Turbulent Flame interaction with (i) droplets and (ii) inert walls

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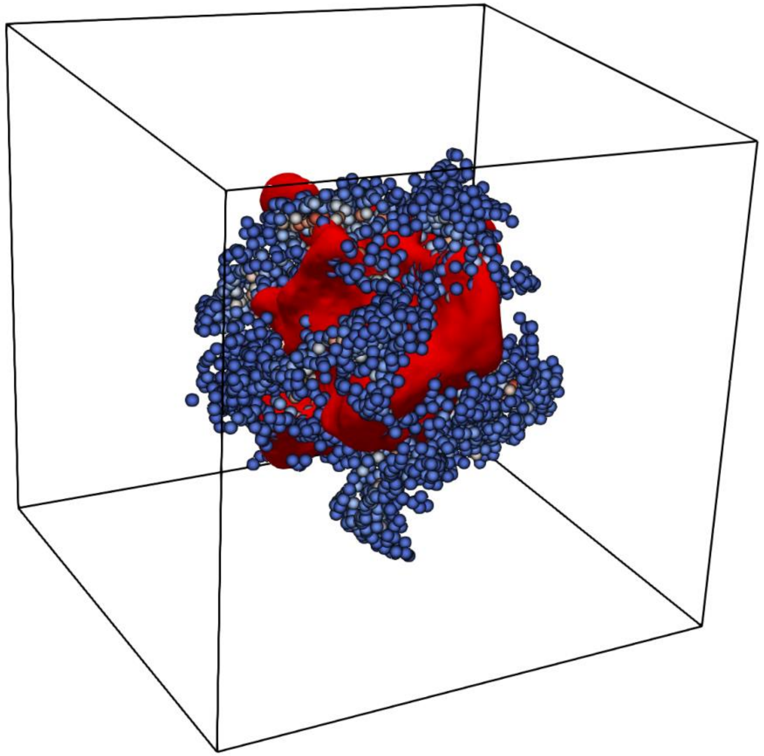
Motivation and Objectives



Combustion of multiscale phenomenon:

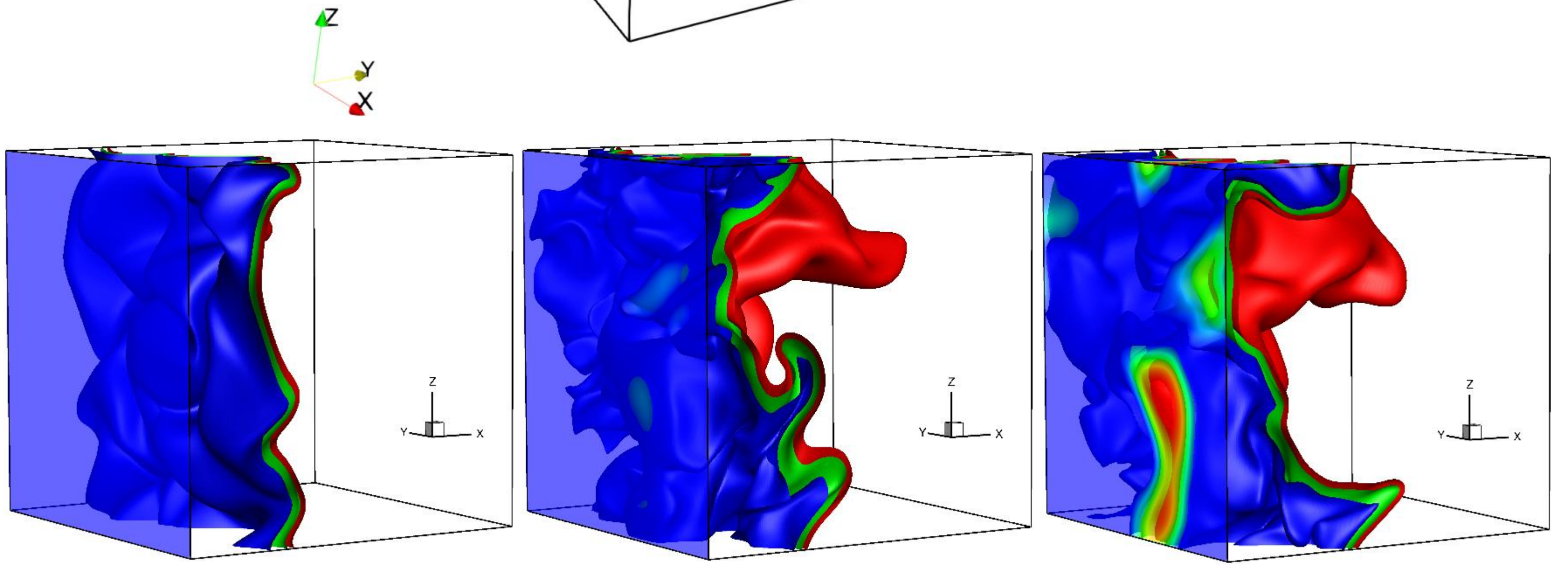
- Internal Combustion (IC) engines
- Gas turbines
- Industrial furnaces

Combustion of droplet-laden mixtures:

- Flame structure and wrinkling
- Evolution of flame surface area
- Evolution of burned gas volume

Flame-Wall interaction (FWI):

- FWI in fully developed boundary layer.
- Influence of wall boundary condition on the flame evolution.
- Comparison of flame surface evolution with statistically planar turbulent flames.



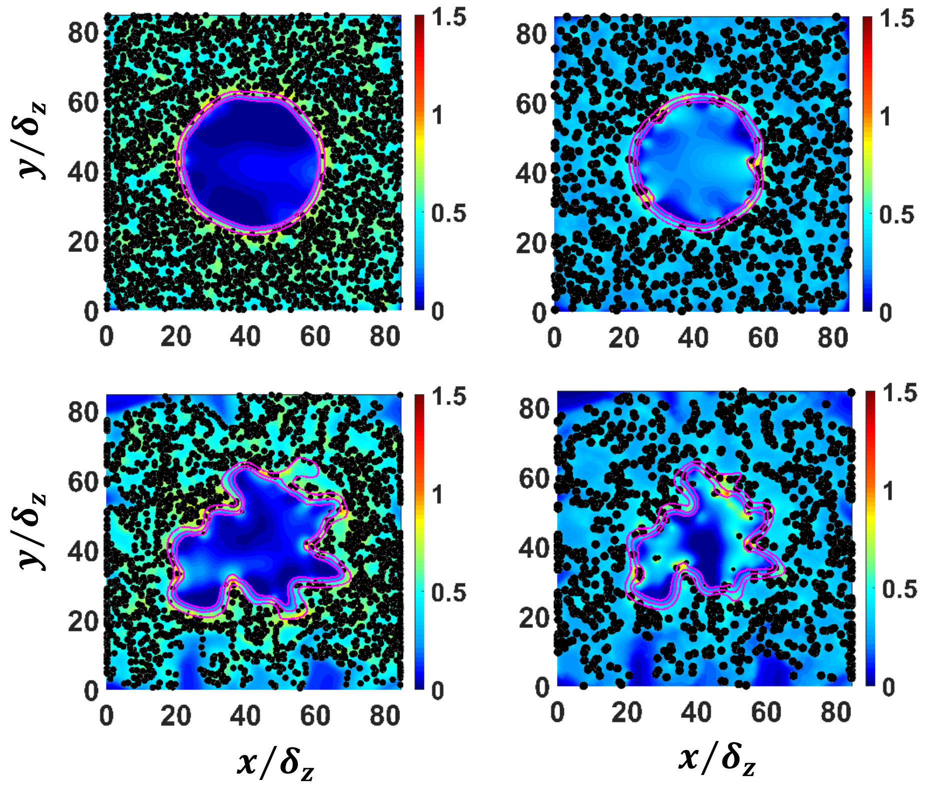
Direct Numerical Simulation

- Liquid phase-Lagrangian Approach is used for droplets following the approach proposed by Reveillon & Vervisch.

- Gaseous phase- Eulerian Approach is used to solve for gas phase combustion.

- Code: 3D,compressible DNS code, SENGA
  - 10th order central difference scheme
  - Time advancement: Explicit low-storage 3rd order Runge-Kutta scheme.

- A single-step chemical mechanism is used.

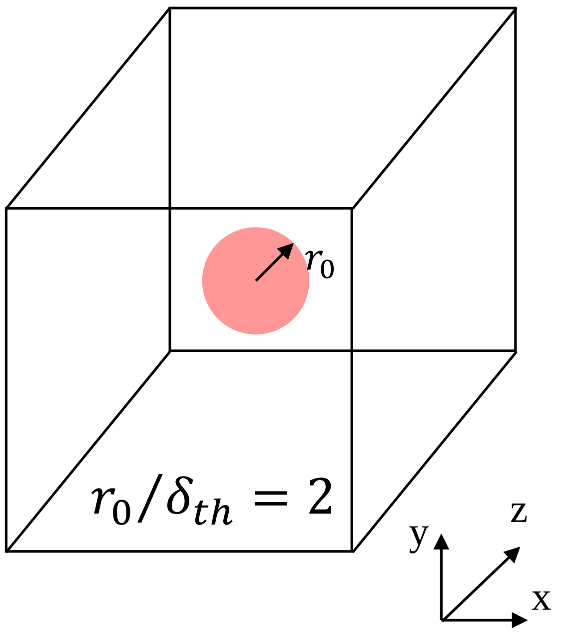


[1]Reveillon, J., Vervisch, L.: Spray vaporization in non-premixed turbulent combustion modelling: a single droplet model. Combust. Flame 121, 75–90 (2000).

[2]Jenkins, K.W., Cant, R.S., Direct numerical simulation of turbulent flame kernels, 2nd AFOSR Conf. DNS and LES (1999).

Simulation set-up for spray flames

- 3D flame kernel simulations with droplet laden mixtures have been performed.
- Domain: $(84.49\delta_z)^3$ (where $\delta_z = \alpha_{T0}/S_{b(\phi_g=1)}$ is the Zel'dovich flame thickness)
- Grid number: $(512)^3$
- Initial turbulent field: Incompressible, homogeneous, isotropic (decaying turbulence).
- Reacting flow field initialisation: 1D steady state spray flame solutions (from COSILAB) specified in the radial direction.



$u'/S_{b(\phi_g=1)}$	L_{11}/δ_{th}	a_d/δ_{th}	ϕ_{ov}	$\tau = \frac{T_{ad(\phi_g=1)} - T_0}{T_0}$
0, 4.0	2.5	0.04, 0.05, 0.06	1.0	6.54

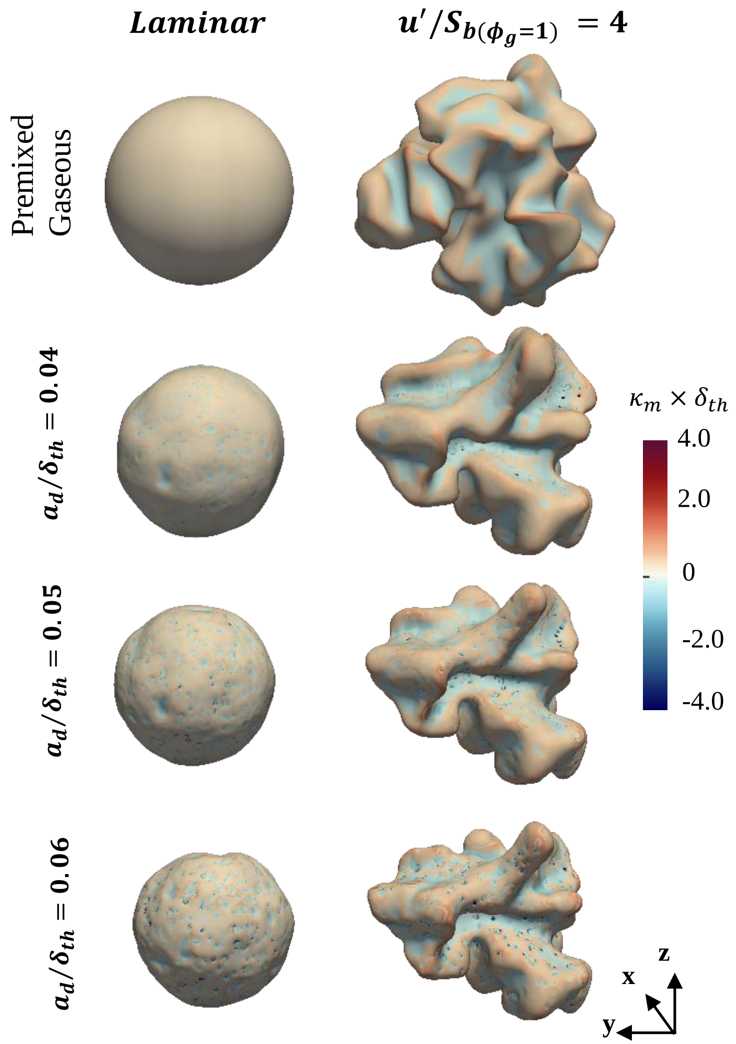
Reaction progress variable:

$$c = \frac{(1-\xi)Y_{O\infty} - Y_O}{(1-\xi)Y_{O\infty} - \max(0, [\xi_{st} - \xi]/\xi_{st})Y_{O\infty}}$$

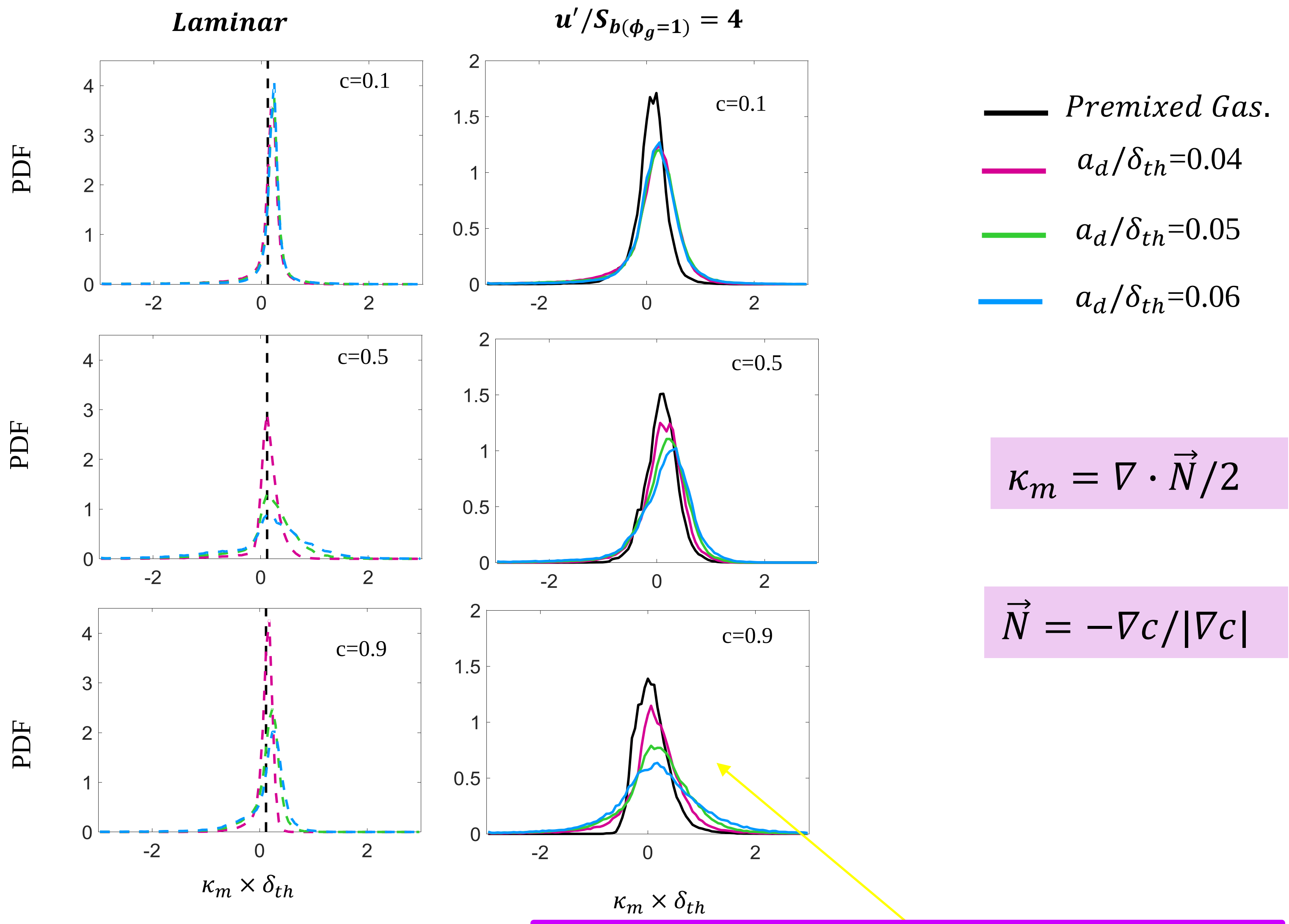
Mixture fraction:

$$\xi = \frac{(Y_F - Y_O/s + Y_{O\infty}/s)}{(Y_{F\infty} - Y_{O\infty}/s)}$$

Droplet Induced Wrinkling



Instantaneous view of $c = 0.5$ isosurface coloured with local values of $\kappa_m \times \delta_{th}$ at $t = 2.1t_{chem}$.

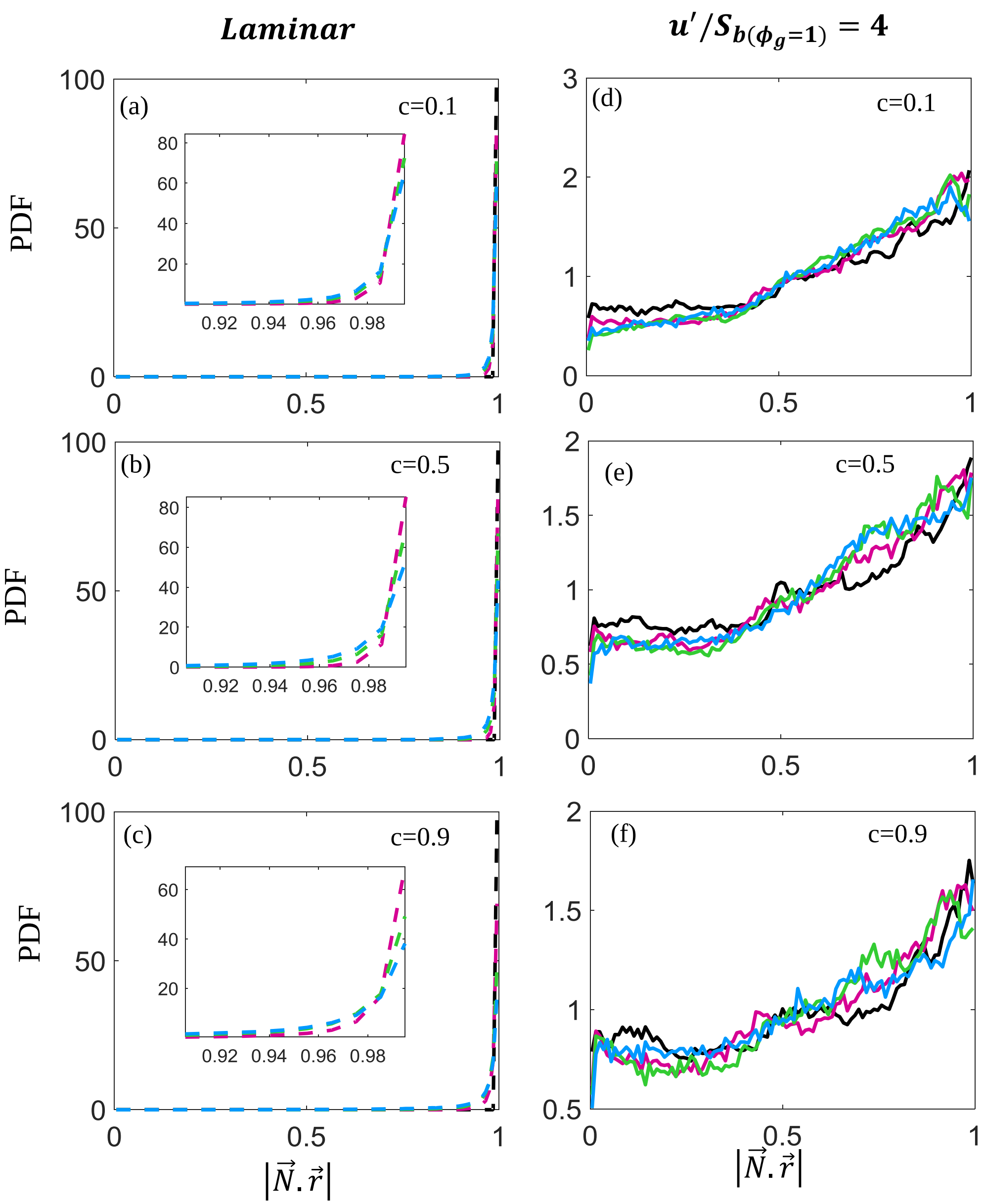


$$\kappa_m = \nabla \cdot \vec{N}/2$$

$$\vec{N} = -\nabla c/|\nabla c|$$

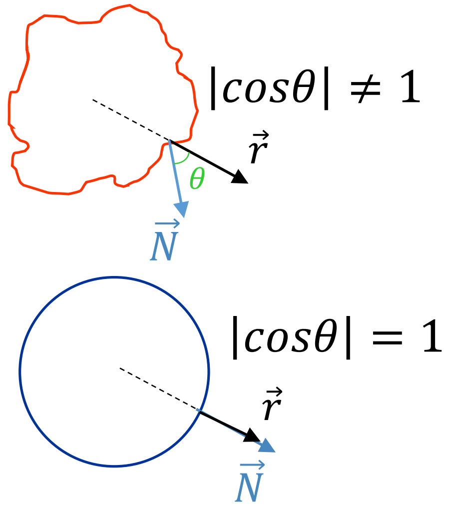
Prominent effect of large droplets

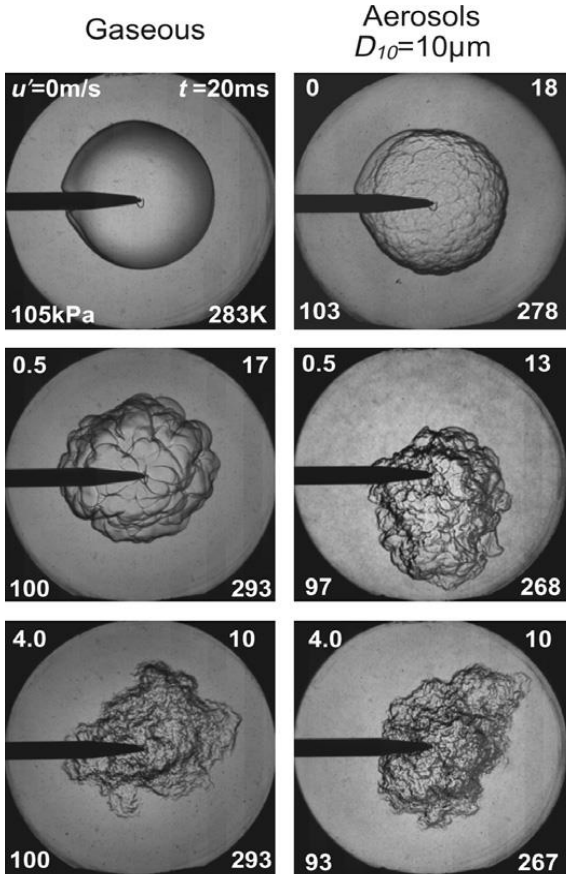
Flame Wrinkling



- *Premixed Gas.*
- a_d/δ_{th}=0.04
- a_d/δ_{th}=0.05
- a_d/δ_{th}=0.06

$\vec{N}$: local flame normal
$\vec{r}$: unity radial vector from the center of mass of the flame kernel



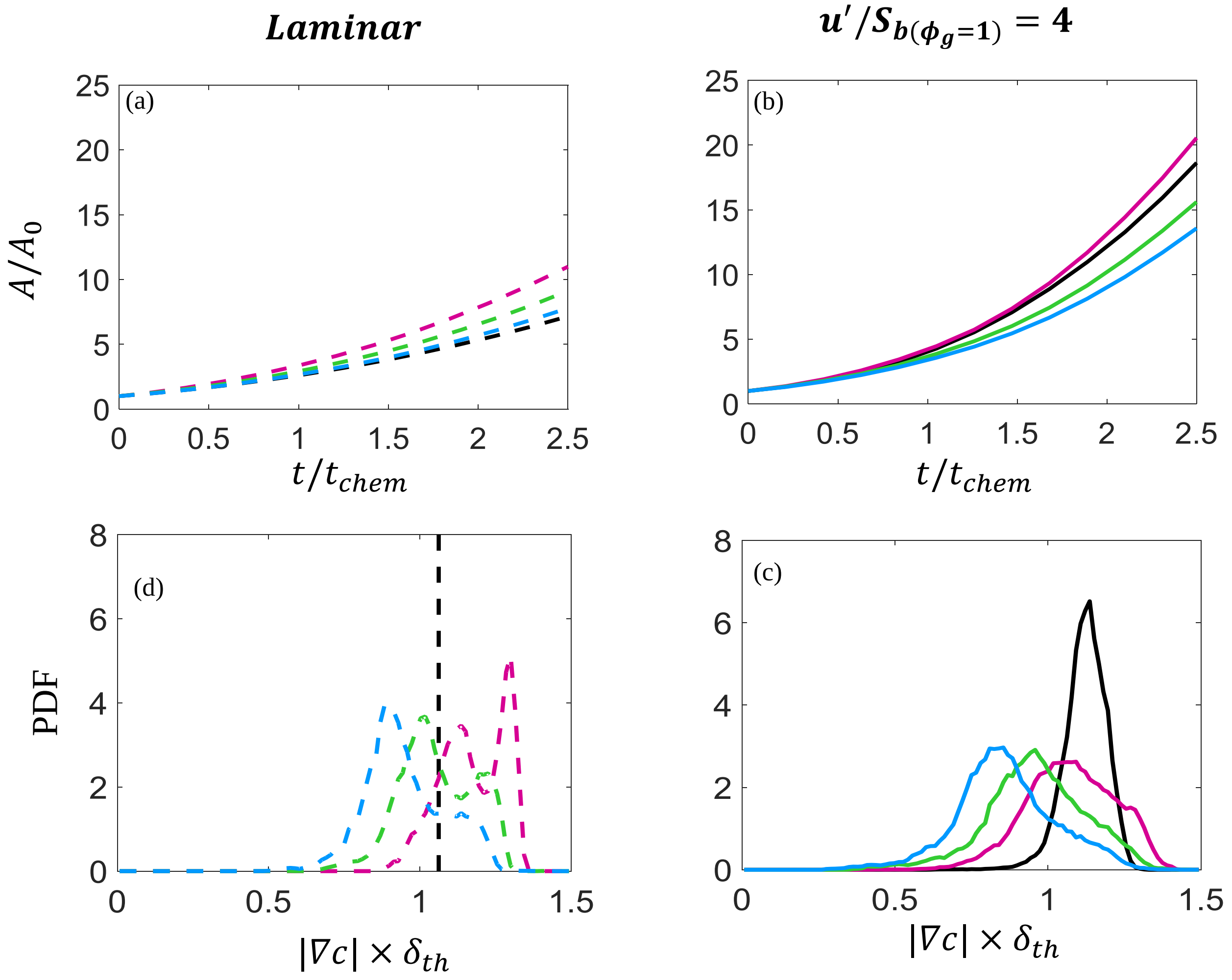


Flame images from gaseous and aerosol flames at ϕ_{av}= 1.2 and different values of u`[1]

[1]Lawes, M., Saat, A.: Burning rates of turbulent iso-octane aerosol mixtures in spherical flame explosions. Proc. Combust. Inst. 33, 2047–2054 (2011).

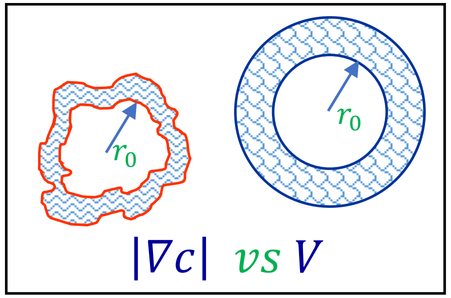
Evolution of flame surface area

Premixed Gas. — a_d/δ_{th}=0.04 — a_d/δ_{th}=0.05 — a_d/δ_{th}=0.06



Flame surface area normalised with its initial value A/A_0

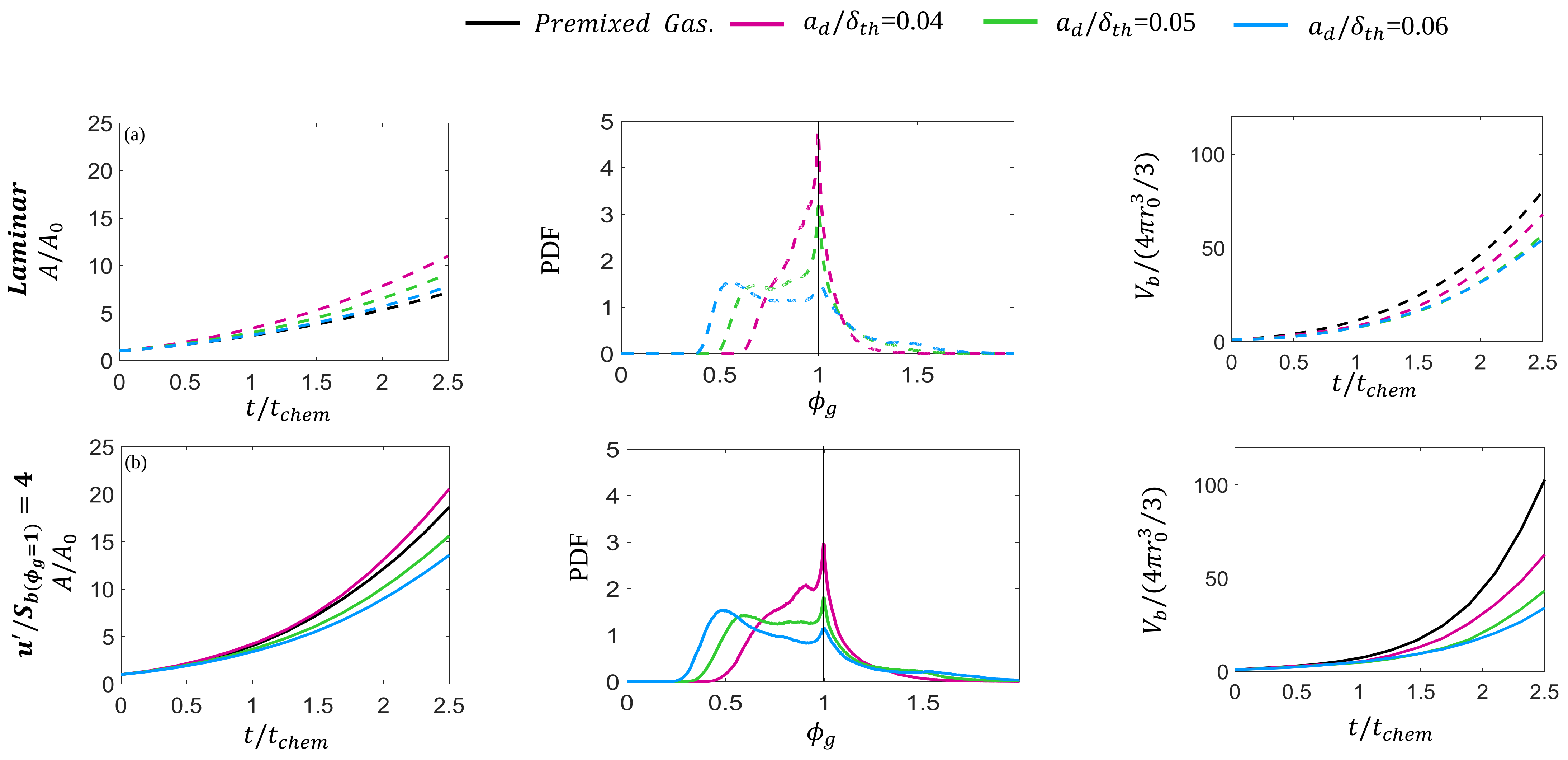
$$A = \int |\nabla c| dV$$



A_0 → flame surface area A of a spherical laminar flame of initial radius $r_0 = 2\delta_{th}$.

PDF of $|\nabla c| \times \delta_{th}$ on $c = 0.5$

Gaseous equivalence ratio and burned gas volume



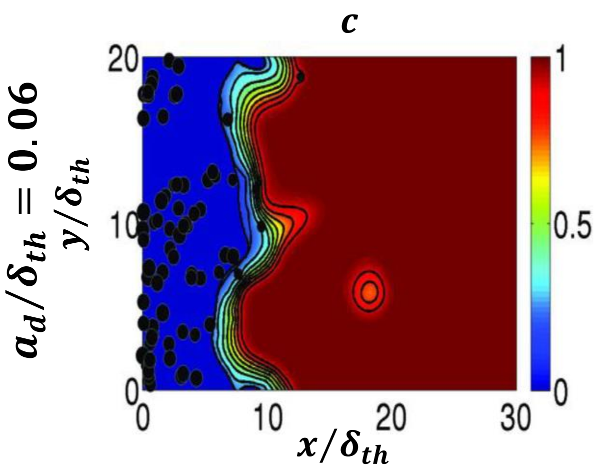
Flame surface area normalised with its initial value A/A_0

PDF of ϕ_g in the region corresponding to

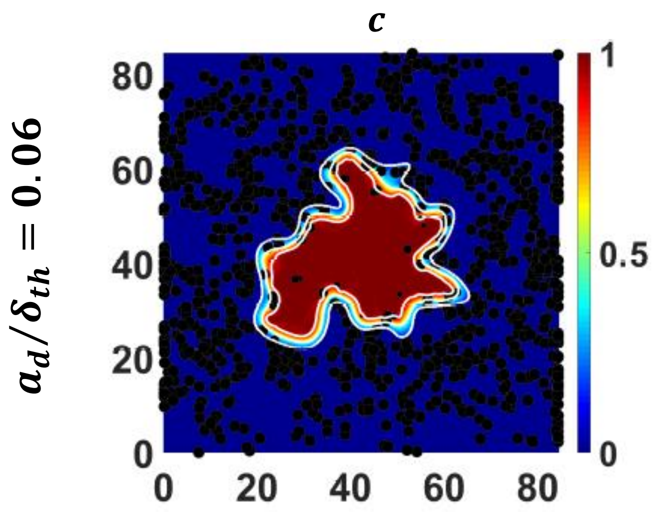
$0.01 \leq c \leq 0.99$

Normalised volume $V_b/(4\pi r_0^3/3)$ of the region with $c \geq 0.99$

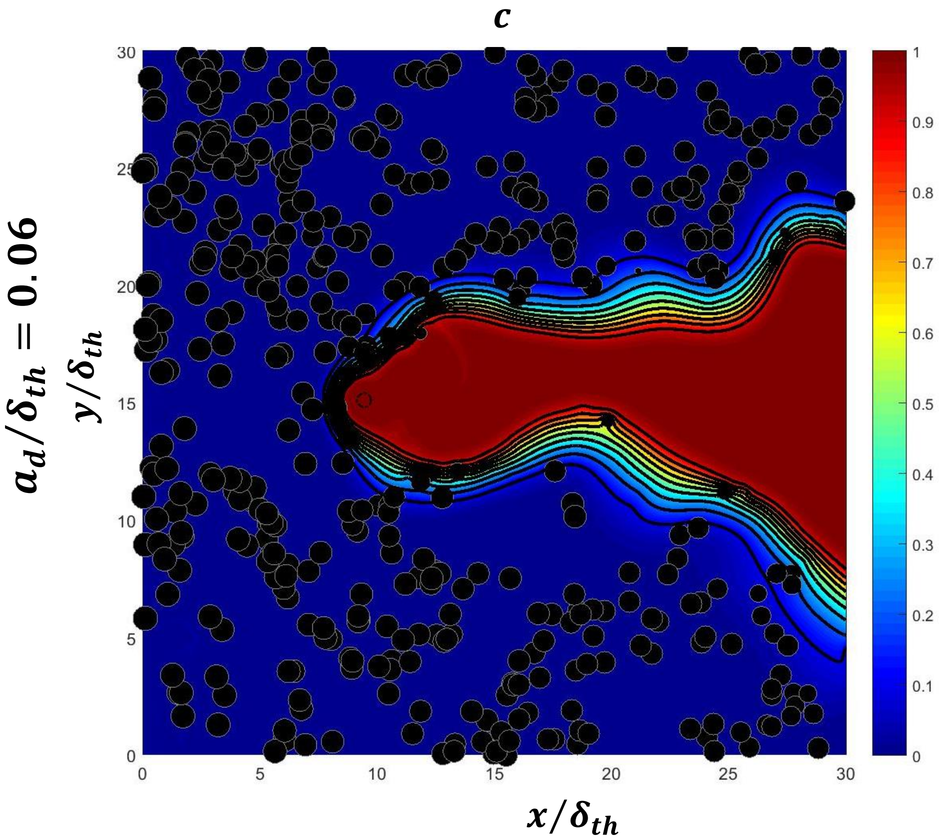
Influence of flame configuration



Planar Spray Flame[1]



Spherical Expanding Spray Flame[2]



$V - Flame$ **Configuration**

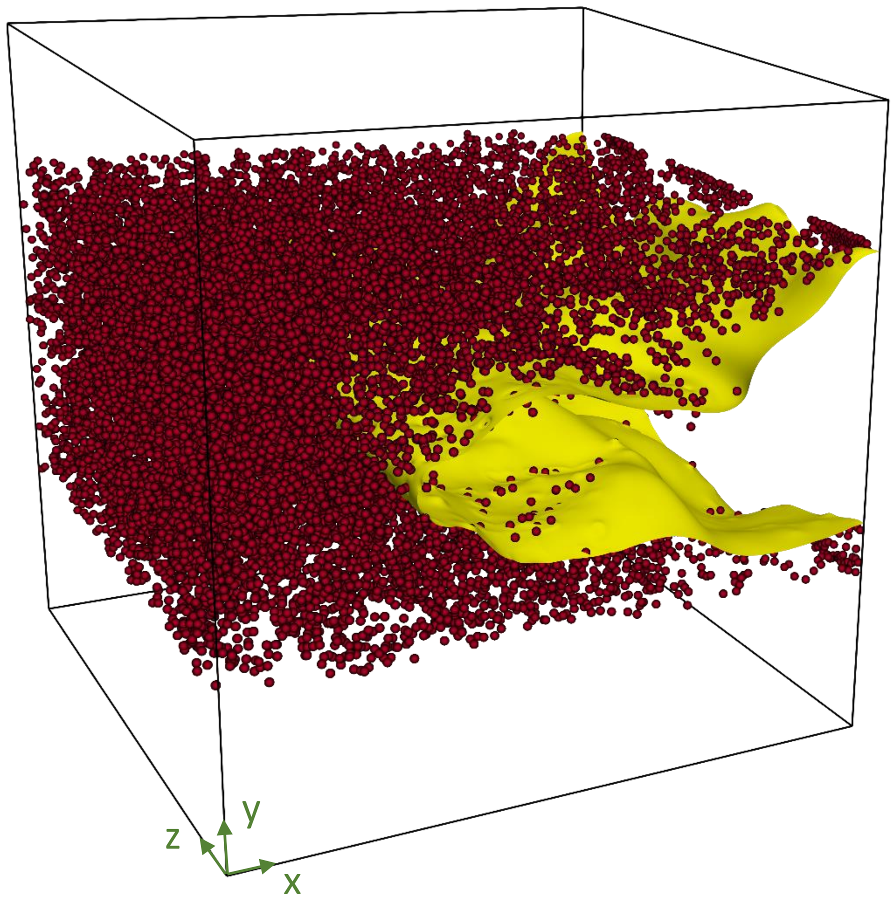
[1]D.H. Wacks, N. Chakraborty, and E. Mastorakos, “Statistical Analysis of Turbulent Flame-Droplet Interaction: A Direct Numerical Simulation Study,” Flow, Turbul. Combust. 96, 573 (2016).

2G. Ozel Erol, J.Hasslberger, M. Klein, and N. Chakraborty, “A direct numerical simulation analysis of spherically expanding turbulent flames in fuel droplet-mists for an overall equivalence ratio of unity”, Physics of Fluids, 30,(2018)

Influence of flame configuration

Simulation Parameters

- *Domain:* $(63.3\delta_z)^3$ (where $\delta_z = \alpha_{T0}/S_{b(\phi_g=1)}$ is the Zel'dovich flame thickness)
- *Grid number:* $(384)^3$
- Equivalence ratio: $\phi_d = 1.0$
- Initial rms: $u'/S_{b(\phi_g=1)} = 2.0$
- Longitudinal integral length-scale: $L_{11}/\delta_{th} = 2.5$
- mean inlet velocity of $\bar{u}_{mean}/S_{b,st} = 5.$
- Holder position (x,y): $(120\Delta x, 192\,\Delta y)$
- Heat release parameter: $\tau = \frac{T_{ad(\phi_g=1)} - T_0}{T_0} = 6.4$
- Droplet diameter: $a_d/\delta_{th} =$ 0.04,0.05 and 0.06



Reaction progress variable isosurfaces at $c =$0.7 for $a_d/\delta_{th} = 0.06$ initial droplet diameter, at $t = 1t_{flow}$.

Flame-wall interaction

- Flame wall interaction in a fully developed boundary layer channel flow is investigated.

- Some basic definitions used in these flows are:

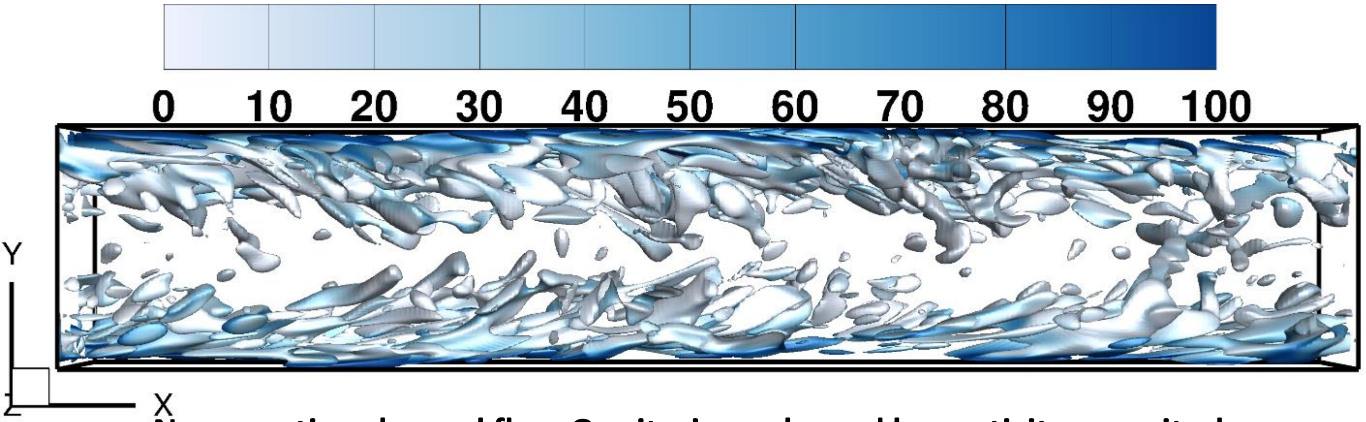
- Wall shear stress $\tau_{wall} = \overline{\mu \frac{\partial u}{\partial y}}\Big|_{y=0}$.

- Wall friction velocity $u_\tau = \sqrt{\frac{\tau_{wall}}{\rho}}$.

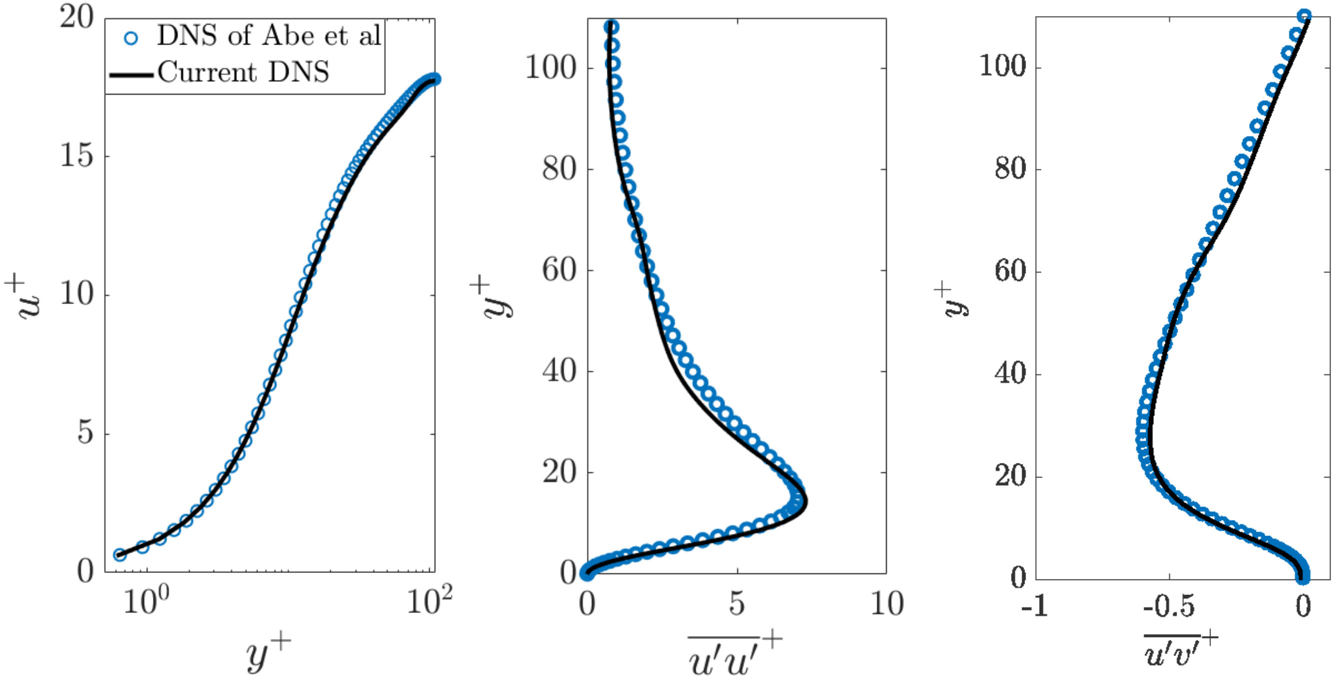
- Reynolds number based on wall friction $Re_\tau = \frac{\rho u_\tau h}{\mu}$.

- Non-dimensional distance from the wall $y^+ = \frac{u_\tau y}{\nu_{wall}}$.

Non-reacting channel flow



Non-reacting channel flow Q-criterion coloured by vorticity magnitude

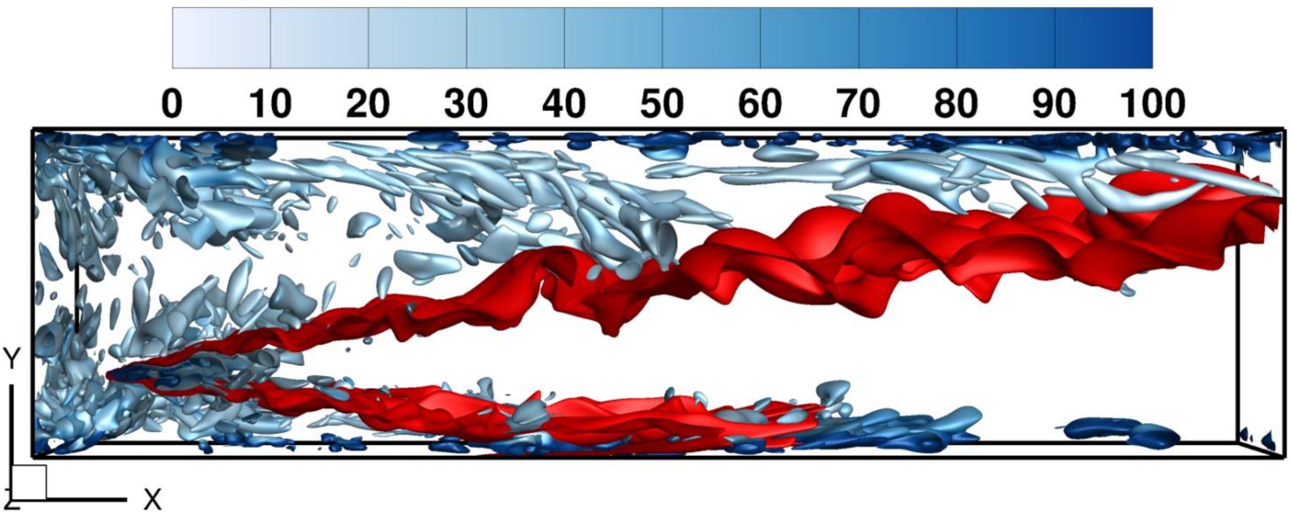


Non-reacting channel flow mean velocity and Reynolds stress profiles

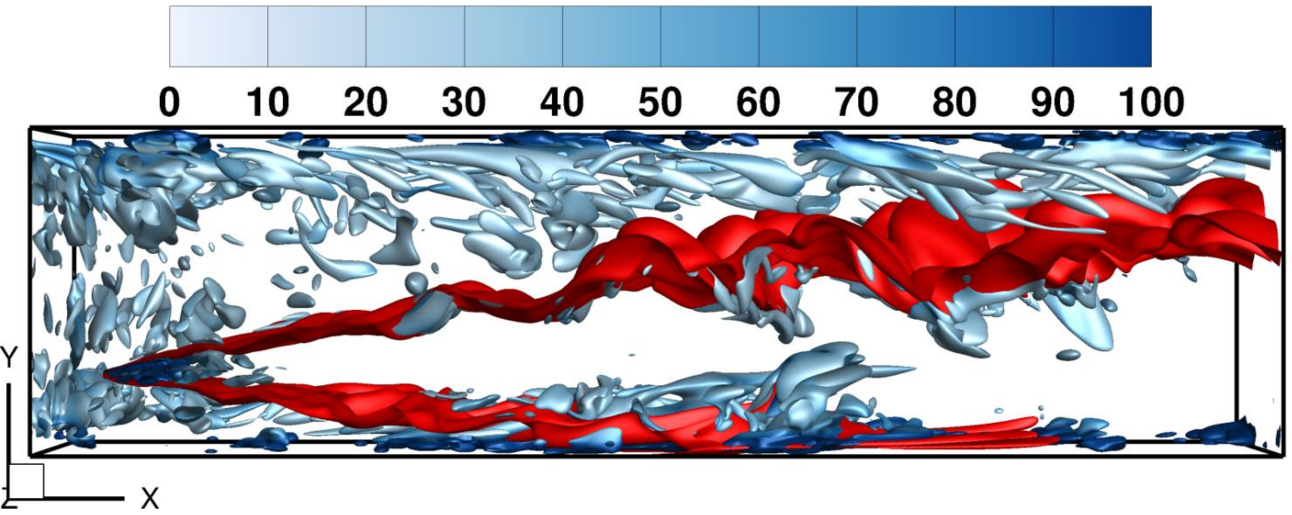
DNS data of Abe et al is available at http://www.rs.tus.ac.jp/~t2lab/db/index.html

- Domain size $10.67h \times 2h \times 4h$.
- $1920 \times 360 \times 720$ (approx. 0.5 billion) grid points.
- $Re_\tau = 110$ for the non-reacting channel.
- $y^+ = 0.6$ at the wall and at least two grid points are in $y^+ \leq 1.0$ region.
- Data validated against DNS of Abe et al.
- Data is recorded in time on the wall normal (y-z) plane.
- Approximately 5 TB of data is generated as inflow conditions for 3 flow through times.

V-flame-wall interaction



V-flame with adiabatic walls Q-criterion coloured by vorticity magnitude



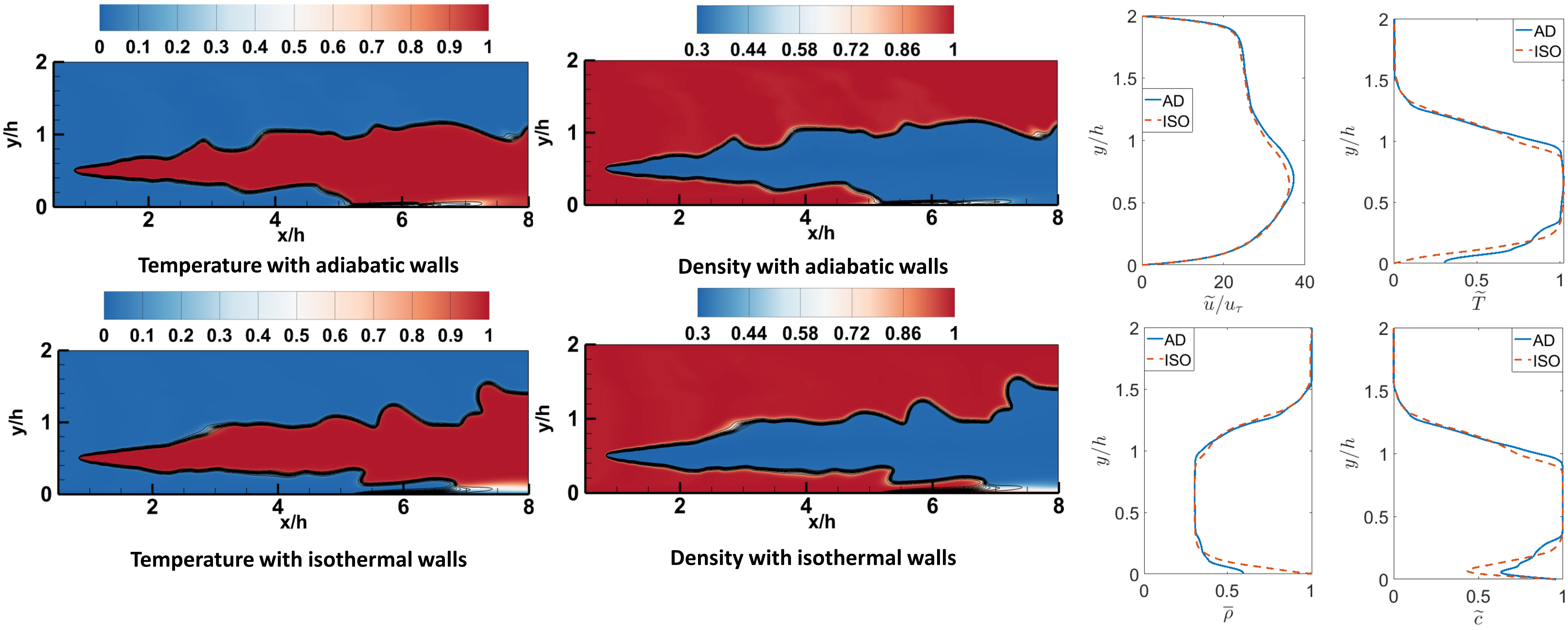
V-flame with isothermal walls Q-criterion coloured by vorticity magnitude

- V-flame is investigated in the $Re_\tau = 110$ channel flow with inert walls.
- Configuration similar to that of Alshaalan & Rutland[1] and Gruber et al.[2] is used.
- The flame holder is placed in the log layer region of the channel flow at $y^+ = 55$.
- Two wall conditions have been simulated :
  - Isothermal walls
  - Adiabatic walls
- The flame is representative of methane $\phi = 1.0$, $Le = 1.0$ with $S_L/u_\tau = 0.7$.
- Flame behaviour on the bottom wall is different for the two conditions simulated.

[1]**TM Alshaalan, CJ Rutland** *Symposium (International) on Combustion 27 (1), 793-799*

[2] **A Gruber, R Sankaran, ER Hawkes, JH Chen** Journal of Fluid Mechanics 658, 5-32

V-flame-wall interaction



V-flame-wall interaction

- Volume integrated reaction at each y/h:

$$\Omega_{y/h} = \frac{1}{\rho_0 S_L h^2} \int_v \dot{\omega}\, dv$$

- Volume integrated flame surface at each y/h:

$$S_{y/h} = \frac{1}{h^2} \int_v |\nabla c| \; dv$$

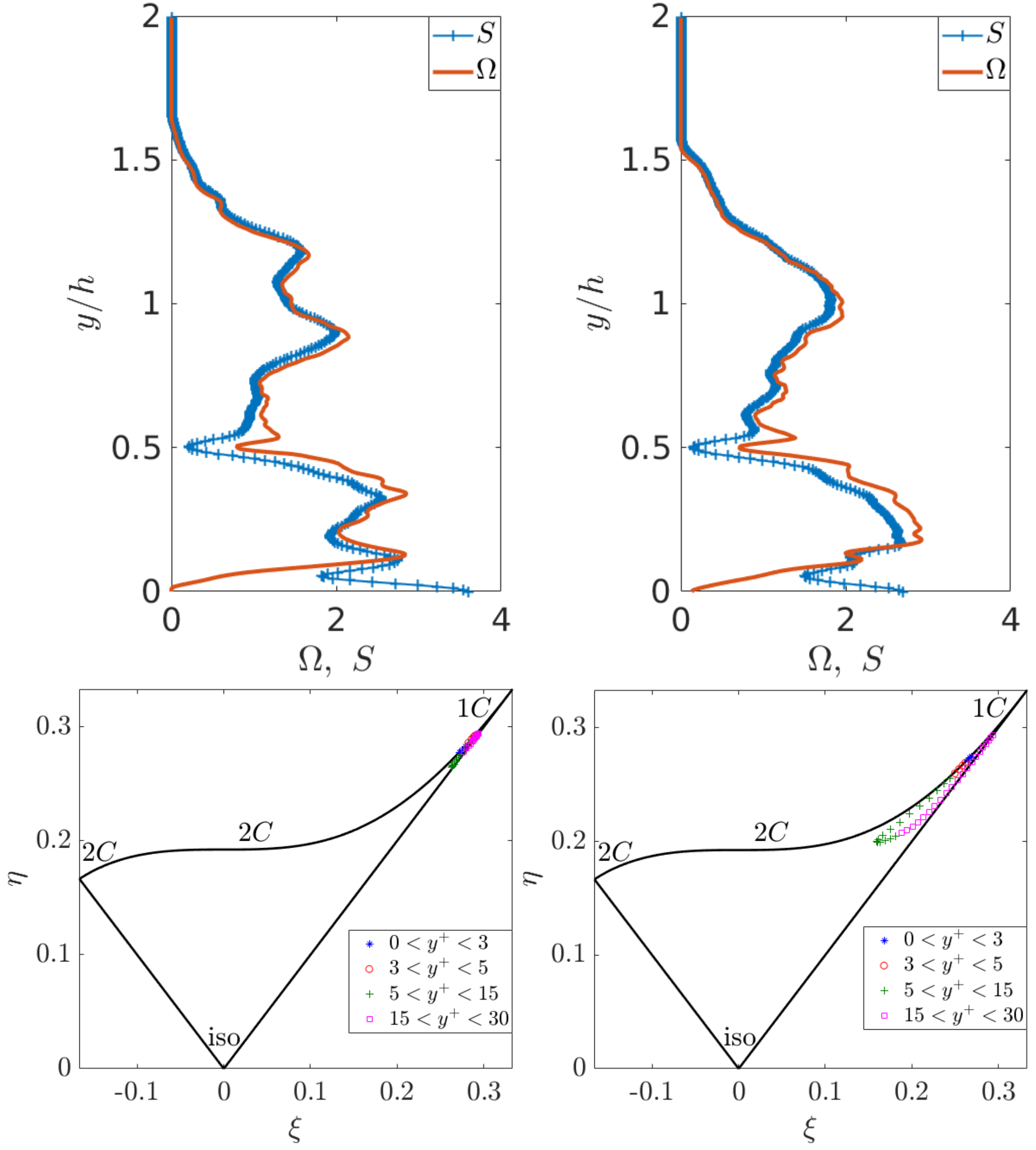
- The anisotropy tensor is defined as :

$$b_{ij} = \frac{\widetilde{u_i' u_j'}}{\widetilde{u_k' u_k'}} - \frac{1}{3}\delta_{ij}$$

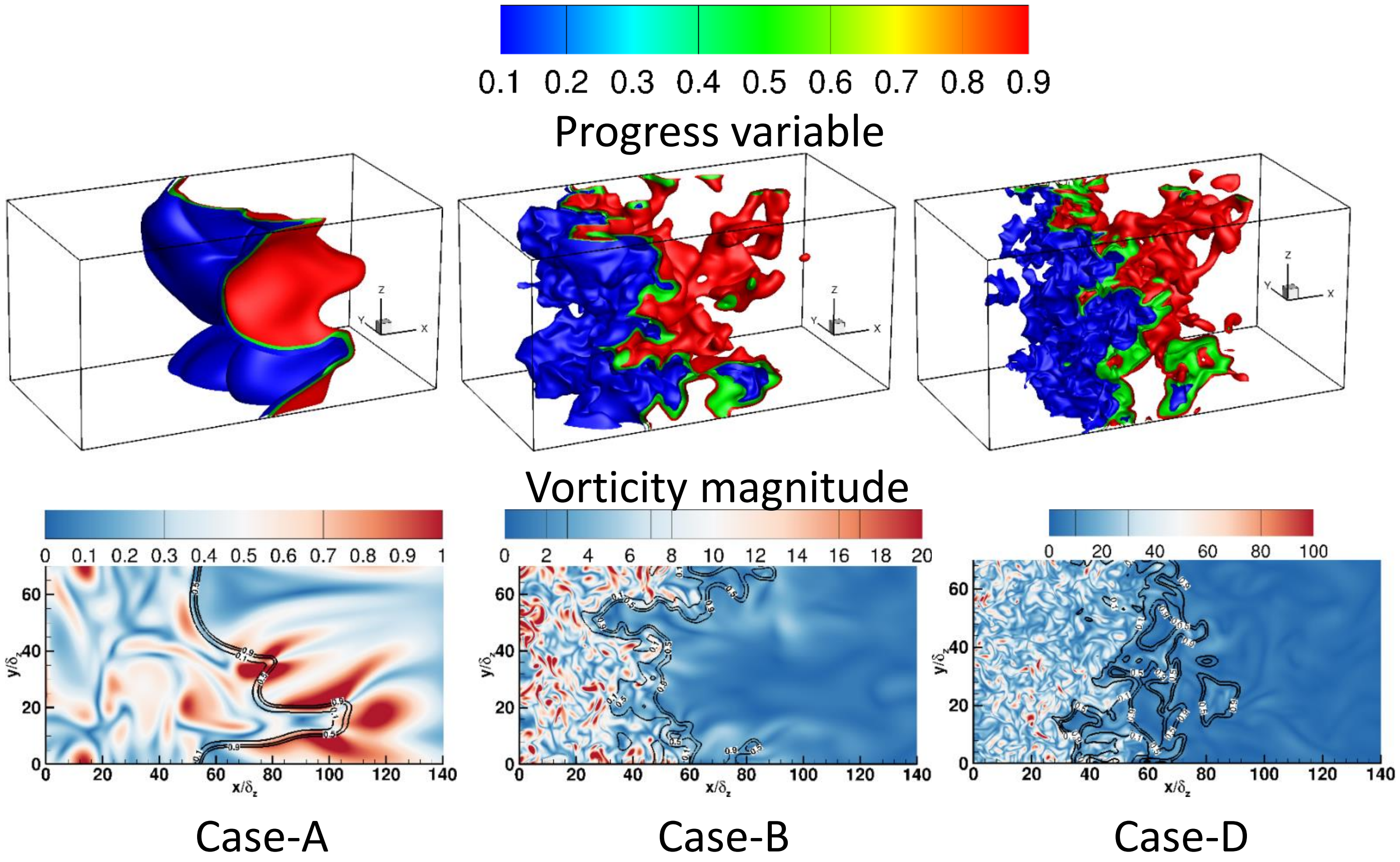
- The second and third invariants of b_{ij} are defined as :

$$6\eta^2 = b_{ij} b_{ji}$$

$$6\xi^3 = b_{ij} b_{jk} b_{ki}$$



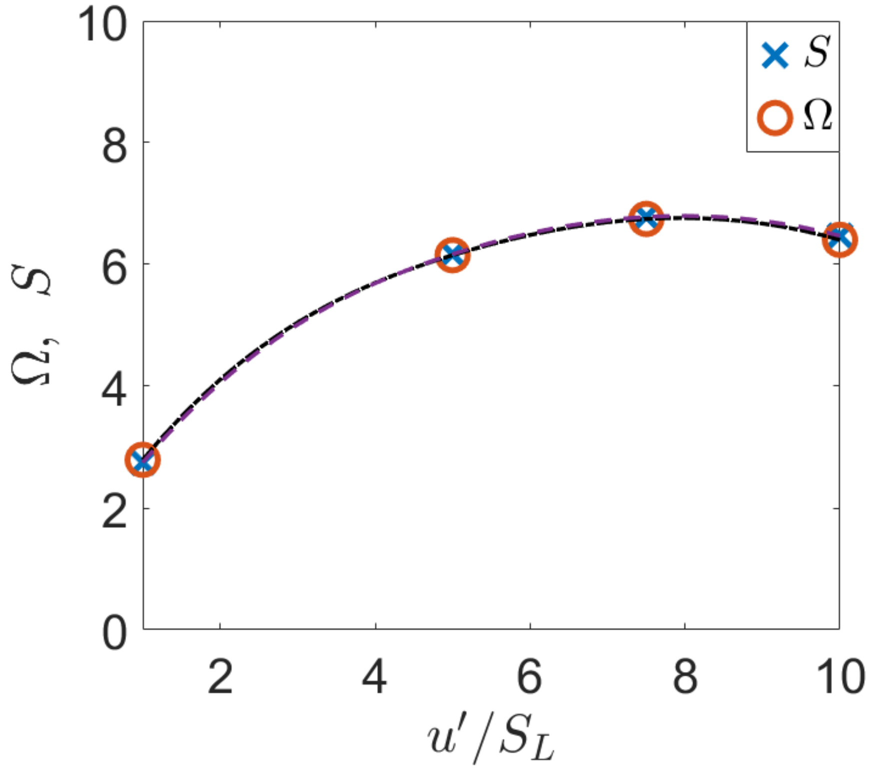
Comparison with planar flames



	u'/S_L	Ka	Da	Re_l
Case-A	1	0.577	3	7.56
Case-B	5	6.454	0.6	37.80
Case-C	7.5	11.858	0.4	56.70
Case-D	10	18.257	0.3	75.60

[1]**M Klein, N Chakraborty, S Ketterl** *Flow Turbulence Combust* (2017) 99: 955

- Turbulent planar flame simulations have been performed.
- Turbulence is forced upstream of the flame using modified Lundgren's forcing[1].



Conclusions

Droplet flame interaction

- Both **turbulence** and **droplet size** have an important influence on the flame structure.
- **Droplet induced wrinkling** effects are prominent for laminar cases and for small turbulence intensities. It is masked at high turbulence intensities.
- Predominantly fuel-lean **combustion mode** for droplet cases.
- **The growth rate of flame area** decreases with increasing droplet diameter.
- Smaller **burned gas volume** for larger droplet diameters.

Flame-wall interaction

- Changes in the thermal wall boundary conditions have an influence on the flame behaviour.
- The turbulent burning rate and the flame area do not remain proportional to each other in the near wall region.
- Changes in the behaviour of the Reynolds stresses are believed to cause a these changes in the case of adiabatic walls.
- Further investigation of the joint PDFs of reaction rate and Reynolds stress are ongoing to investigate this further.

Acknowledgments

We would like to acknowledge the financial support from
EPSRC (**EP/P022286/1**) and the computational
support from ARCHER (**EP/K025163/1**),
Cirrus(**Tier2 facility**) and
ROCKET the HPC facility at Newcastle University.
20000KAUs used on ARCHER