Flame Self-Interaction and Flow Topology in Turbulent Homogeneous Mixture n-heptane MILD Combustion

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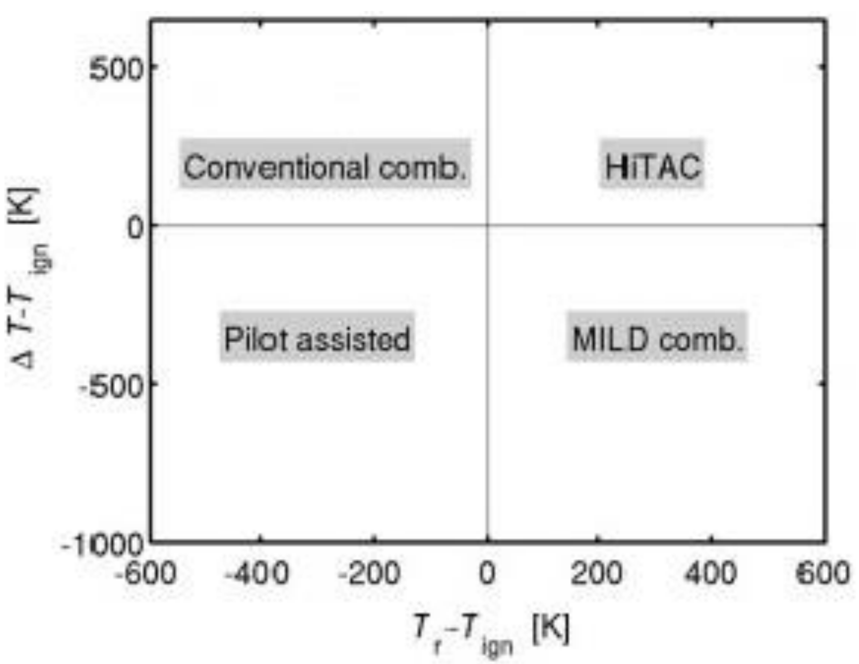
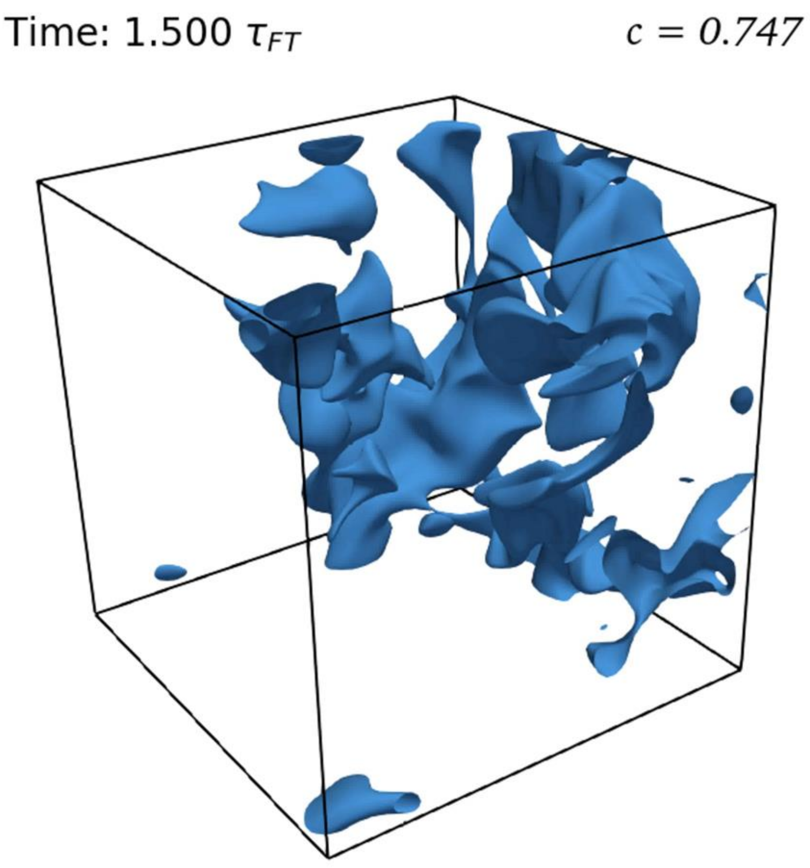
Introduction

- New stringent environmental regulations necessitate the development of novel combustion techniques that are both highly efficient and environmentally friendly is becoming more pressing
- Moderate or Intense Low-oxygen Dilution (MILD) combustion is one such technique that shows potential to achieve both high-energy efficiency and ultra-low emissions



Introduction

- OH-PLIF visualisations showed the presence of flame fronts in MILD combustion[1]
- Indications of distributed burning were revealed through temperature measurements[1]
- Minamoto, Swaminathan and co-workers[2] indicated that the distributed burning could be due to the interaction of thin reaction zones



1. T. Plessing, N. Peters and J. G. Wünning, Proc. Comb. Inst, 27 (1998) 3197-3204
2. Y. Minamoto, N. Swaminathan, R. S. Cant, T. Leung, Combust. Flame, 161 (2014) 2801-2814

Introduction

Local Flame Topology

- Local Flame Self-interactions topology influences the occurrence of events such as pocket burnout and cusp formation
- Such events significantly affect the balance of flame area production and destruction, and thus have and influence on overall burning rate and flame propagation.
- The geometry of the flame and the local topology of FSI events play an important role when using the flamelet approach.

Objectives

- Assess the probability of the various FSI events in a homogeneous mixture n-heptane MILD combustion.
- Investigate the effects of turbulence intensity and dilution level on FSI.
- Investigate the link between local flow topology and FSI events.

Characterizing Flame Topology

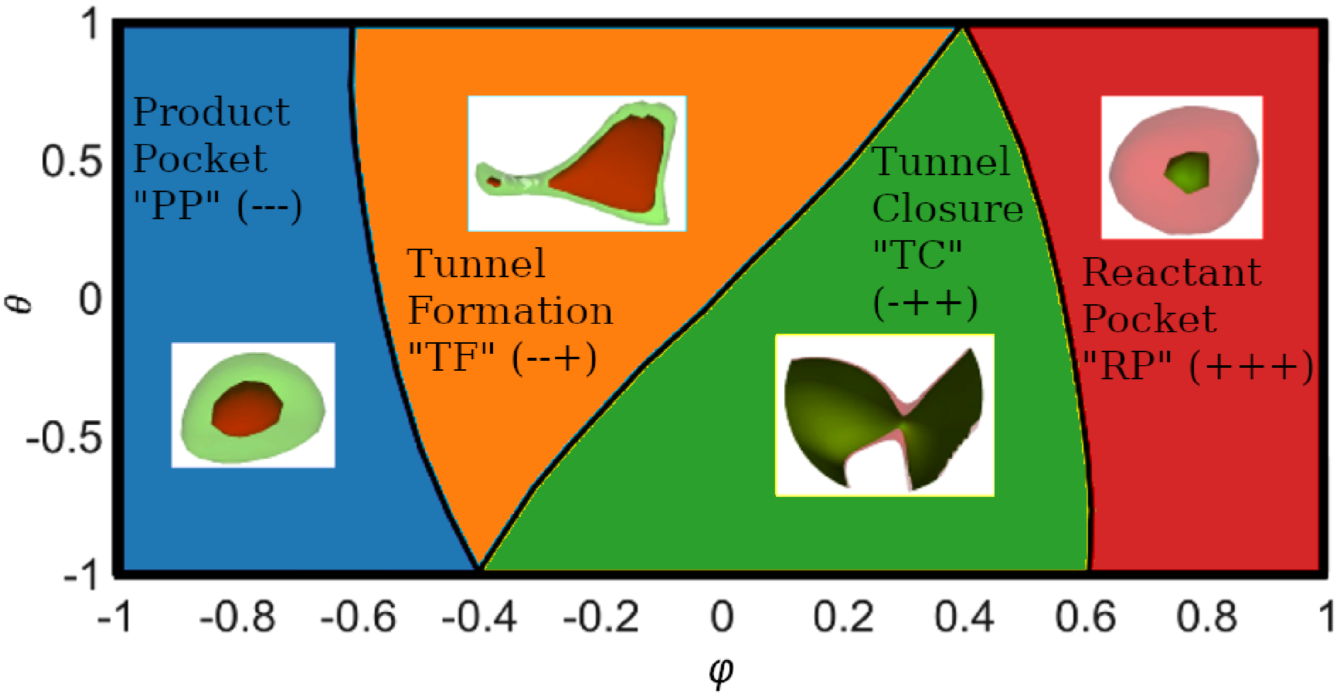
- Critical point theory as reported by Griffith et al.[1]
- Automatic feature extraction using complex wavelet transform, e.g. Dunstan et al.[2]
- Minkaowski functional based approach
  - In MILD combustion, Minamoto et al.[3] used Minkaowski functionals to study the morphology of the reaction zones in methane-air mixtures

1. R. A. C. Griffiths, J. H. Chen, H. Kolla, R. S. Cant, and W. Kollmann. Proc. Combust. Inst., 35 (2015) 1341–1348
2. T. D. Dunstan, N. Swaminathan, K. N. C. Bray, and N. G. Kingsbury. Combust. Sci. Tech., 185(2013):134–159
3. Y. Minamoto, N. Swaminathan, R. S. Cant, T. Leung, Combust. Flame, 161 (2014) 2801-2814

Methodology

- The critical point theory has been adopted in this study to both flame and flow topologies:
  – FSI following the methodology by Griffith et al.(2015)

$$c(\mathbf{a}+\mathbf{x}) = c(\mathbf{a}) + 0.5\mathbf{x}^T \underline{\underline{\mathbf{H}}}\big(c(\mathbf{a})\big)\mathbf{x} + \cdots$$



Methodology

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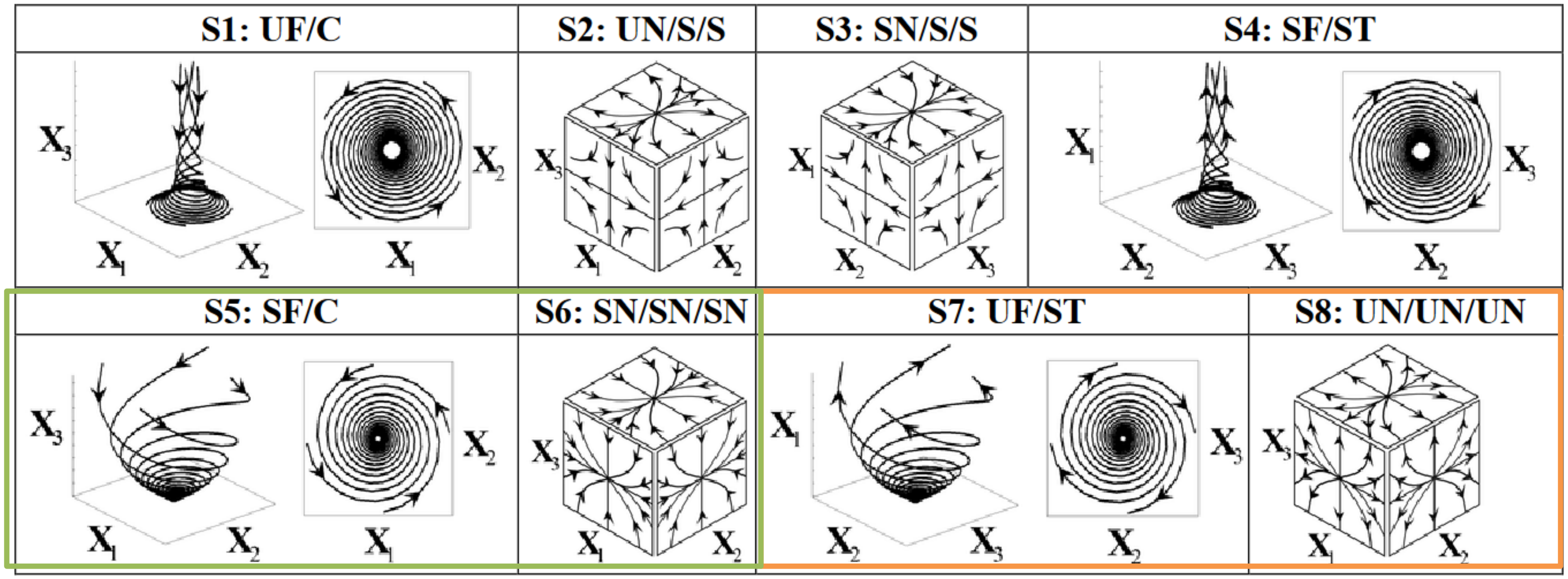
  - FSI following the methodology by Griffith et al.(2015)
  - Flow topology following the methodology reported by Perry and Chong (1987).



$\nabla.\vec{u} < 0$ $\nabla.\vec{u} > 0$

Newcastle University

DNS dataset

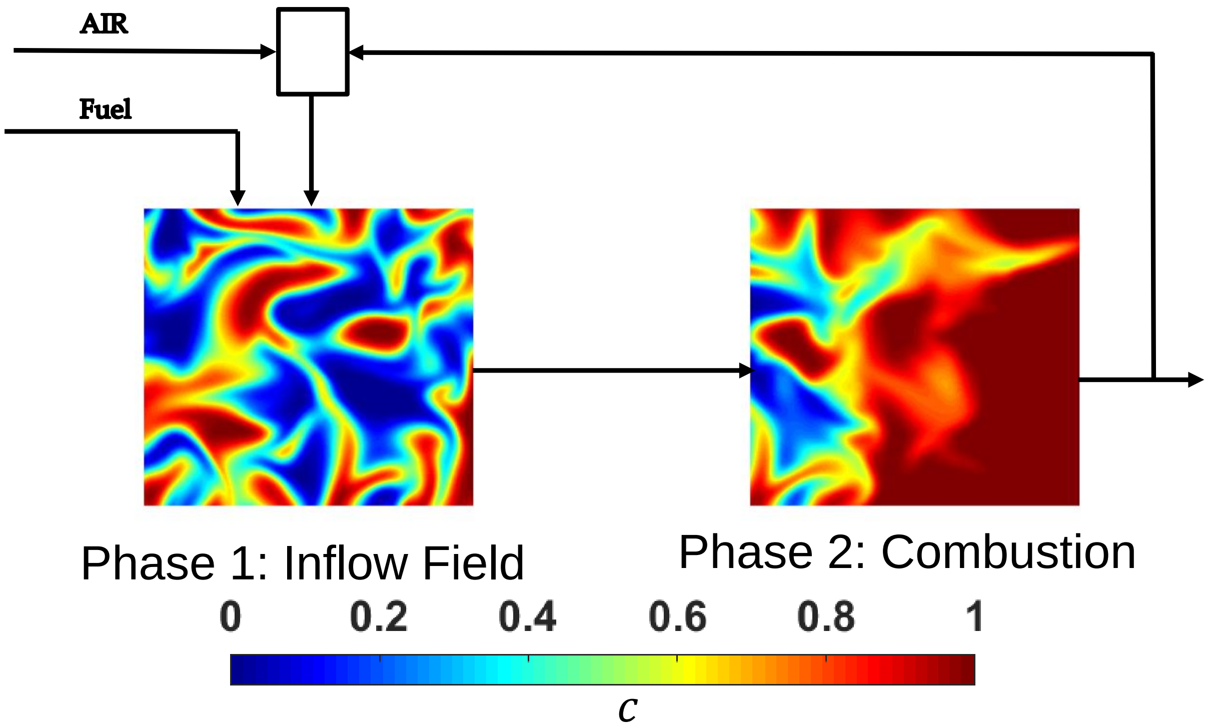
- JHC type, turbulent, homogeneous mixture MILD combustion
- Two dilution levels, and two turbulence intensities
- Cubic Domain $L = 20mm$, Cartesian grid: $N = 216^3$
- Inlet – outlet BCs in the x-direction, Periodic elsewhere
- Turbulence levels are comparable to Oldenhof et al.[1]
- $T_r = 1100K$, comparable to the experiment of Ye et al.[2]
- 22 species - 18 steps chemical mechanism of Liu et al.[3]

Case	$X_{O_2,2}$	$X_{CO_2,2}$	$X_{H_2O,2}$	ϕ	S_L [m/s]	δ_f [m]	u' [m/s]	ℓ_0 [m]
HM-A1	0.045	0.097	0.112	0.8	0.420	4.55×10^{-4}	2.0	2.0×10^{-3}
HM-A2	0.045	0.097	0.112	0.8	0.420	4.55×10^{-4}	4.0	2.0×10^{-3}
HM-B	0.030	0.106	0.122	0.8	0.246	7.84×10^{-4}	2.0	2.0×10^{-3}

1. E. Oldenhof, M. J. Tummers, E. H. van Veen, and D. J. E. M. Roekaerts. Combustion and Flame, 158 (2011) 1553–1563.
2. J. Ye, P. R. Medwell, M. J. Evans, and B. B. Dally. Combust. Flame, 183 (2017) 330–342.
3. S. Liu, J. C. Hewson, J. H. Chen, and H. Pitsch. Combust. Flame, 137 (2004) 320–339

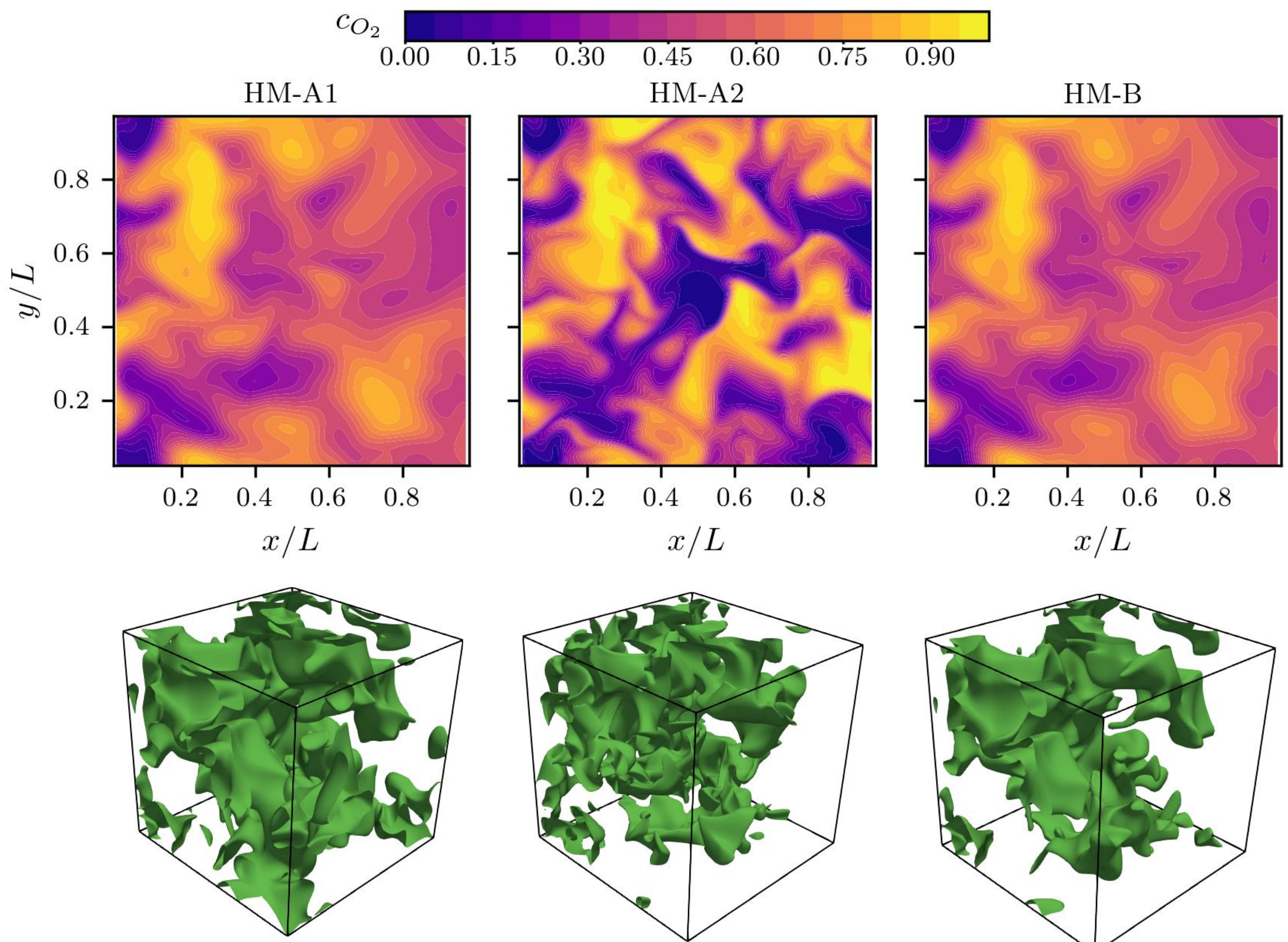
Initial Fields

- The initial scalar fields were generated following the methodology by Minamoto et al.[1]



1. Y. Minamoto, T. D. Dunstan, N. Swaminathan, R. S. Cant, Proc. Combust. Inst, 34 (2013) 3231-3238

Progress Variable Field

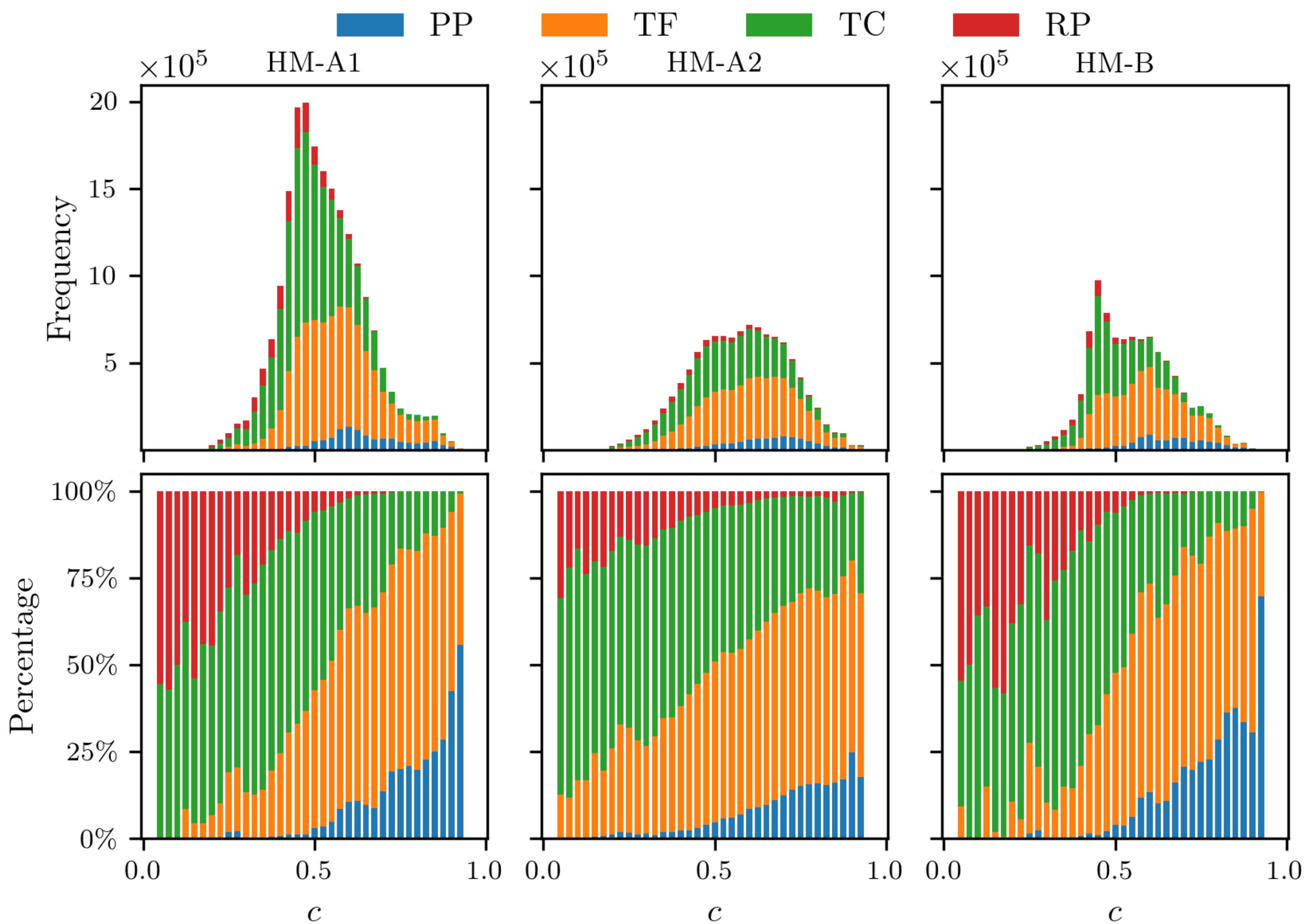


$u' = 2.0\frac{m}{s}, X_{O_2} = 4.5\%$

$u' = 4.0\frac{m}{s}, X_{O_2} = 4.5\%$

$u' = 2.0\frac{m}{s}, X_{O_2} = 3.0\%$

FSI events



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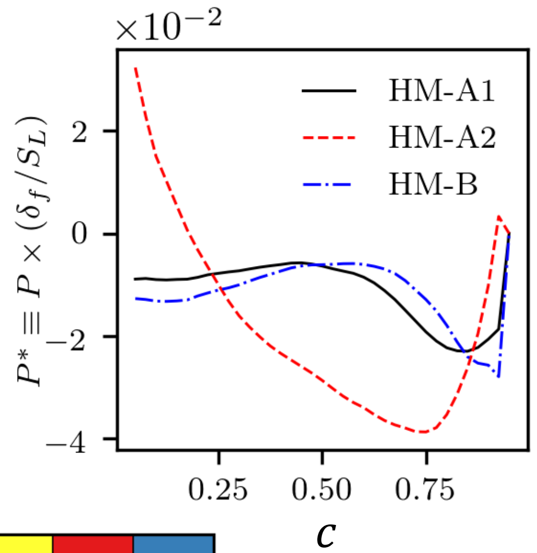
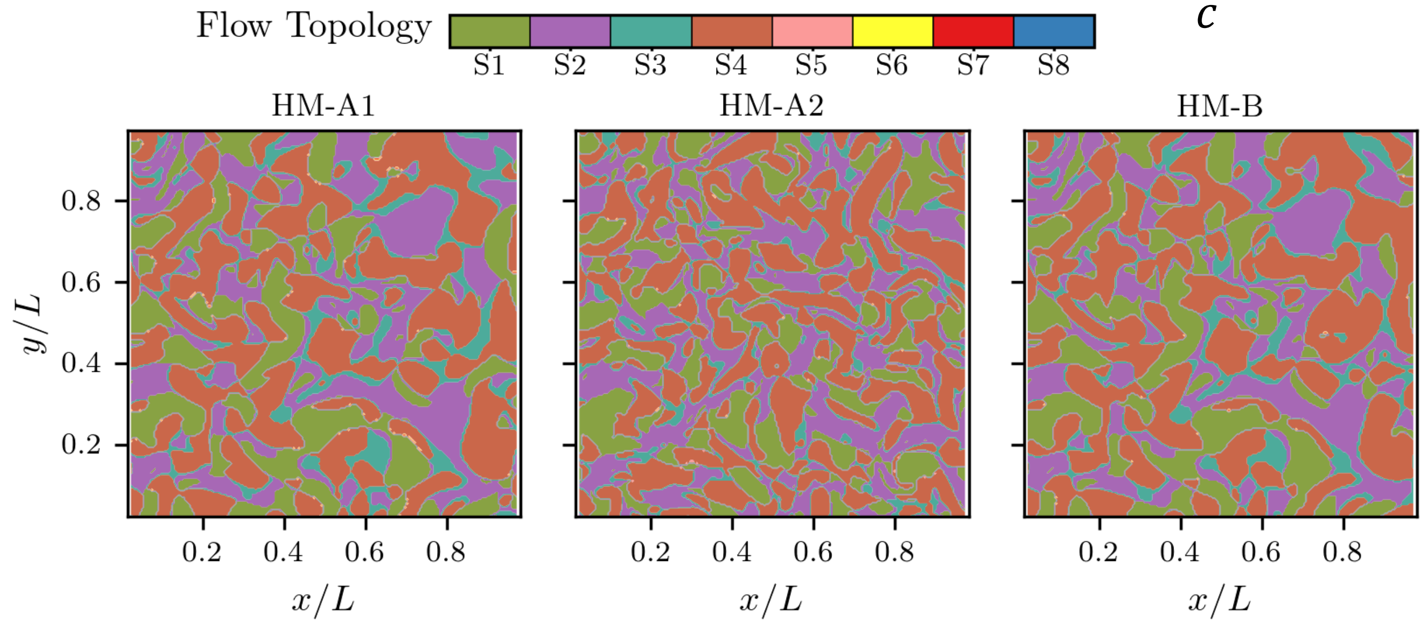
Flow Topologies

- $P = -\nabla . \vec{u}$
- Mean values of P^* remain small in the current MILD setup





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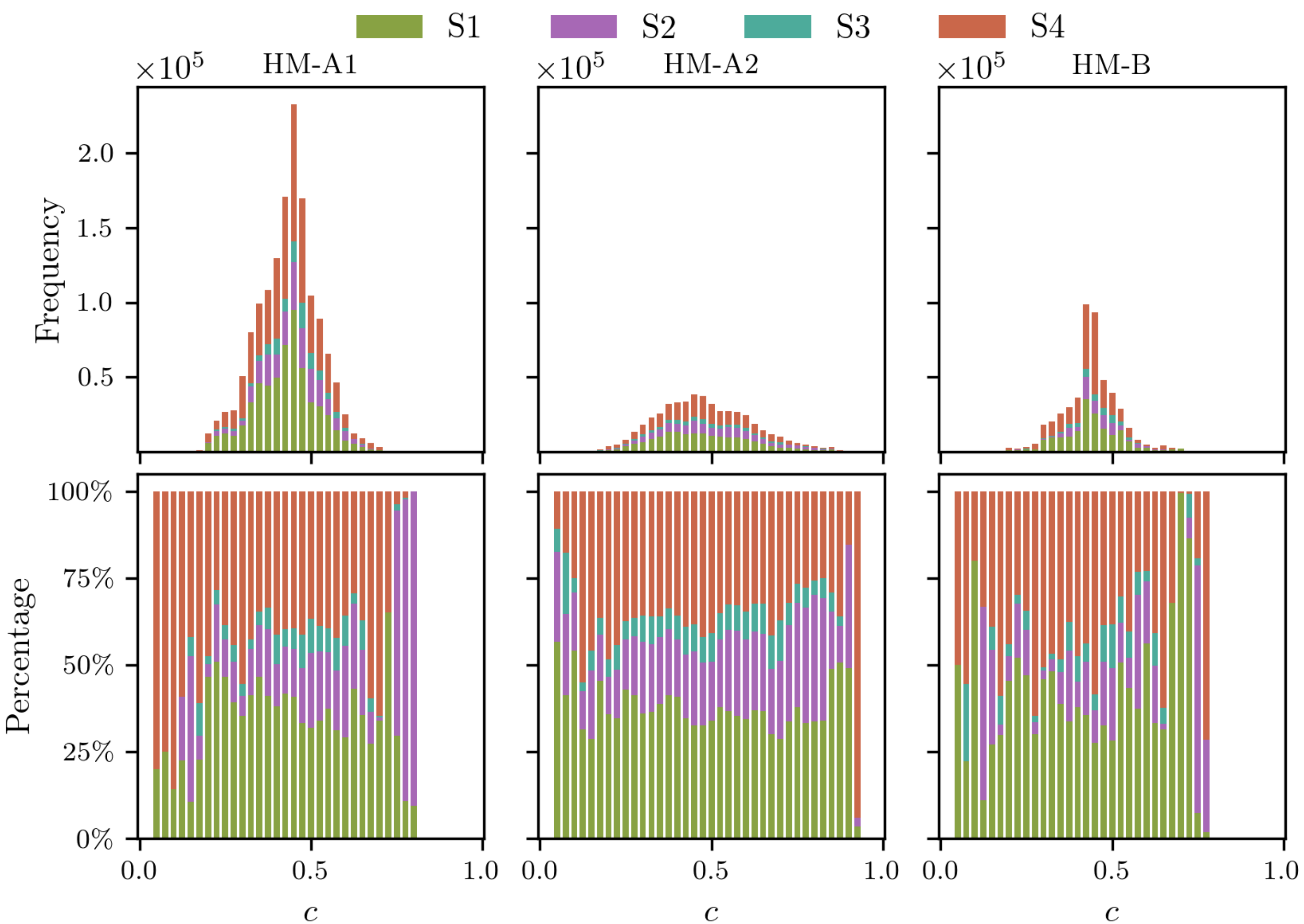
Flow Topologies - RP



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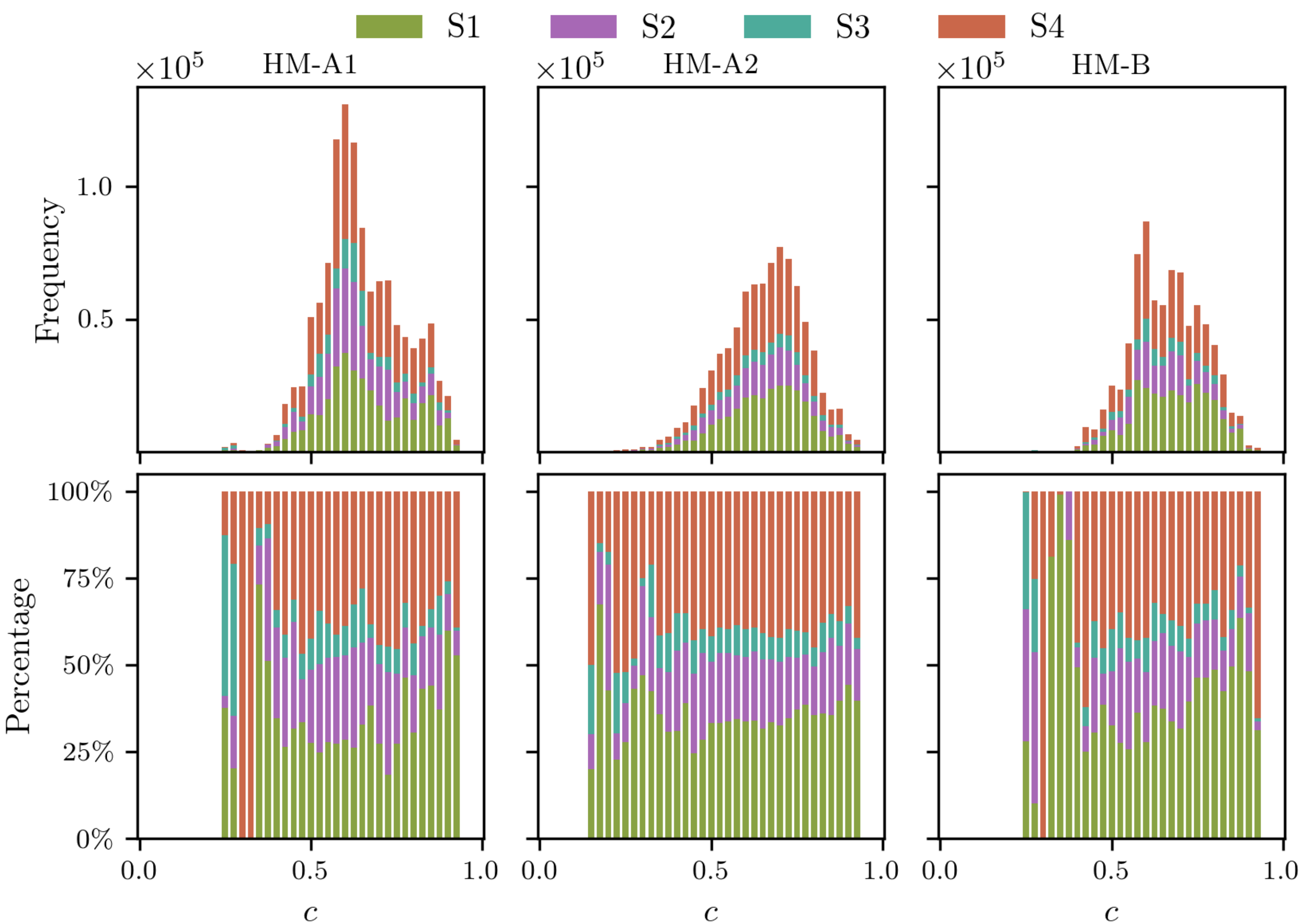

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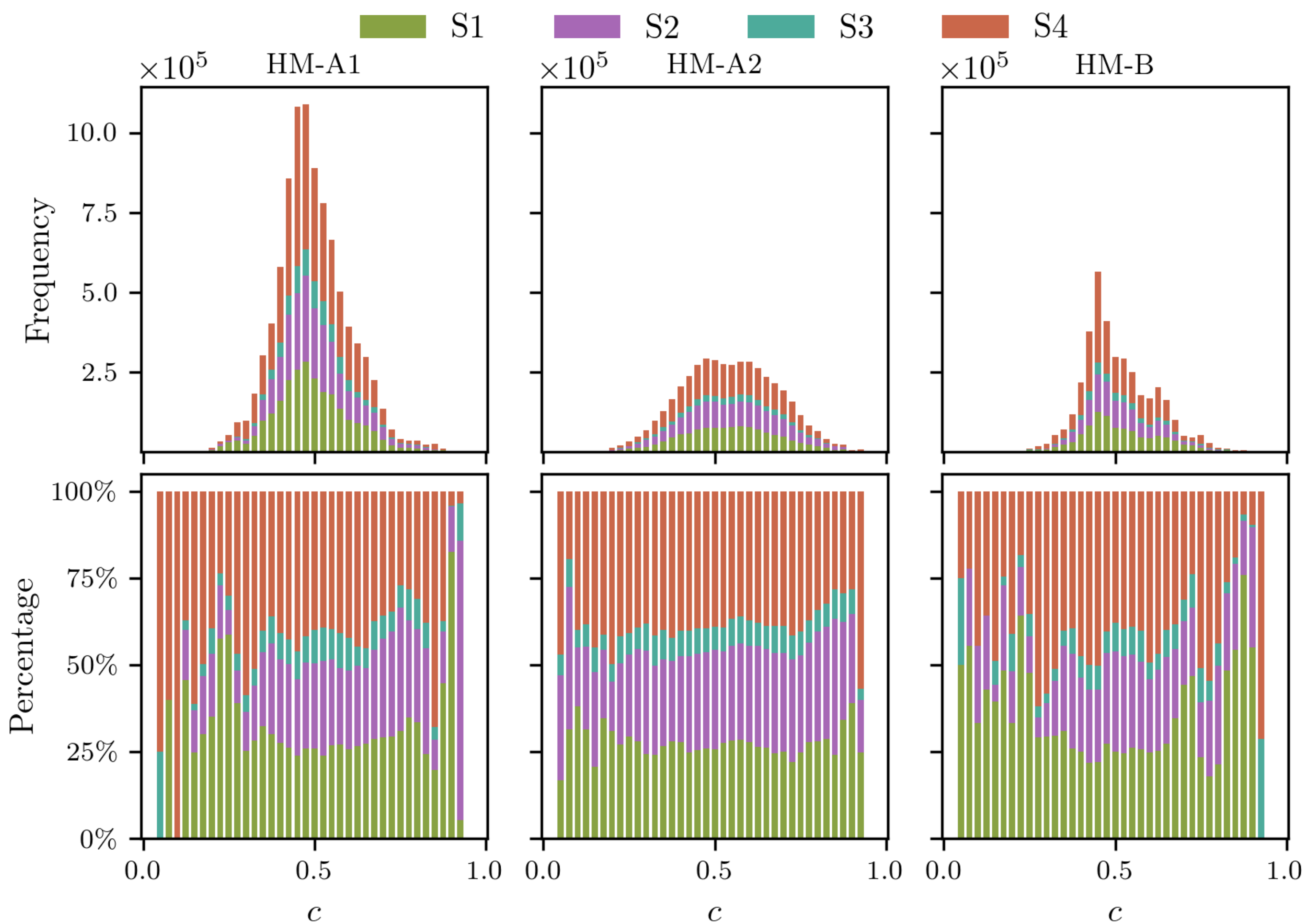
Flow Topologies - TC



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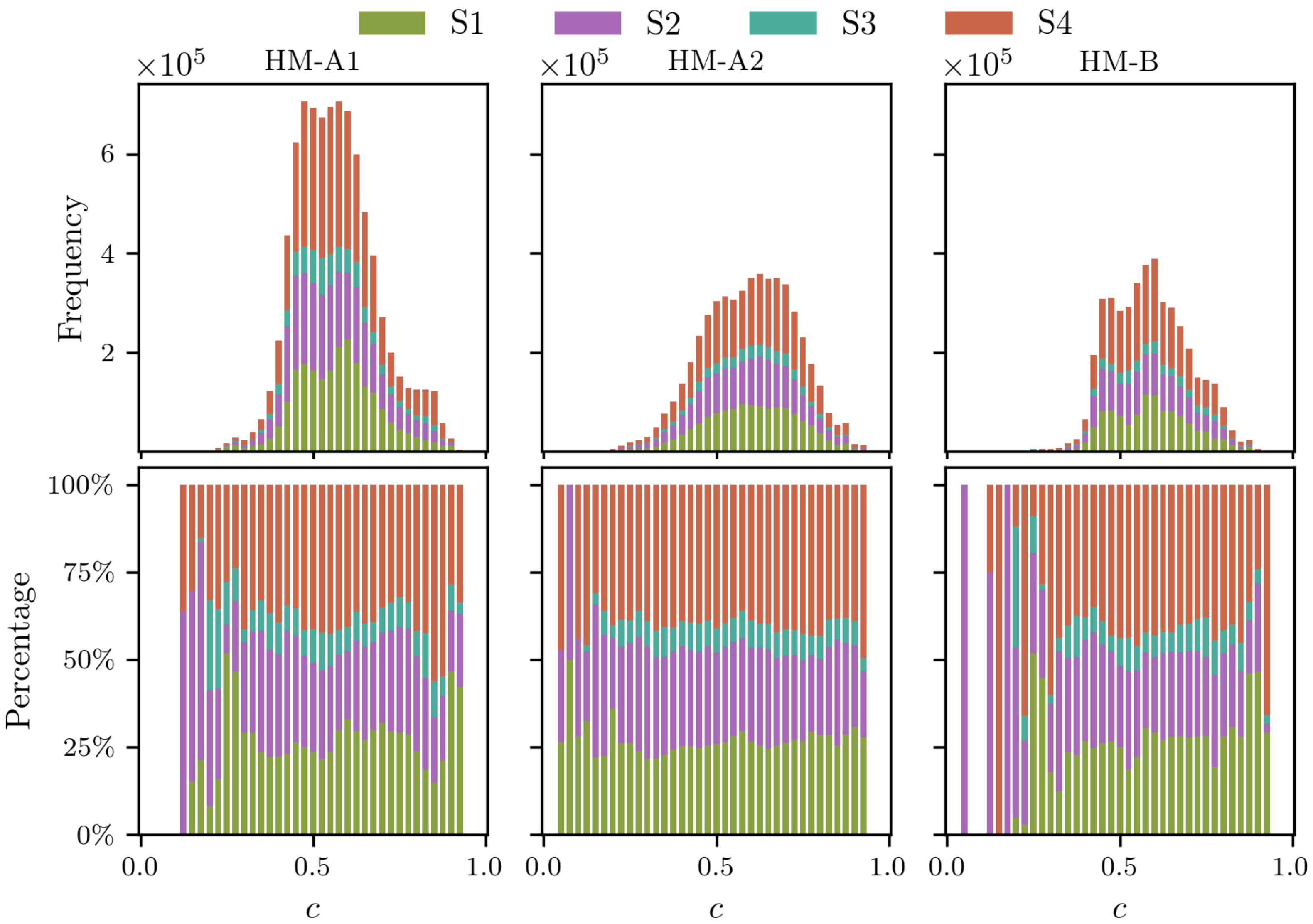
Flow Topologies - TF



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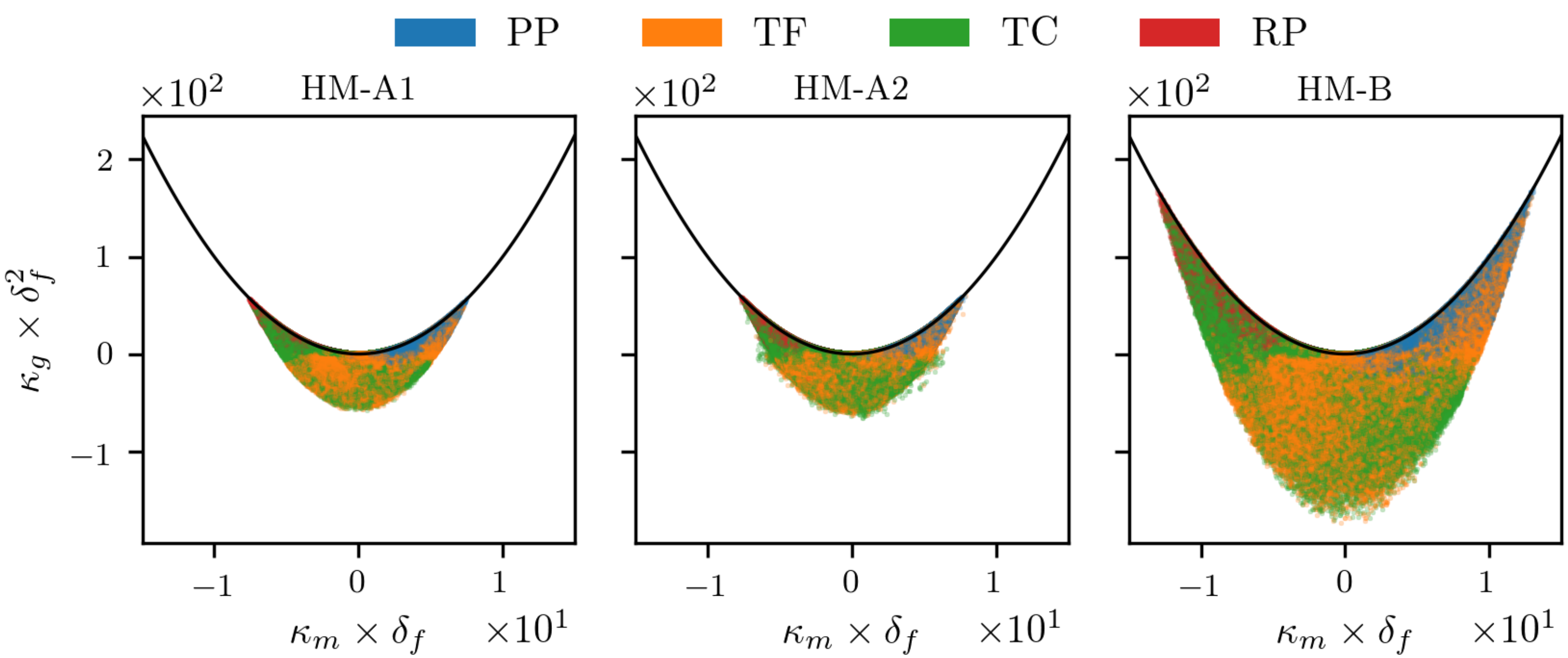
Mean and Gauss Curvatures



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Conclusions

- The peak frequencies of FSI events occur at around $c = 0.5$
- Tunnel formation and tunnel closure type events are the most probable across the flame.
- The low dilatation rate in MILD combustion leads to flow topologies comparable to that seen in incompressible flows.
- The focal flow topologies are the most probable across all FSI events.
- The unstable nodal/saddle/saddle type topology becomes important in cylindrical flame topologies and its effect increases with turbulence intensity.
- Increasing the dilution factor led to higher levels of mean and Gauss curvatures.

THANK YOU