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DNS analysis of flame propagation for systematic variations in turbulence scales and intensity

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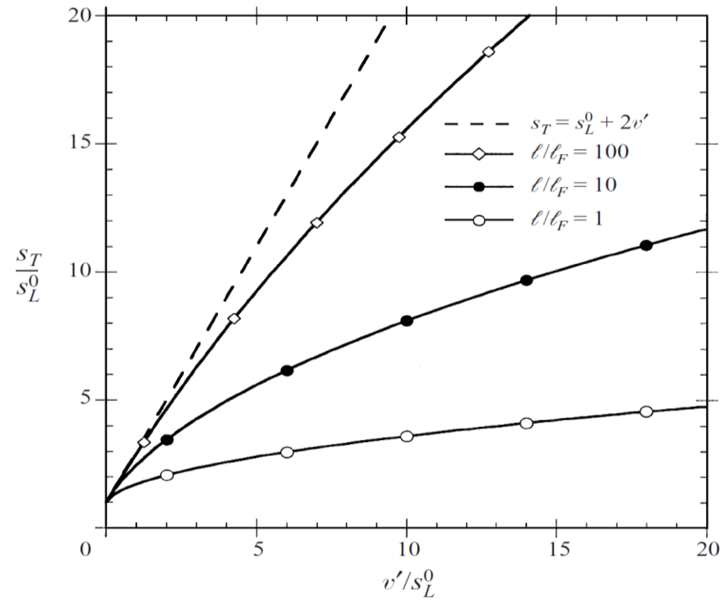
Introduction

- Flame speed, area and number of flame-flame interactions change with both intensity of turbulence and its associated length scales.
- Most studies focus on variation of turbulence intensity.
- Current analysis provides DNS datasets with systematic variations in turbulence intensity u' as well as integral length scales l_0 .
- Figure shows prediction by Peters [1].



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1. N. Peters "The turbulent burning velocity for large-scale and small-scale turbulence". Journal of Fluid Mechanics 384 (1999), pp. 107–132

Flame Speed and Area

- In corrugated flame regime the flames speed and flame area follow the relation

$$\frac{s_T}{s_L} \sim \frac{A_T}{A_L} => \frac{s_T}{s_L} = \frac{A_T}{A_L} I_0$$

where s_T and A_T can be evaluated as

$$s_T = -\frac{1}{\rho_u Y_{u,F} A_0} \int_V \omega_F dV$$

$$A_T = \int_{-\infty}^{\infty} \Sigma \delta (c - c^*) dV$$

- In thin reaction zones regime, turbulent diffusivity D_T can also affect the flame propagation.

$$s_T / s_L = \frac{A_T}{A_L} \left(1 + \frac{D_T}{D}\right)^{1/2}$$

Flame-Flame Interactions

- Evaluated by finding critical points [2, 3]
- 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.

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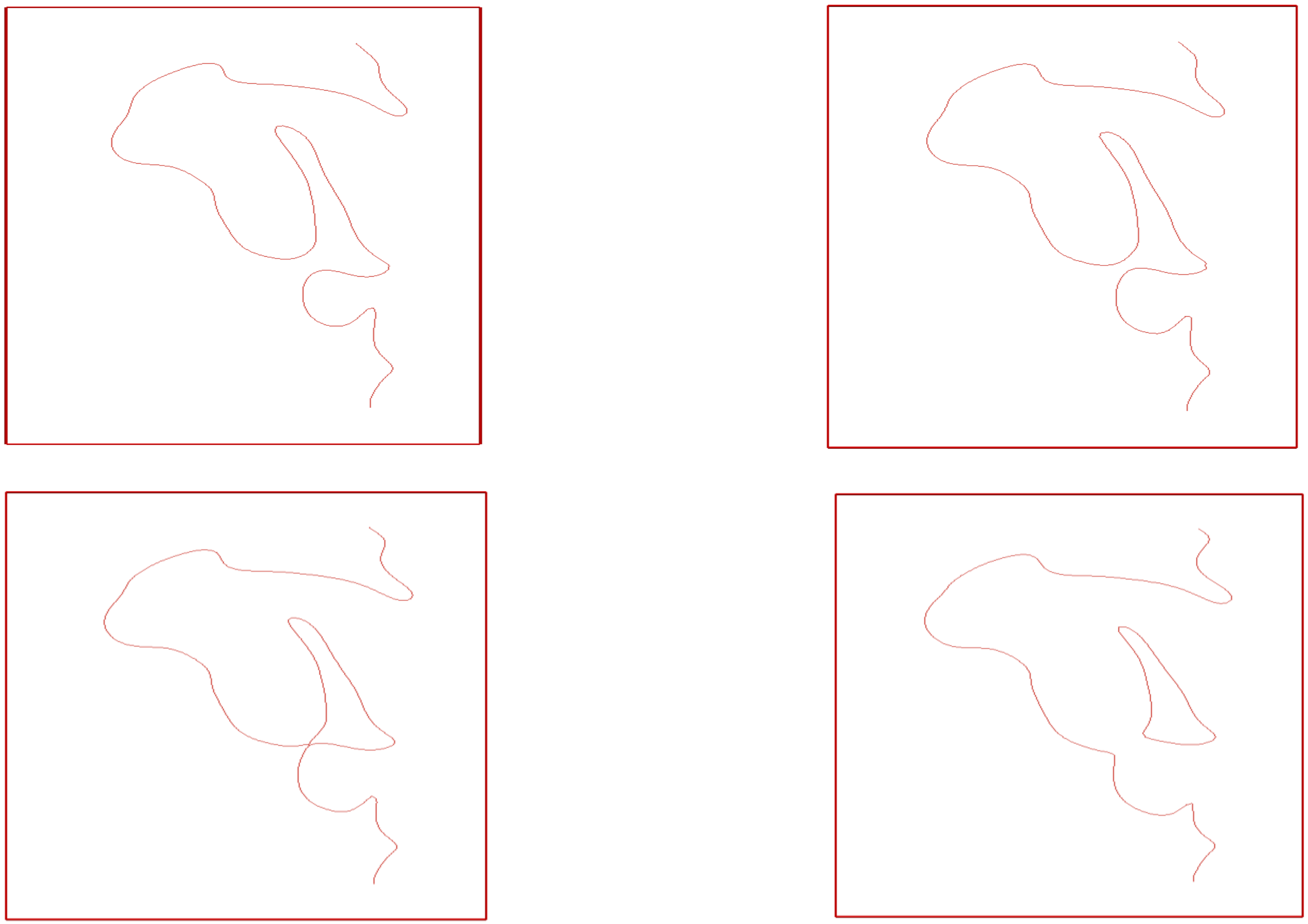
2. J. Milnor, Analysis of Math. Studies, Princeton University Press (1963) p. 51.
3. R.A.C. Griffiths, J.H. Chen, H. Kolla, R.S. Cant, W. Kollman, Proceedings of the Combustion Institute, 35 pp. 1341-1348 (2014)

Flame-Flame Interactions (contd…)



Objectives

1. Create a well resolved DNS dataset with systematic variations in integral length scale l_0 as well as turbulence intensity u'.

2. Evaluate the flame properties such as flame speed, flame area and flame-flame interactions.

3. Find something interesting.

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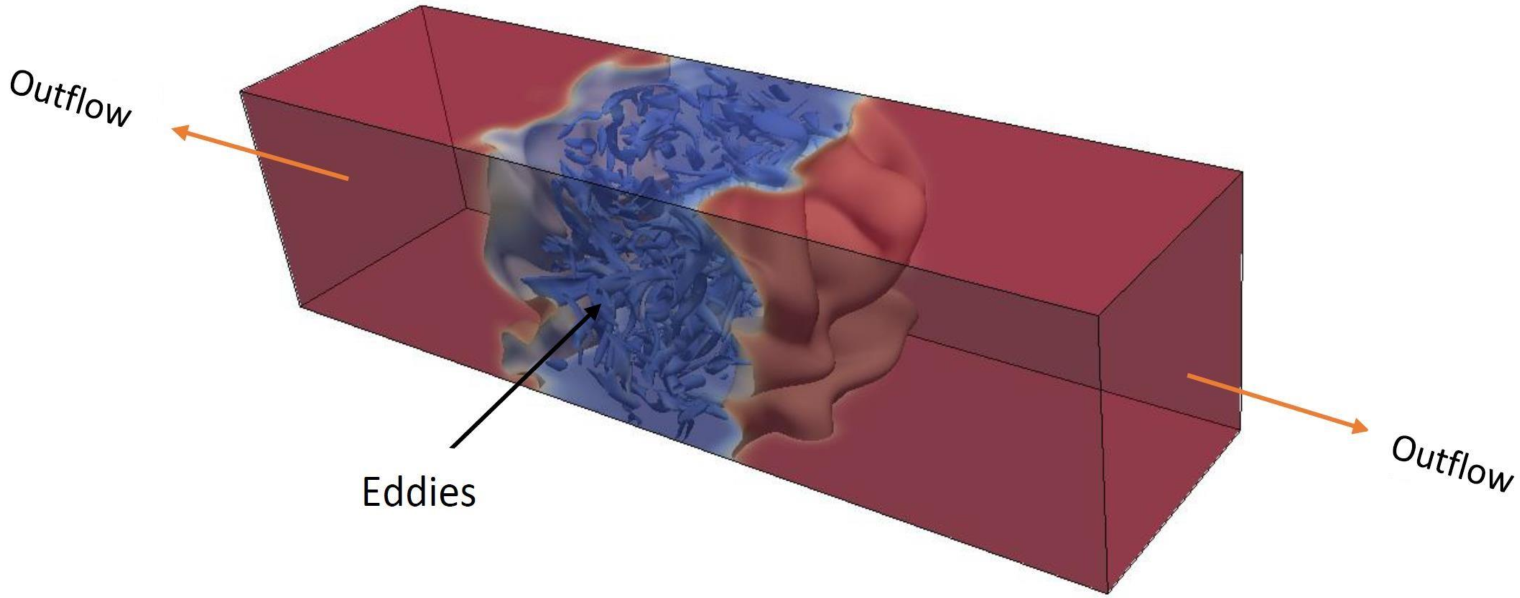
Numerical analysis

- DNS code Senga2 written by Professor Stewart Cant based on tenth-order finite-difference scheme for spatial discretisation and fourth order five-stage Range-Kutta algorithm for time-stepping
- The Navier-Stokes equation is solved in fully compressible form together with continuity, energy and species equations.
- Both reduced and detailed chemical schemes are available for hydrogen-air and methane-air combustion
- The Navier-Stokes Characteristic Boundary Condition (NSCBC) formulation is used to set up boundary conditions in Senga2

DNS Dataset Description

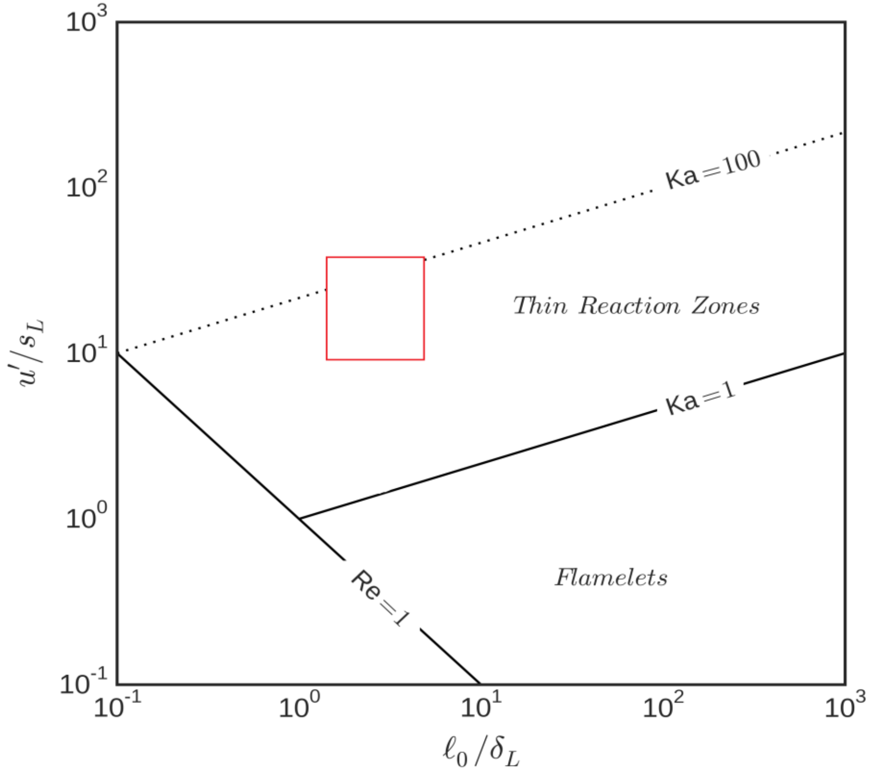
- A pair of statistically planar flames facing each other with fresh reactants between them are simulated in a cuboidal domain of cross section 5mm x 5mm.
- The boundaries are set as periodic in the y− and z−directions. Both the +x and −x boundaries are set as outflow
- The mesh spacing is varied in each case to match the Kolmogorov scale.

Twin Flame Configuration



Dataset description

- Turbulence intensity u' is systematically varied from $10s_L$ to $40s_L$, whereas the integral length scales are varied from $l_0 = 5.0\delta_L$ to $1.25\delta_L$.



DNS Dataset – The Matrix

	$\ell_0 = 5\delta_L$	$\ell_0 = 2\delta_L$	$\ell_0 = 1.25\delta_L$
$u' = 10s_L$			
Ka	14.14	22.36	28.28
Da	0.5	0.2	0.125
Re	50	20	12.5
η (μm)	39.27	24.85	20.33
Δx (μm)	41.66	26.04	20.833
$u' = 20s_L$			
Ka	40.0	63.25	80.0
Da	0.25	0.1	0.0625
Re	100	40	25
η (μm)	28.76	18.19	14.38
Δx (μm)	26.04	17.36	13.02
$u' = 30s_L$			
Ka	73.5	116.2	
Da	0.166	0.0667	
Re	150	60	
η (μm)	23.48	14.85	
Δx (μm)	22.72	13.02	
$u' = 40s_L$			
Ka		178.9	
Da		0.05	
Re		80	
η (μm)		12.86	
Δx (μm)		11.90	

Twin Flame Configuration

(a) $\ell_0 = 5.0\delta_L$

(b) $\ell_0 = 2.0\delta_L$

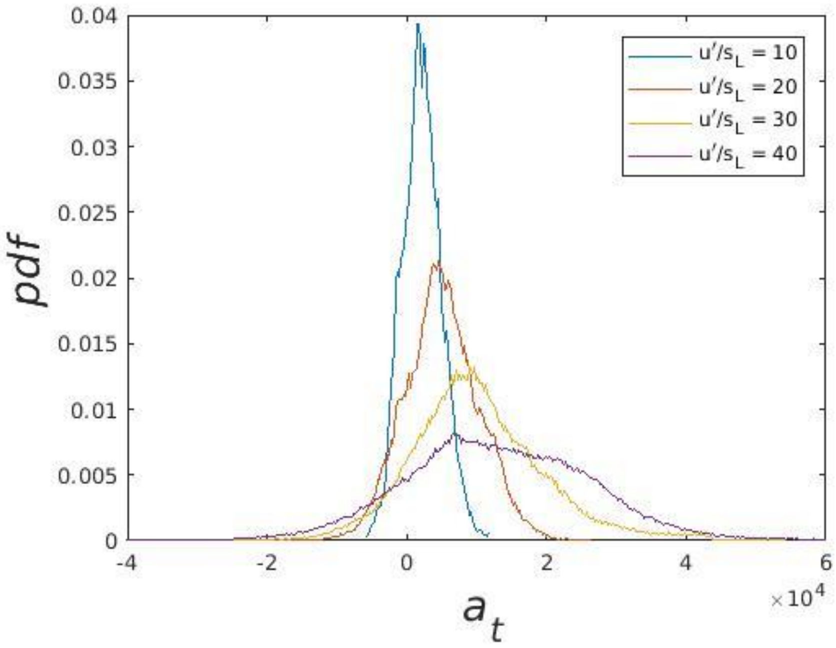
(c) $\ell_0 = 1.25\delta_L$

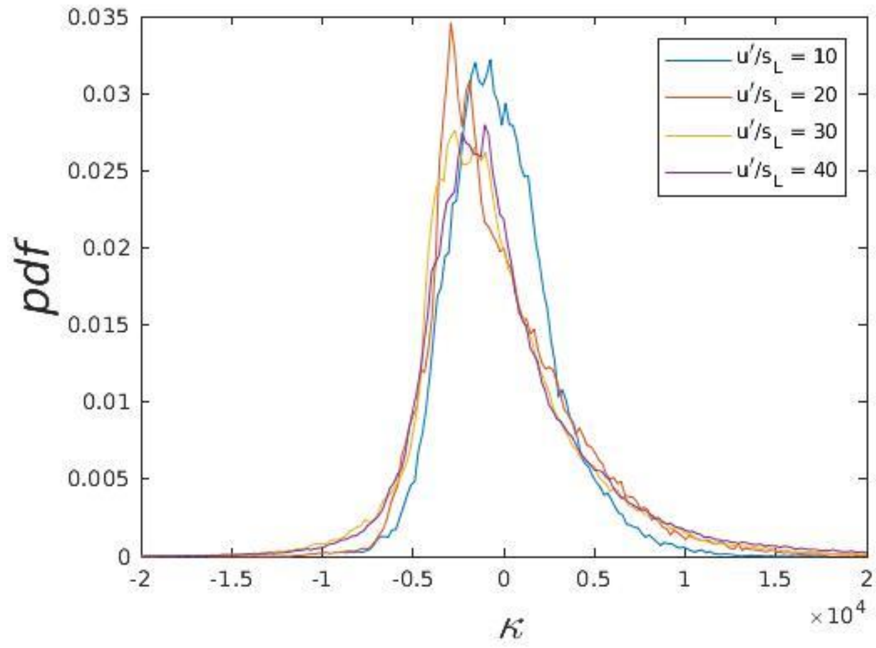
Results Strain and Curvature PDFs

- Pdfs for varying u' are presented here represented by different colours.
- All cases correspond to $l_0 = 2.0\delta_L$

$$a_T = (\delta_{ij} - n_i n_j)\frac{\partial u_i}{\partial x_j}$$

$$\kappa = \frac{1}{2}\frac{\partial n_i}{\partial x_i}$$

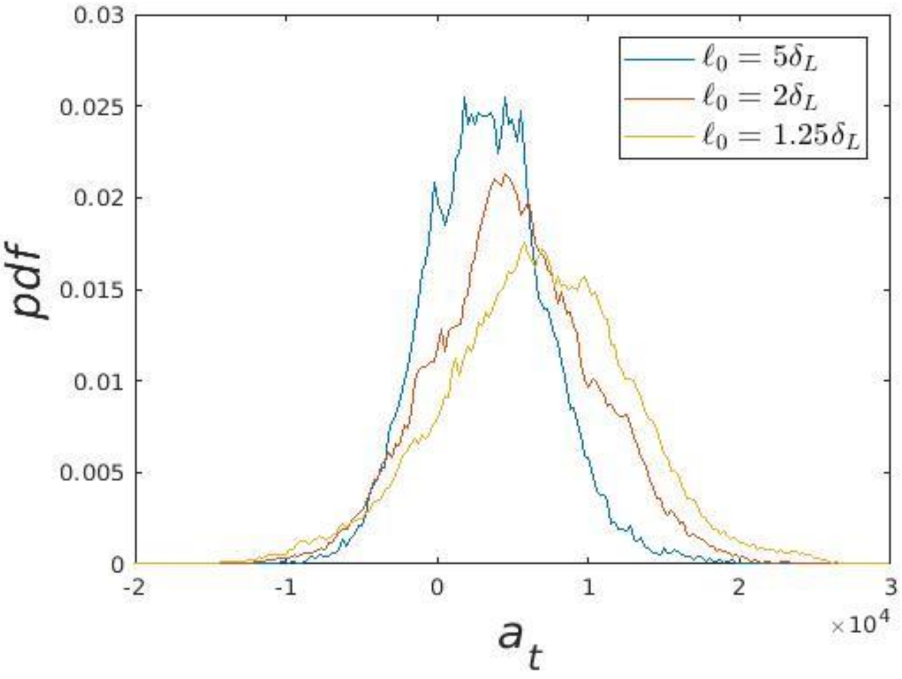


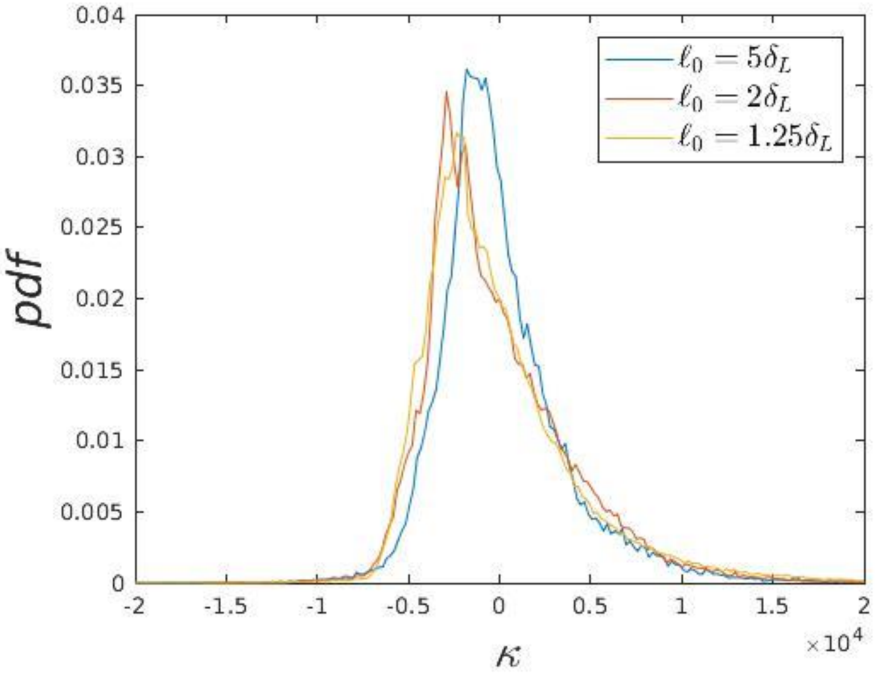


G. V. Nivarti and R. S. Cant. "Direct numerical simulation of the bending effect in turbulent premixed flames". Proceedings of the Combustion Institute 36 (2017), pp. 1903–1910.

Results – Strain and Curvature PDFs

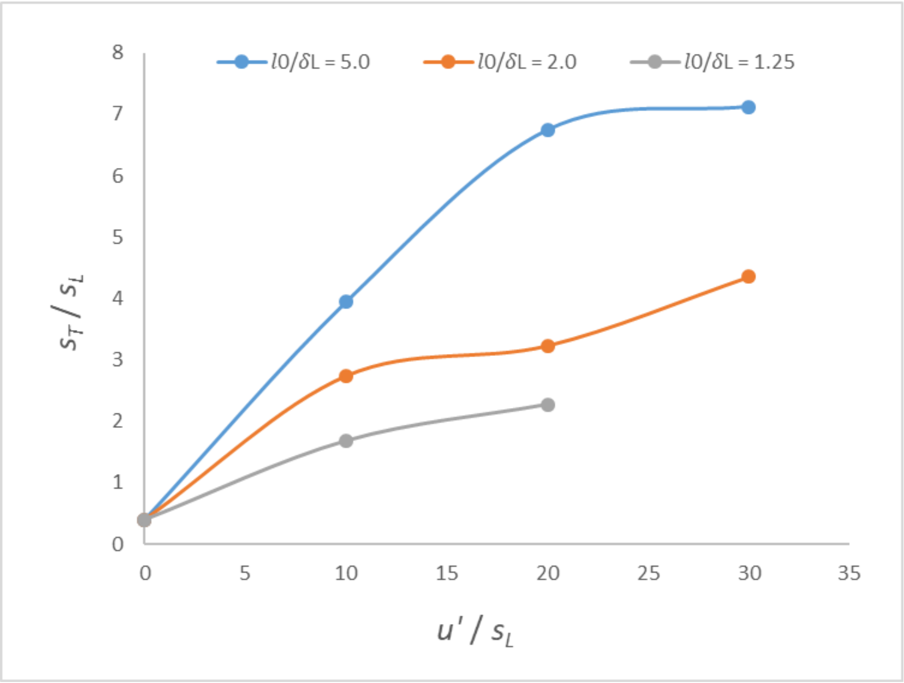
- Tangential Strain Rate and Mean Curvature pdfs for varying l_0 and u'/s_L = 20 are presented here represented by different colours.



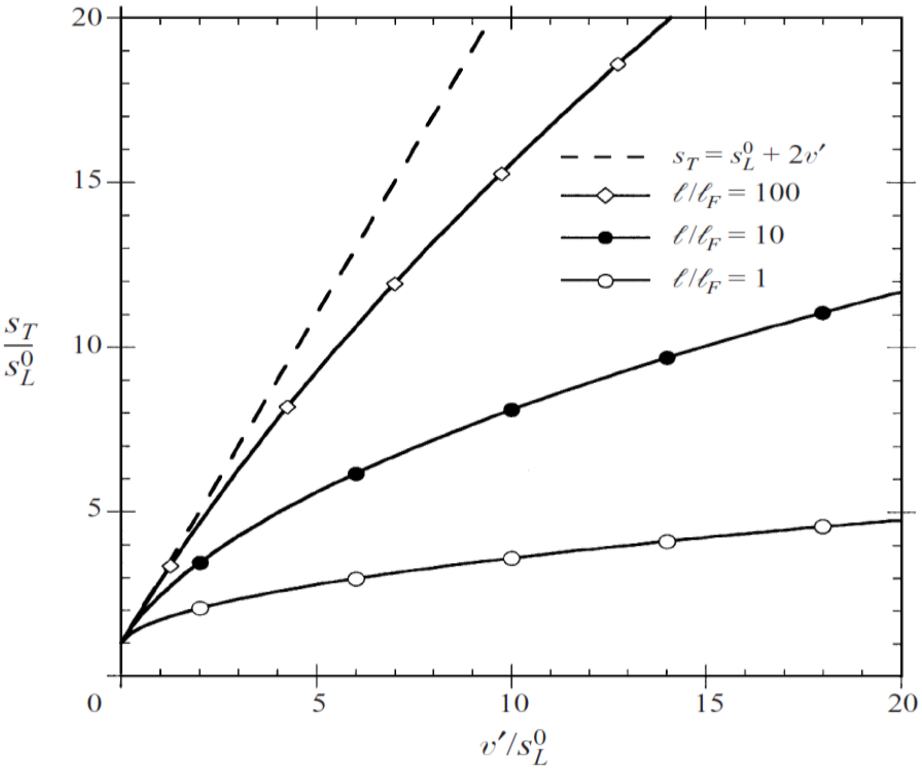


Flame Speed, Area and Flame-Flame Interactions

u'	ℓ_0/δ_L	s_T/s_L	A_T/A_L	I_0	FF
$10s_L$	5.0	3.94	3.89	1.012	1987
	2.0	2.74	2.75	0.996	4551
	1.25	1.68	1.71	0.984	5745
$20s_L$	5.0	6.74	6.41	1.050	16882
	2.0	3.23	3.22	1.002	24506
	1.25	2.27	2.37	0.958	31574
$30s_L$	5.0	7.12	6.52	1.091	59966
	2.0	4.35	4.17	1.042	67779
$40s_L$	2.0	4.388	4.147	1.058	153606



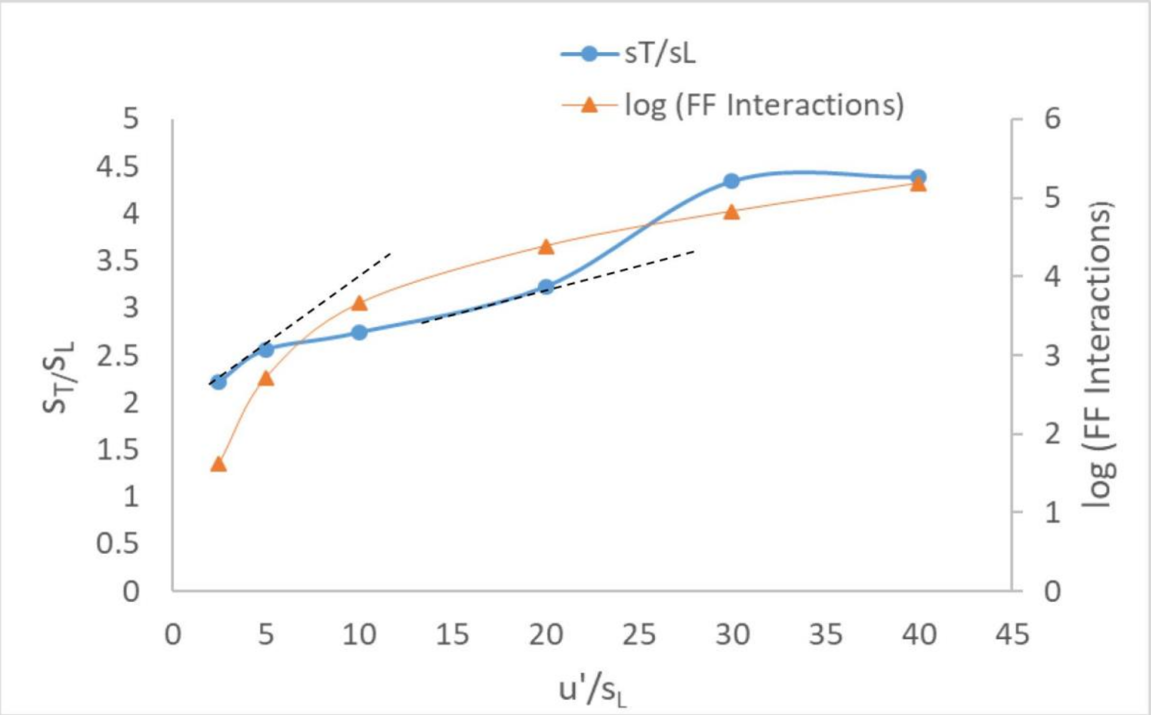
l0/δL = 5.0
l0/δL = 2.0
l0/δL = 1.25
s_T / s_L
u' / s_L
0
1
2
3
4
5
6
7
8
0
5
10
15
20
25
30
35



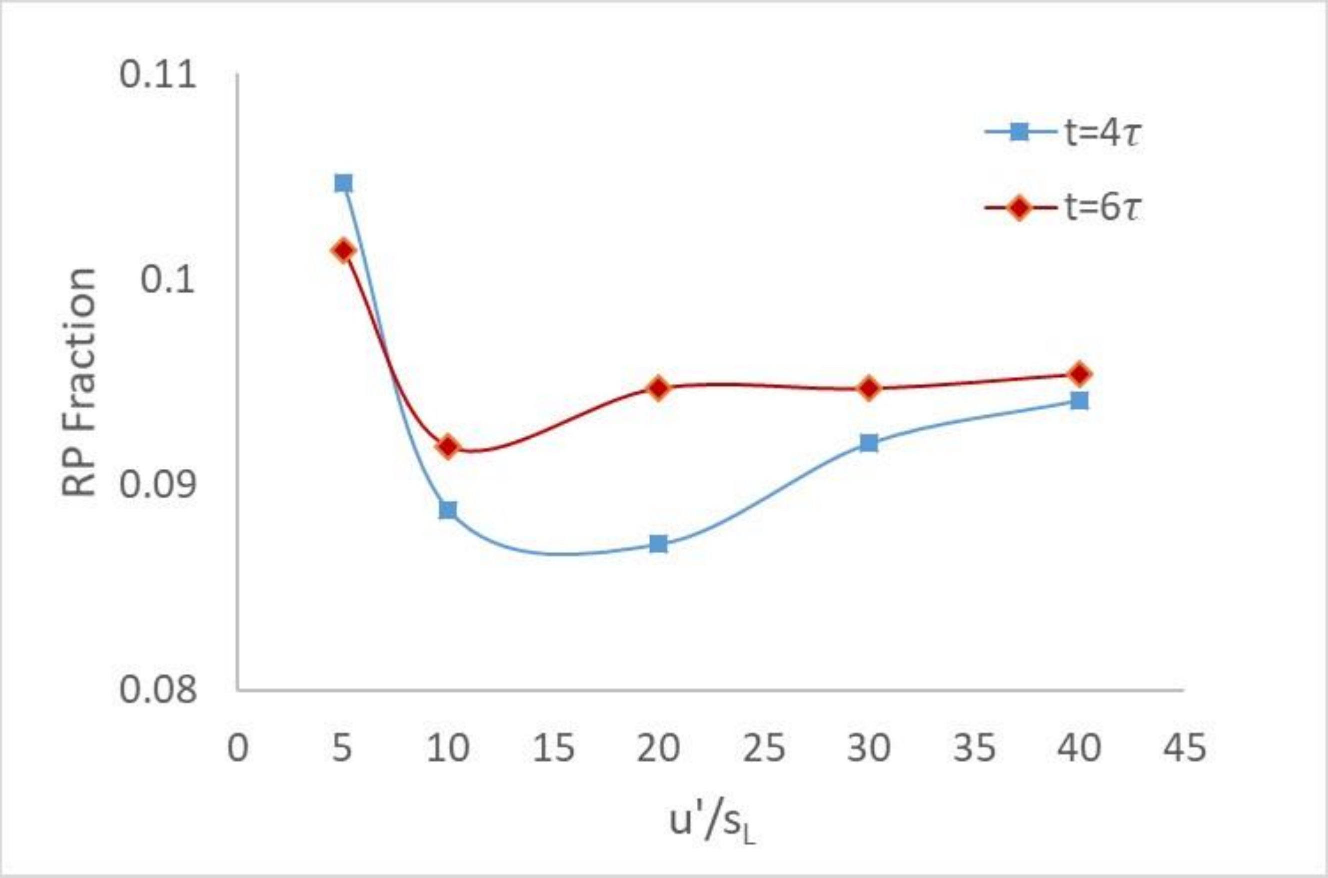
$s_T = s_L^0 + 2v'$
$\ell/\ell_F = 100$
$\ell/\ell_F = 10$
$\ell/\ell_F = 1$
$\frac{s_T}{s_L^0}$
v'/s_L^0
0
5
10
15
20

Bending (and Reverse Bending?)

- Flame speed at different values of u'/s_L and fixed l_0 (= $2.0\delta_L$)
- Orange line shows the log of total number of flame-flame interactions.



Bending (and Reverse Bending?)



Future Work

- In progress: DNS dataset with variation in both integral length scales l_0 and turbulence intensity u'.
- Run the simulation longer to get better estimate of flame properties.
- Study the effects of flame-flame interactions on overall flame propagation.
- Evaluate turbulent diffusivity D_T : transition between DH1 and DH2.

Acknowledgements

UK CTRF
UK CONSORTIUM ON TURBULENT REACTING FLOWS

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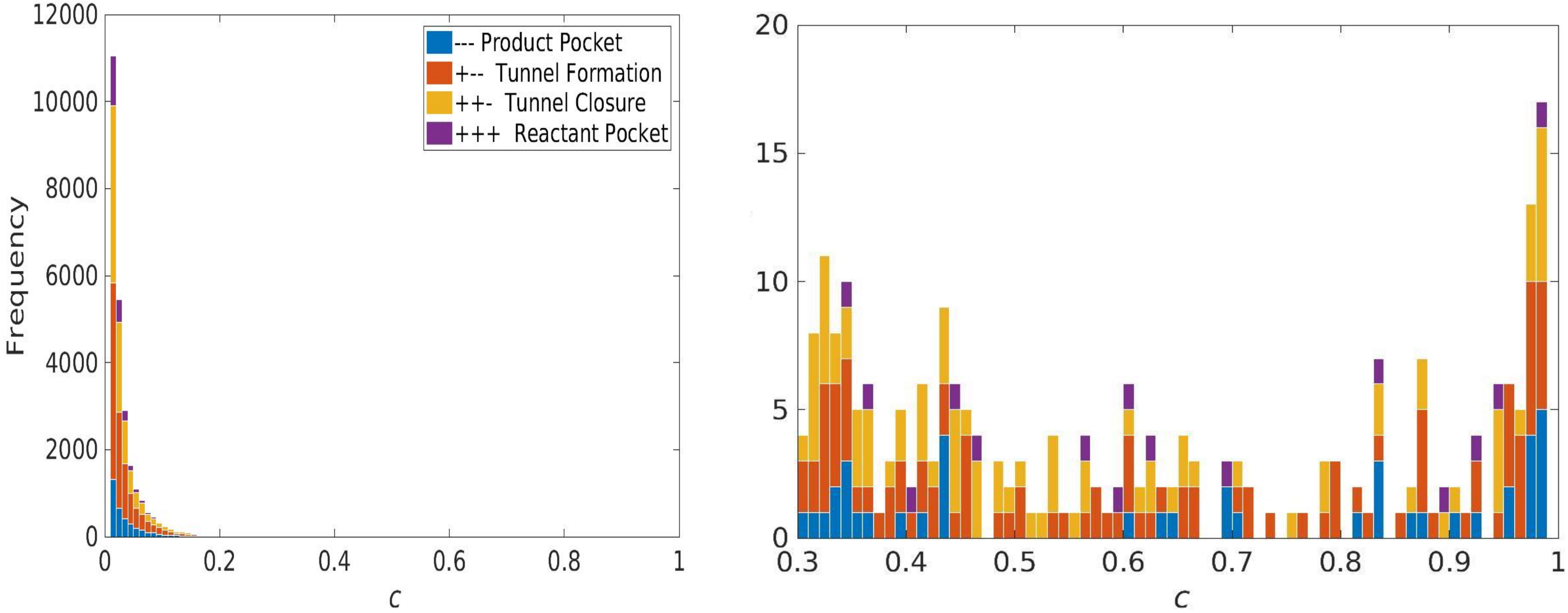
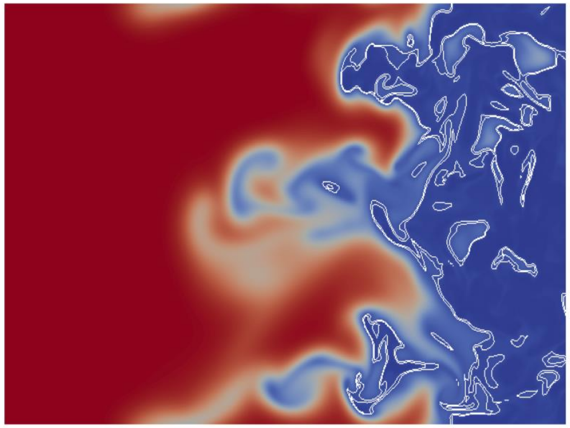
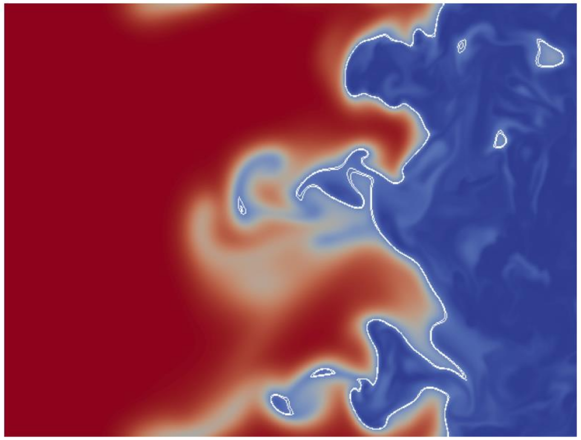


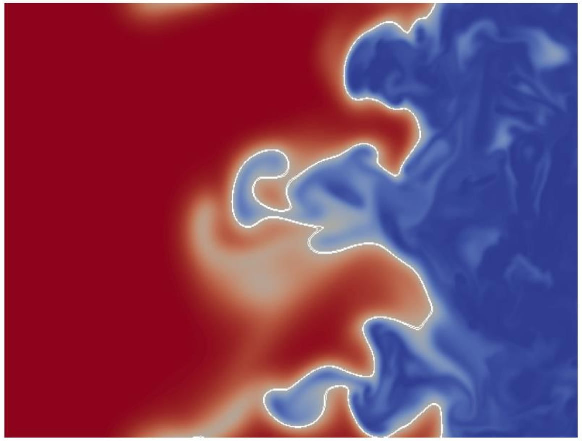
--- Product Pocket
+-- Tunnel Formation
++- Tunnel Closure
+++ Reactant Pocket
Frequency
c
c



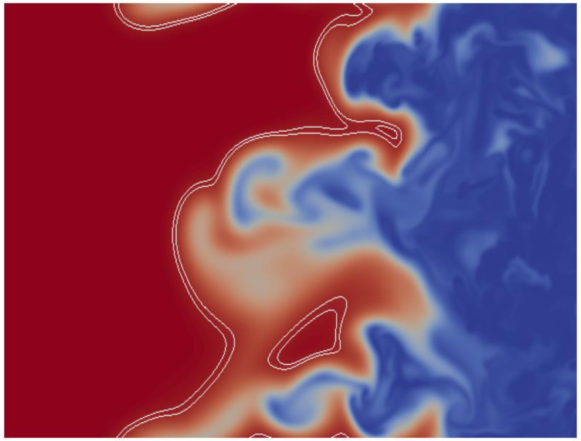
(a) Iso-contours at $c = 0.05$ and 0.07



(b) Iso-contours at $c = 0.20$ and 0.22



(c) Iso-contours at $c = 0.50$ and 0.52



(d) Iso-contours at $c = 0.90$ and 0.92