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Flame-Flame Interaction and Thermoacoustic Instability

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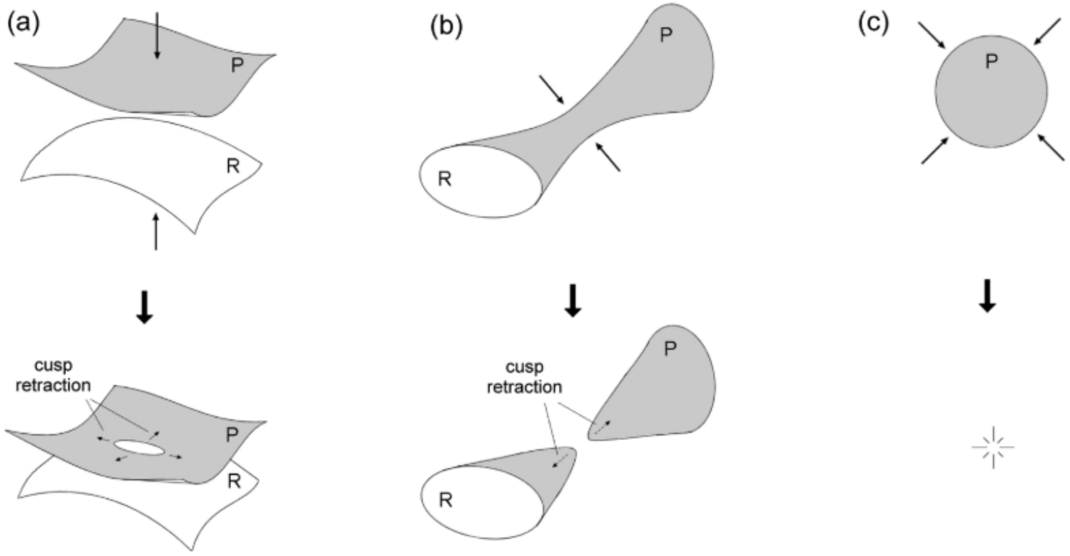
Motivation

- Flame-Flame interaction can :
  - Induce unstable mode bifurcation (J. Dawson et al. 2014)
  - Increase heat release (B. Ranganath et. al. 2006)
  - Change the symmetry of a system (N. Worth et al. 2012)
  - Create a major source of noise (M. Talei et al. 2012)
  - Influence driving forces for thermoacoustic instability (R. Balachandran et al. 2005)
  - Induce local changes in topology → Today's focus
- How do the flow/scalar topologies compare between a single flame and duel flames?
- Can multiple flames be modelled with a single equivalent?

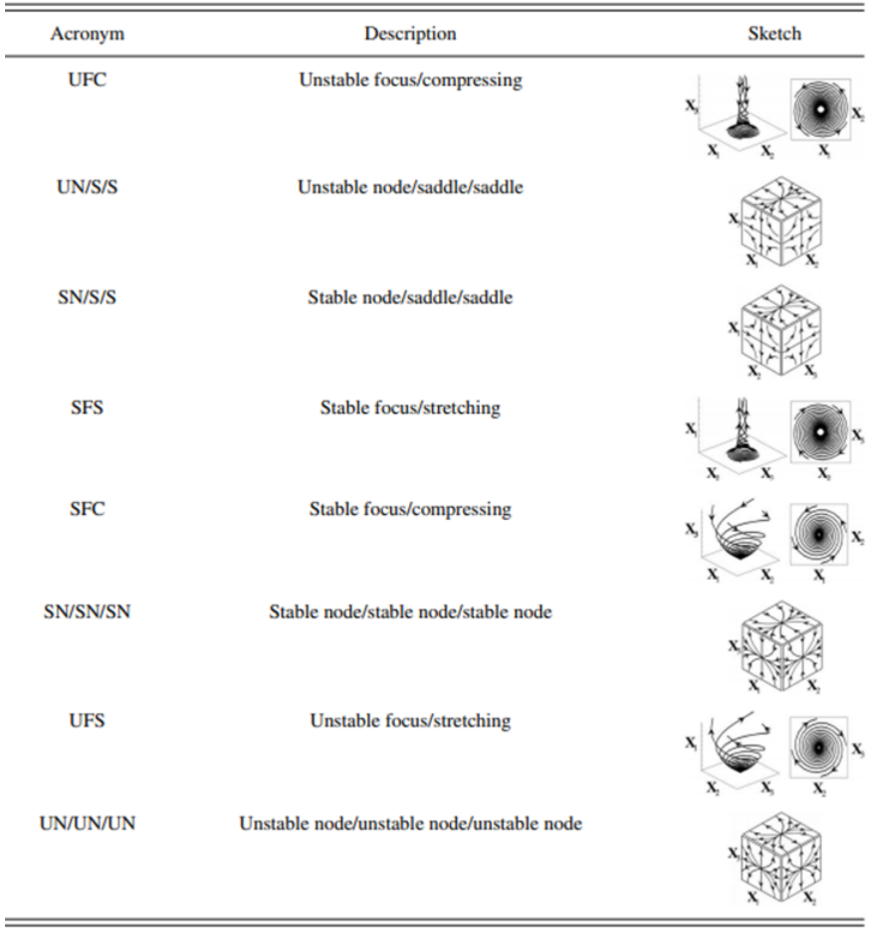
Type of interaction

- Normal Interaction:
  - -Initial acceleration
  - -Merging
  - -Cusp formation (negative curvature)
  - -Cusp recovery (loss of flame surface)
- Counter-normal Interaction:
  - -Against normal direction of propagation
  - -Driven by turbulence/high positive curvature
  - -Longer time scale



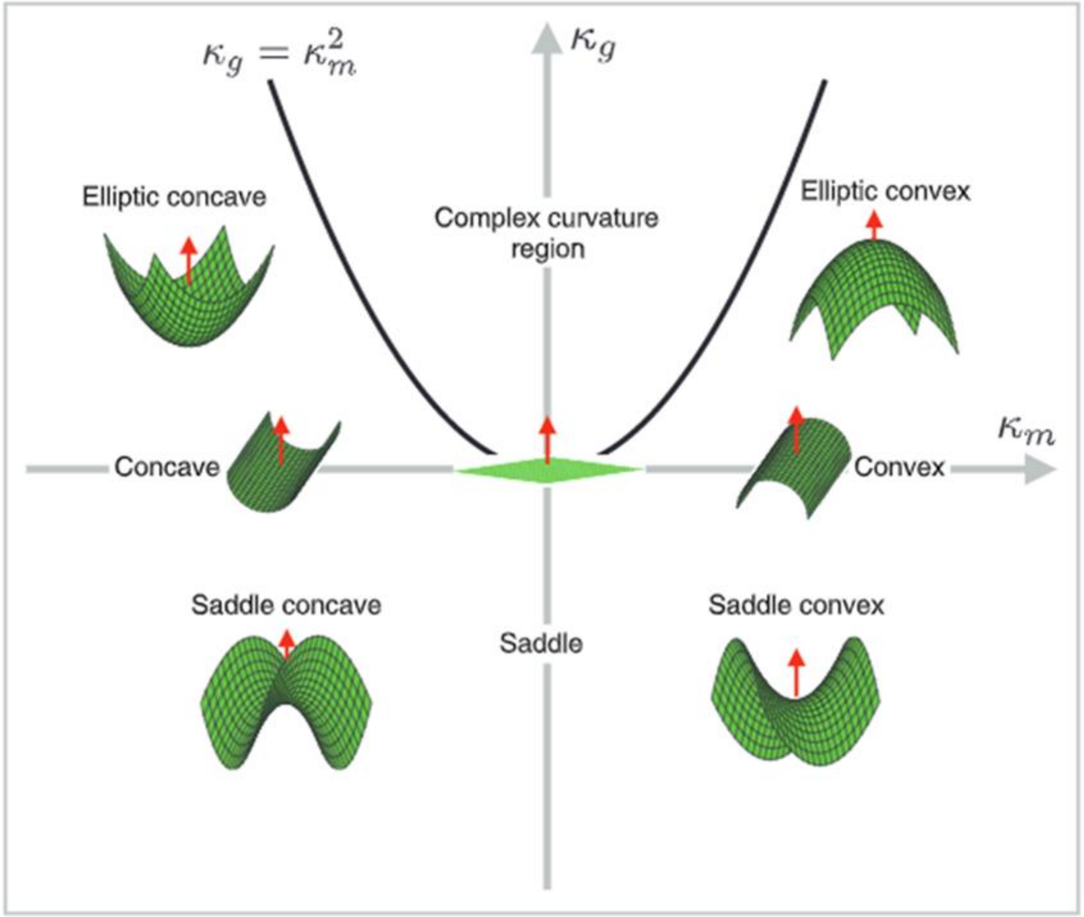
Source: T. Dunstan, N. Swaminathan et al. 2013

Flow and Scalar Topologies



Acronym	Description	Sketch
UFC	Unstable focus/compressing	
UN/S/S	Unstable node/saddle/saddle	
SN/S/S	Stable node/saddle/saddle	
SFS	Stable focus/stretching	
SFC	Stable focus/compressing	
SN/SN/SN	Stable node/stable node/stable node	
UFS	Unstable focus/stretching	
UN/UN/UN	Unstable node/unstable node/unstable node	

L. Cifuentes et al. 2016



W. Han et al 2019

Numerical Methodology

- CompReal- inhouse, finite difference code
- Fully compressible, density based solver
- Skew-symmetric (4th order) discretisation
- High order Runge-Kutta integration in time
- Chemkin interface
- Navier-Stokes Characteristic Boundary Conditions
- Turbulent inflow generator
- LES with modified Artificially Thickened Flame (ATF) closure – need to preserve gradients in regions of flame

ATF

“Classical”

- Transformation: $\xi(x) = \int \mathcal{F}(x')dx'$

$$\frac{\partial \rho Y}{\partial \tau} + \frac{\partial \rho u_i}{\partial \xi_i} - \frac{\partial}{\partial \xi_i}(\rho D \mathcal{F} \frac{\partial Y}{\partial \xi_i}) - \frac{\dot{\omega}}{\mathcal{F}} = 0$$

- Reduced effective source term “thickens” the flame but maintains correct flame speed
- Alters nature of turbulence/flame interaction
- Efficiency factor needed to model sub grid flame wrinkling

“Modified”

- Thicken momentum and energy transport equations as well – maintains correct Damkohler number

$$\frac{\partial \bar{\rho}\tilde{u}_i}{\partial \tau} + \frac{\partial \bar{\rho}\tilde{u}_i\tilde{u}_j}{\partial \xi_j} + \frac{\partial \bar{P}}{\partial \xi_i} = \frac{\partial 2\mathcal{F}\mu\bar{\tilde{S}}^*_{ij}}{\partial \xi_j} + (1-\Omega)\frac{\partial \tau^{sgs}_{ij}}{\partial \xi_j}$$

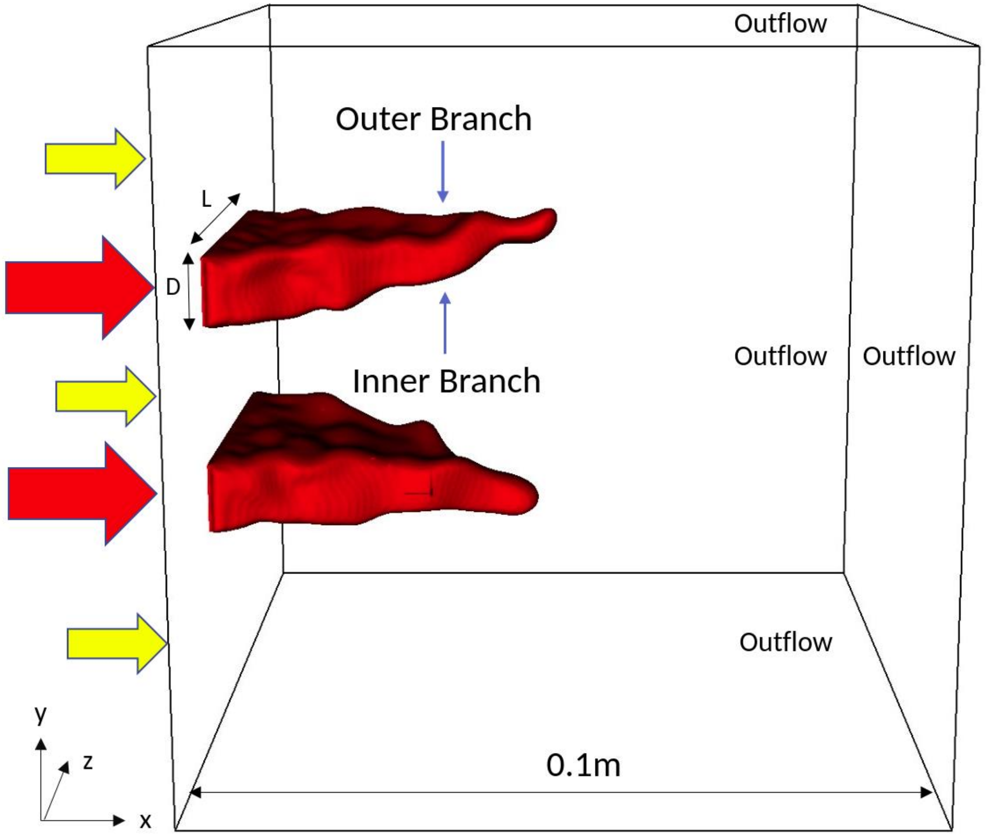
$$\frac{\partial \bar{\rho}\tilde{Y}_k}{\partial \tau} + \frac{\partial \bar{\rho}\tilde{u}_j\tilde{Y}_k}{\partial \xi_j} = \frac{\partial}{\partial x_j}\left(\bar{\rho}\mathcal{F}D\frac{\partial \tilde{Y}_k}{\partial \xi_j}\right) + (1-\Omega)\frac{\partial J^{sgs}_j}{\partial \xi_j} + \frac{\dot{\omega}}{\mathcal{F}}$$

$$\mathcal{F} = 1 + (\mathcal{F}_0 - 1)\Omega$$

- No need for efficiency factor

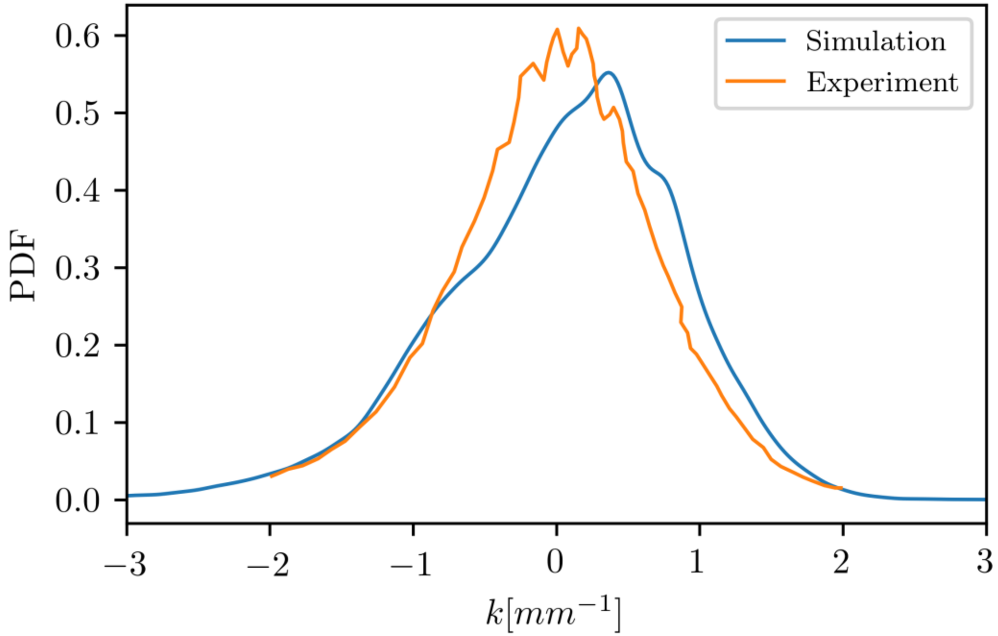
Numerical Setup

- Premixed methane/air flames at unity equivalence ratio
- 30mm flame separation distance
- Two different bulk velocities simulated (12 and 16 m/s) (add re and regime)
- A single flame at 12m/s also simulated for comparison
- 6 million mesh points per flame
- Used grid stretching to attain resolution of the order of unthickened laminar flame thickness
- After thickening have at least 10 points within flame



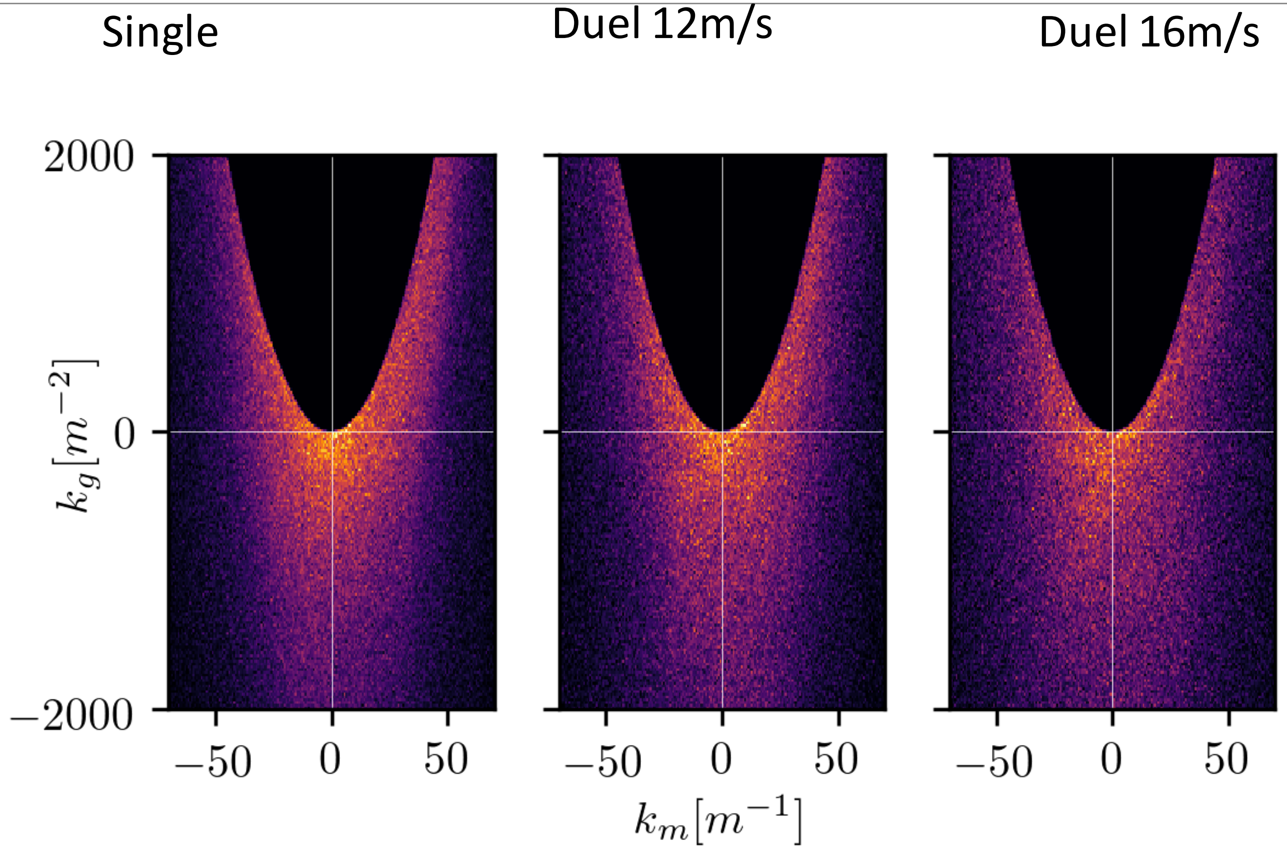
Mean Curvature

- Skewness factor of -0.57 compared with -0.52 from experiment
- Sampled over at least 10 eddy turnover times
- Rescaled into physical dimensions via thickening factor
- Rescaling does not affect *type* of scalar toplogy



Tyagi, Ankit, et al. Combustion and Flame (2019).

Scalar Joint PDFs

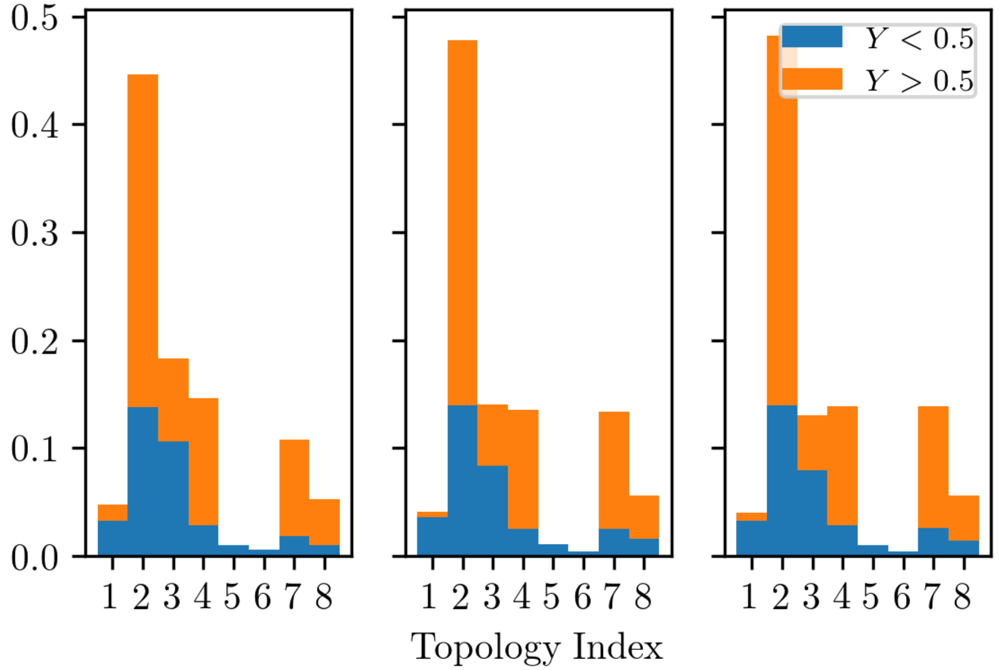


Scalar Structure

- Most probable topology is “nearly flat” as expected
- As velocity increases the distribution becomes wider (i.e. more wrinkling)
- Single flame favours slightly convex structures over slightly concave structures – this bias is decreased in duel flame cases
- Experiments suggest single flame has higher degree of normal flame-flame interaction than the duel case and vice-versa for counter-normal
- Overall, across all scales concave structures are more likely

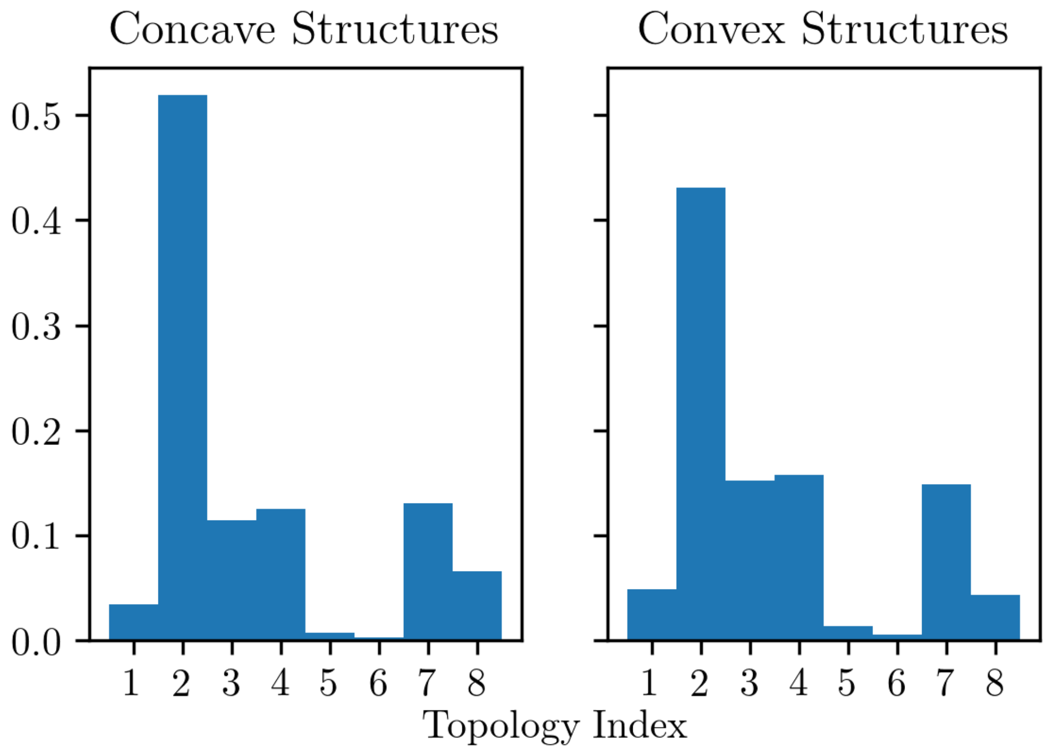
Flow Topologies

- S2 most dominant as expected
- S4 and S7 disappear due to destructive of vorticity by positive dilatation
- However S1 and S5 increase when going from reactant to product side – especially for duel flame case. Most likely this is due to the “opening” of the flames increasing compressive topologies
- When adding a second flame, note the increase in S2 and decrease in S3



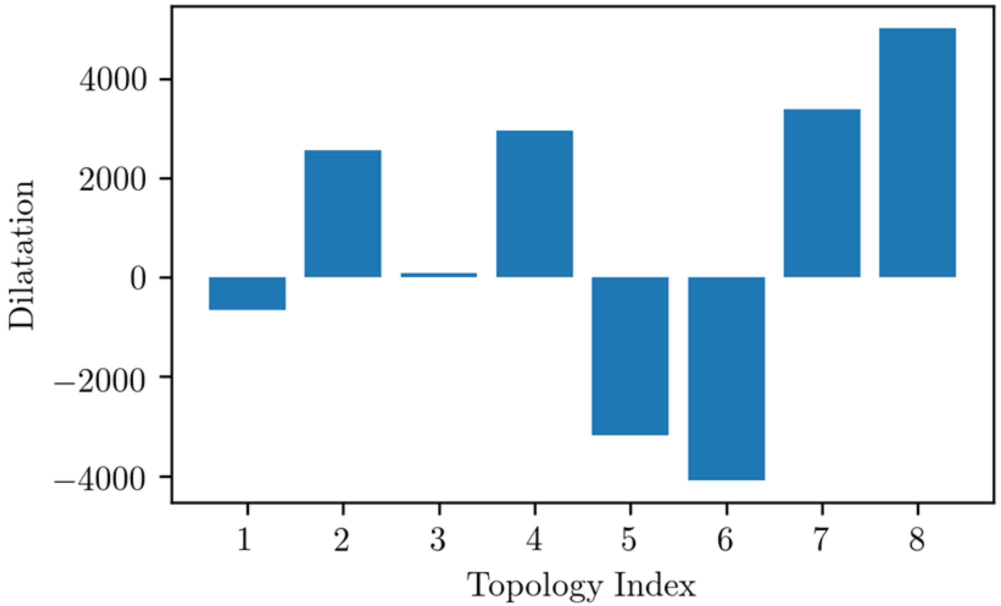
Influence of flow on scalar topologies

- S2- Mostly concave
- S3- Mostly convex
- Decrease in S3 in duel flames shown earlier could be one reason for preference of concave structures
- Proportion of concave structures is 51%,58% and 60% when compared across all scales for the single, duel slow and duel fast flames respectively



Impact of dilatation

- So why does S3 reduce in duel flames?
- S3 occurs in regions of very small dilatation
- Adding a second flame increases mean dilatation
- This could be one of the driving mechanisms for the reduction of S3 observed for duel flames

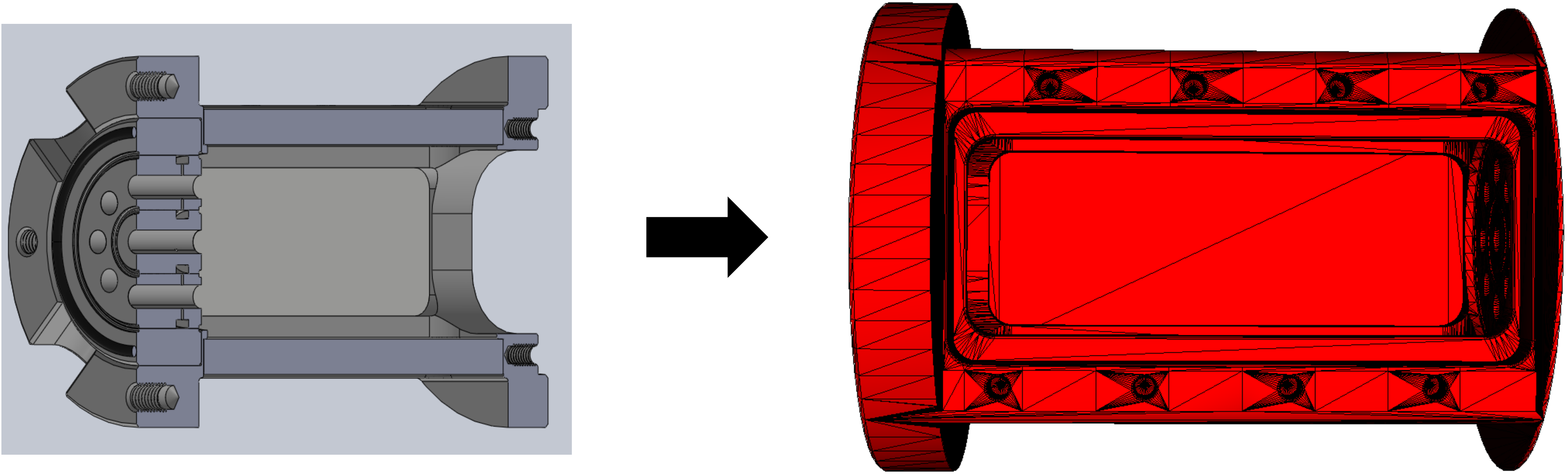


Conclusions

- Overall all flames prefer concave scalar structures over convex
- This agrees well with the experimental findings of normal flame-flame interactions being more prevalent than counter-normal
- Structures which were “nearly” flat showed the opposite trend and favoured convex structures locally for a single flame, this requires further investigation
- Compressive flow topologies not commonly observed in premixed flame were seen to persist across the flame – most likely due to the “opening” effect
- The main effect of adding a second flame was a reduction in convex structures
- This reduction can be attributed at least partly due to the changes in flow topology induced by dilatation

Future work

- Currently working on using AMR to investigate the effect of varying thickening factor
- Effects of varying flame spacing/acoustic forcing
- Extension to multiple flames and application to global stability



Any Questions?

THANK YOU FOR YOUR TIME