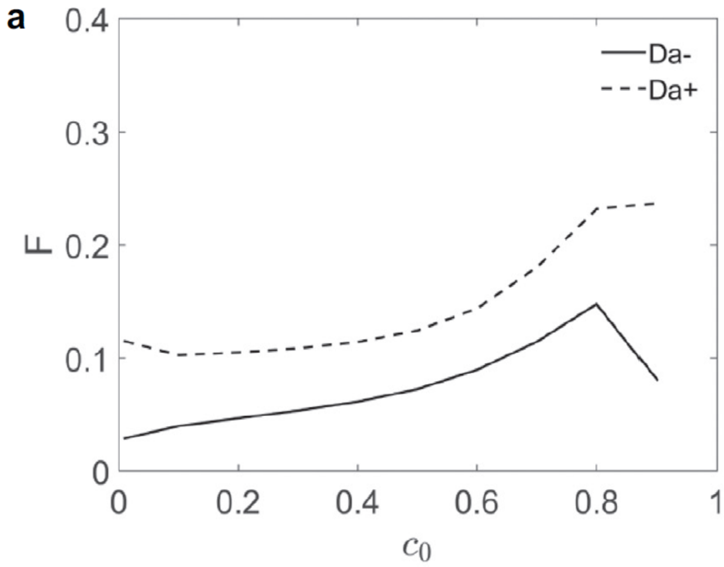


Da- case



Hydrogen results





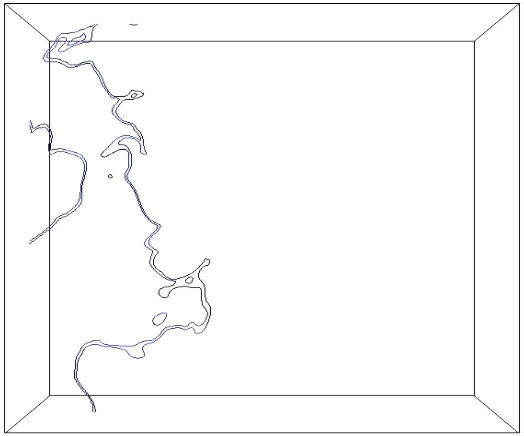
(Left) Absolute value of the mean curvature for Da+ (red) and Da- (blue) cases to represent the net wrinkling of the flame.

(Right) Net contribution of mean shear on total strain.

S. Chaudhuri H. Kolla, H.L. Dave, E.R. Hawkes,J.H. Chen, C.K. Law, Combustion and Flame 184 (2017) 273–285

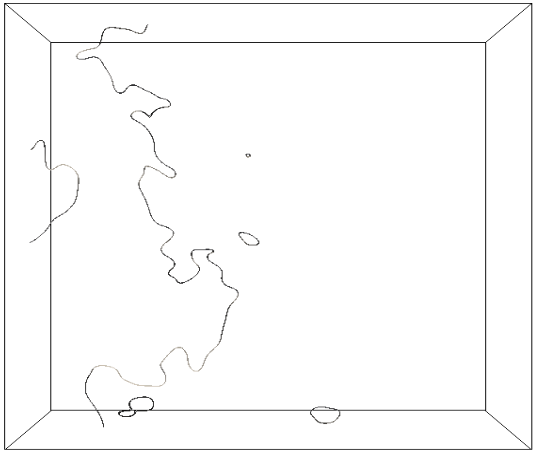
Hydrogen results

c=0.01,0.03

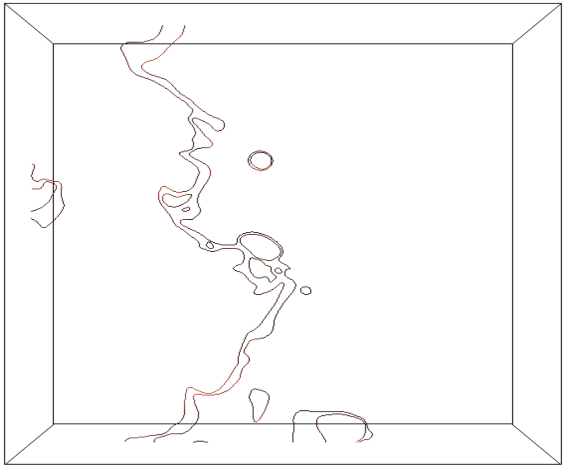


c=0.10,0.12

c=0.50,0.52

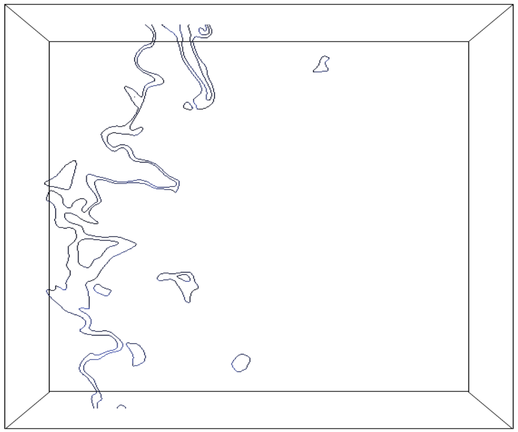


c=0.90,0.92

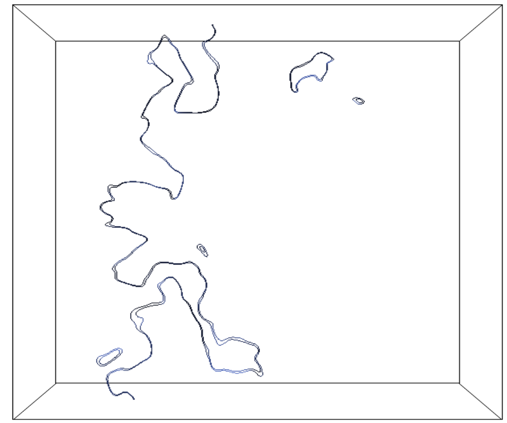


Hydrogen results

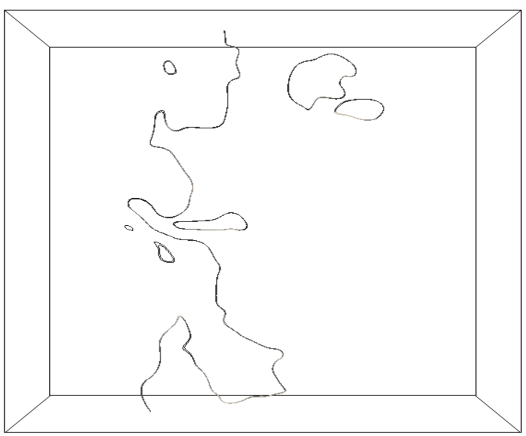
c=0.01,0.03



c=0.10,0.12



c=0.50,0.52



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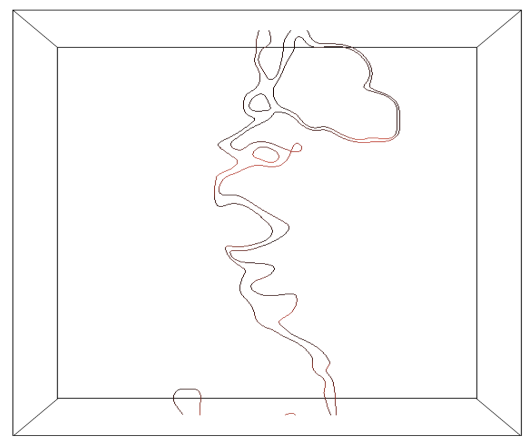
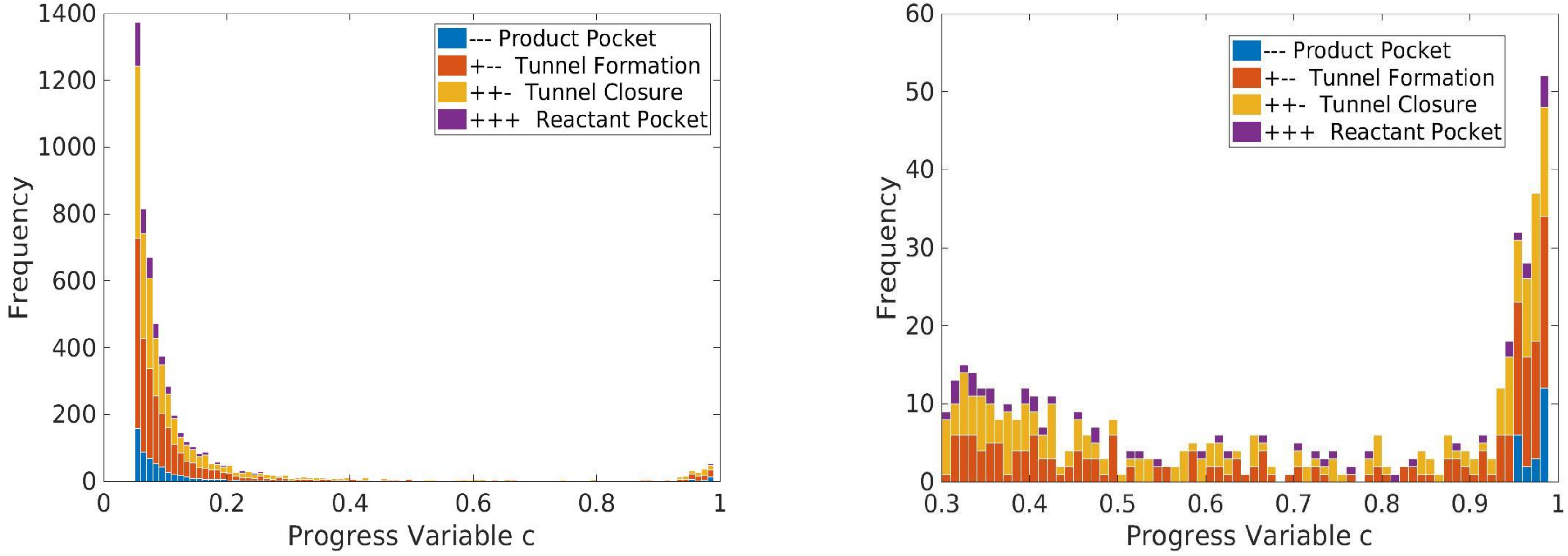


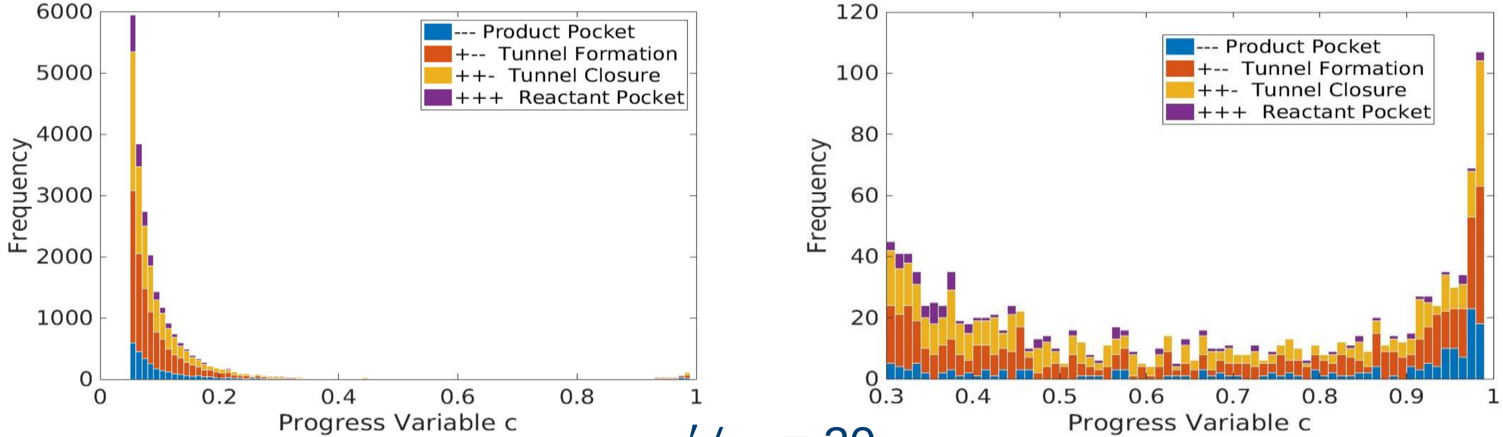
Single-step hydrocarbon flame results

- Histograms of frequency of occurrence of critical points are shown below.
- The colours represent different topologies.

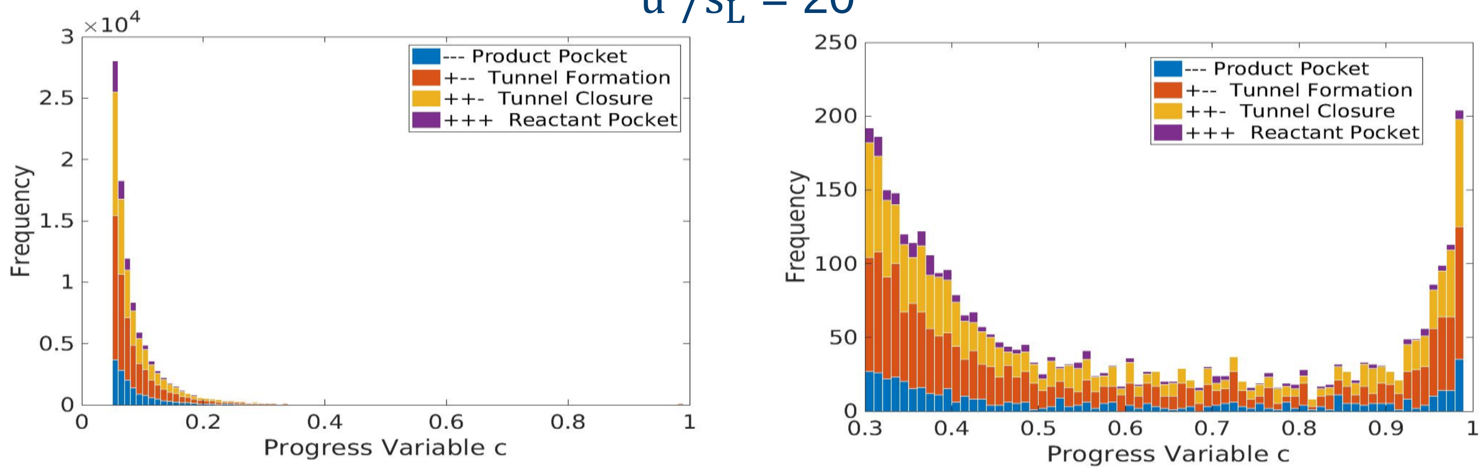


$u'/s_L = 10$

Histograms for single-step hydrocarbon flames

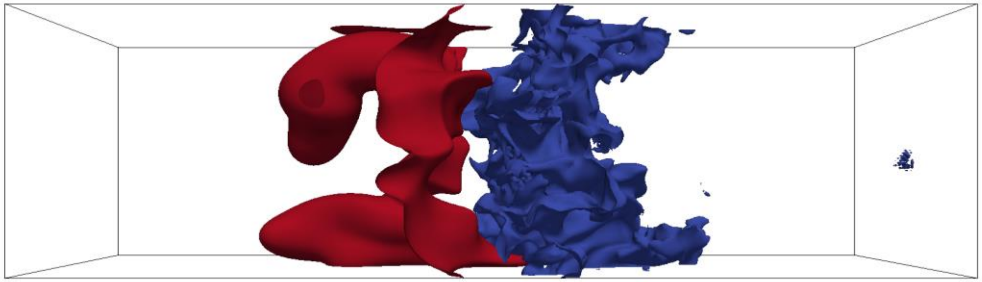


$u'/s_L = 20$

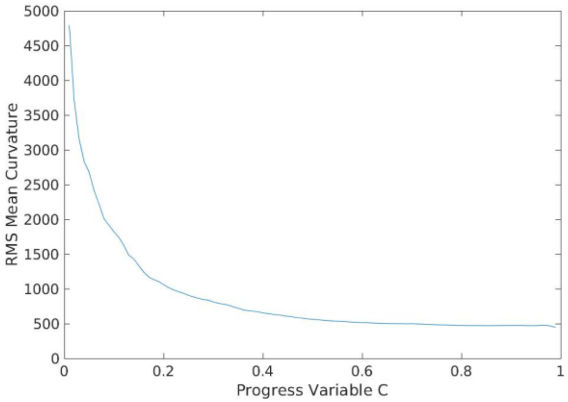


$u'/s_L = 30$

- No non-unity Lewis number or mean shear effects. Turbulence gets dissipated in the products side and hence, much fewer interactions.

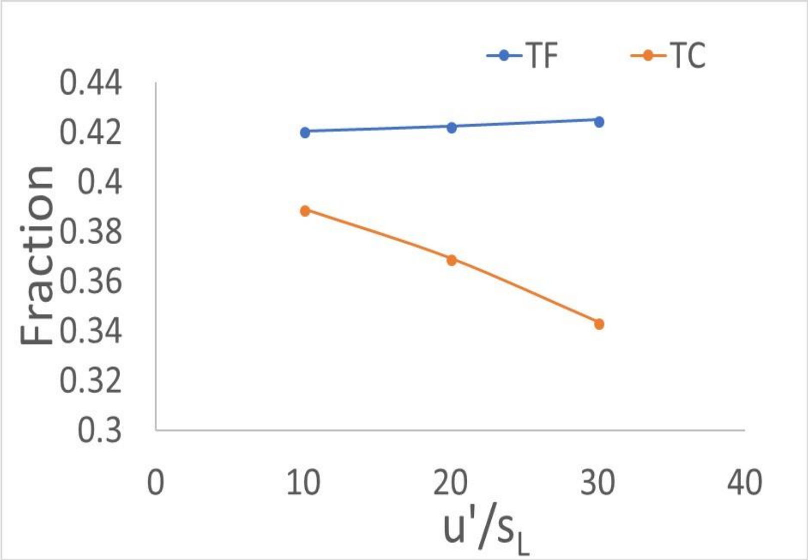


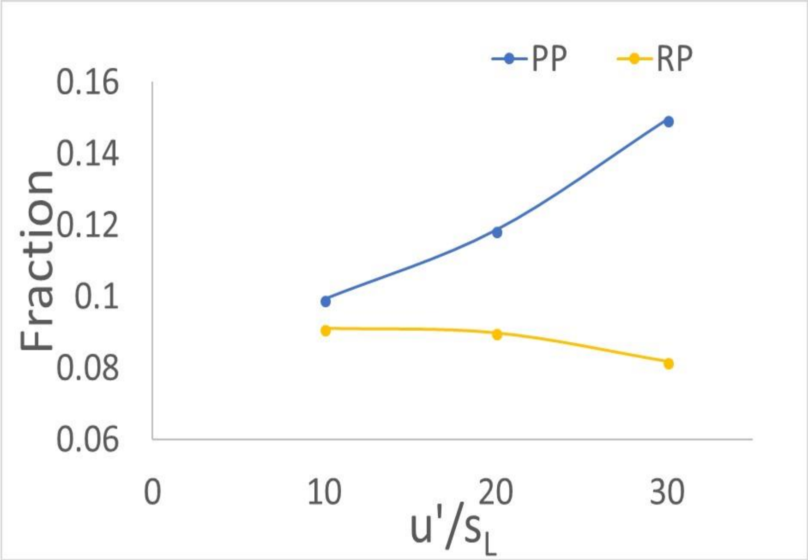
- Absolute mean curvature dissipates across the flame



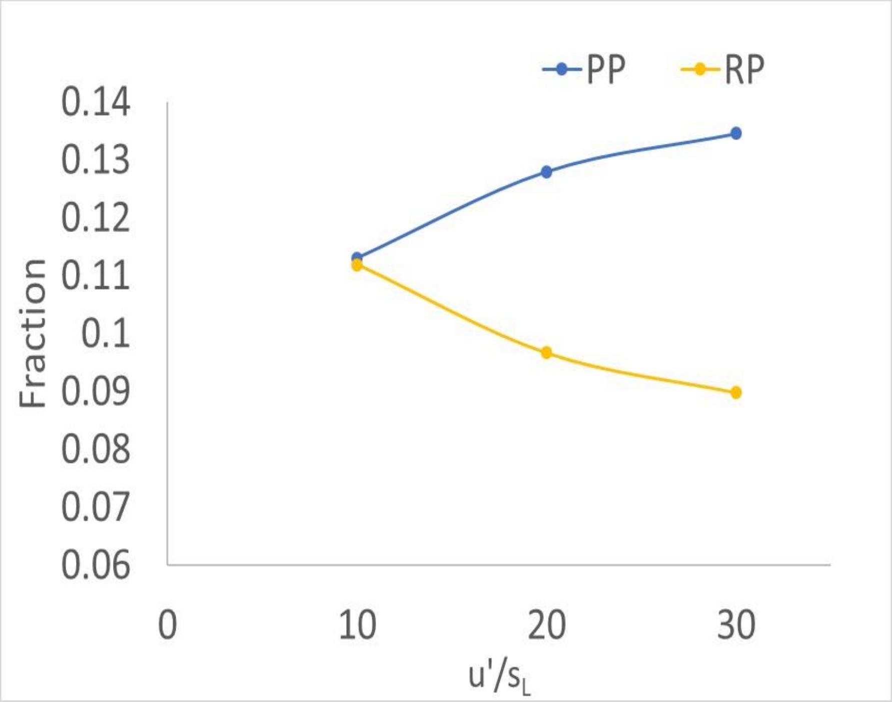
Topology fractions

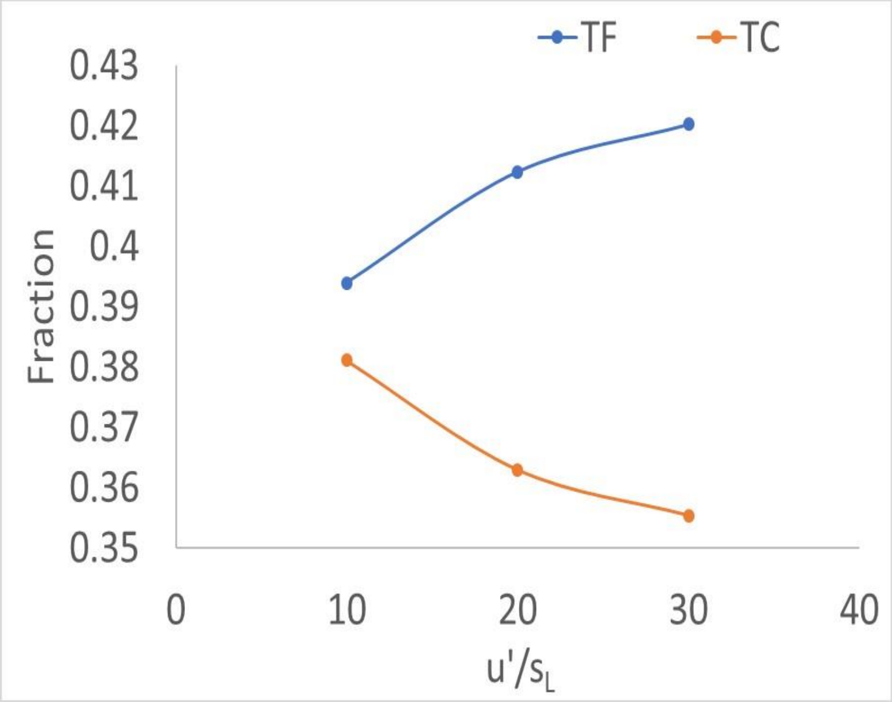
- The fractions of Tunnel Closure (TC) and Reactant Pocket (RP) both drop as the turbulence intensity increases, whereas the fractions of Product Pocket (PP) and Tunnel Formation (TF) rises.





Topology fractions





S. Trivedi, G.V. Nivarti, R.S. Cant: Proceedings of the Combustion Institute, 37(2018)

Conclusions

- Comparison between the flame-flame interaction in hydrogen and hydrocarbon flames is presented
- Flame-flame interactions in hydrogen flame in a shear generated turbulence found mostly at the trailing edge of the flame.
- In hydrocarbon flame-flame interactions are mostly found at the leading edge and are not frequent at the trailing edge.
- More interactions are found for higher turbulence intensities.
- There is an increase in product pocket (PP) and tunnel formation (TF) events with increasing turbulent intensity from $\mathrm{u}'/s_\mathrm{L} = 10$ to $\mathrm{u}'/s_\mathrm{L} = 40$ and a drop in reactant pockets (RP) and tunnel closure (TF) events.

Future Work

- Analyse hydrogen-air flame in a box to separate the effects of mean shear and Le<1 effects.
- In future studies, exact effect of each type of topology in terms of flame propagation and consumption speed will be investigated.
- Pocket burnout and tunnel closure are relatively fast events and hence might result in rapid destruction of flame area and reduced flame propagation speed.
- Use the results and statistics to come up with a model to describe flame area change due to flame-flame interactions.

Acknowledgements

archer

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Thank You