Effects of flame configuration on flame-wall interaction in fully developed turbulent boundary layers

Umair Ahmed[1*], Ilias Konstantinou[1], Nilanjan Chakraborty[1] & Markus Klein[2]

[1]School of Engineering, Newcastle University, Newcastle upon Tyne NE1 7RU
[2]Bundeswehr University Munich, Werner Heisenberg Weg 39,
D-85577 Neubiberg,Germany

[*]umair.ahmed@newcastle.ac.uk

Introduction

- Flame-wall interaction (FWI) occurs in many flows of engineering interest (e.g., Spark Ignition (SI) engines and gas turbines), and modelling these events remains challenging.

- The turbulence structure is altered by the walls, and the interaction of flame elements with walls leads to modifications of the underlying combustion process.

- Spatial and temporal fluctuations of wall temperature induce thermal stresses and strongly affect combustor lifetimes.

- FWI is increasingly becoming important as new combustors are being made smaller to increase energy density and reduce weight.

Introduction

- Typical reaction rate closures in RANS and LES do not account for boundary layer in the modelling approach.

- The main objectives of the present work are :

    i. Understand the flow flame interaction in FWI of different flame configurations in premixed turbulent combustion under isothermal wall boundary conditions.

    ii. To understand the influence of FWI on turbulence and scalar statistics in FWI of of different flame configurations in premixed turbulent combustion.

Direct Numerical Simulation

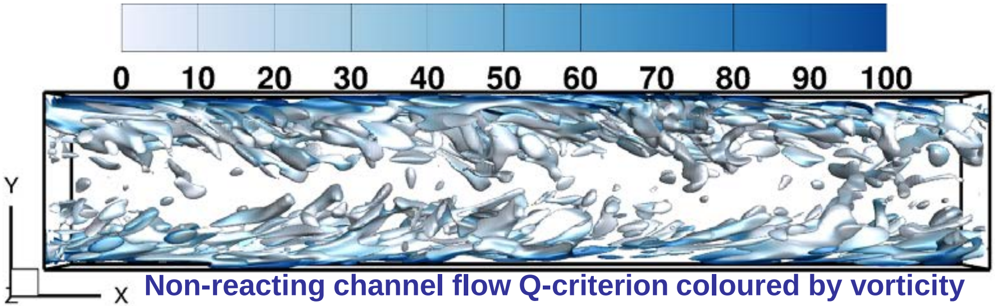
- A well-known three-dimensional compressible DNS code SENGA+[1] is used.
- The code solves conservation equations for mass, momentum, energy and chemical species in non-dimensional form using finite difference method.
- The spatial derivatives are evaluated via a 10^{th} order for internal points and gradually decreasing to 2^{nd} order at the non-periodic boundaries.
- A Runge-Kutta (3rd order explicit) scheme for time advancement.
- A single step irreversible chemical mechanism is used.
- Thermo-physical properties are taken to be constant.

[1]**K. Jenkins, R.S. Cant** *Recent Advances in DNS and LES: Proceedings of the 2nd AFOSR Conference (1999)*

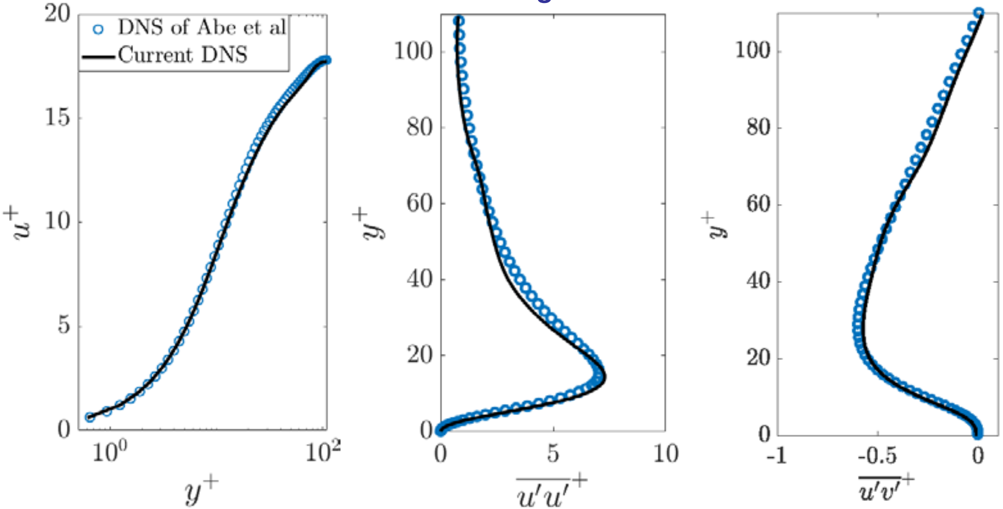
Mathematical Background

- Some basic definitions used in the fully developed boundary layer flows are:
  - Wall shear stress $\tau_{wall} = \mu \frac{\partial u}{\partial y}\Big|_{y=0}$.
  - 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 flow simulation



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



Non-reacting channel flow mean velocity and Reynolds stress profiles

- $Re_\tau = 110$ for the non-reacting channel.
- $y^+ = 0.6$ at the wall and at least two grid points are in $y^+ \leq 1.0$ region.
- Domain size $10.72h \times 2h \times 4h$.
- $1920 \times 360 \times 720$ (approx. 0.5 billion) grid points.
- Data validated against existing DNS.
- Data is recorded in time on the (y-z) plane.

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

Reacting flow simulations

- Two flame configurations have been simulated :
  - V-flame in a turbulent channel flow.
  - Head-on quenching in a turbulent boundary layer.
- V-flame Configuration similar to that of Alshaalan & Rutland[1] and Gruber et al.[2] is used.
- The Head-on quenching configuration is similar to that of Bruneaux et al.[3].
- The heat release parameter in these simulations is $\tau = 2.3$.
- The wall temperature is set to that of the non-reacting air-fuel mixture.
- The flame is representative of methane $\phi = 1.0$, $Le = 1.0$ with $S_L/u_\tau = 0.7$.

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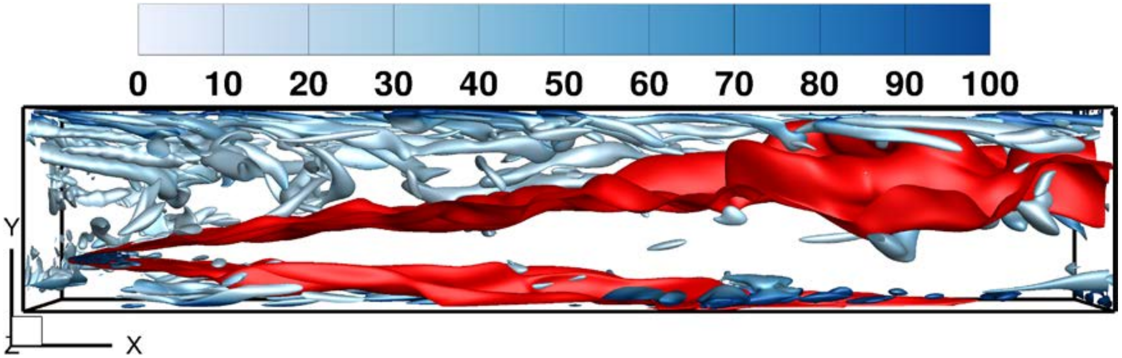
[1]**T. M. Alshaalan, CJ Rutland** *Symposium (International) on Combustion 27* (1998)(1), 793-799
[2]**A. Gruber, R. Sankaran, E. R. Hawkes, J. H. Chen** *Journal of Fluid Mechanics* (2010), 658, 5-32
[3]**G. Bruneaux, K. Akselvoll, T.J. Poinsot, J.H. Ferziger,** *Combust. Flame*, 107 (1996), pp. 27-44

V-flame simulation

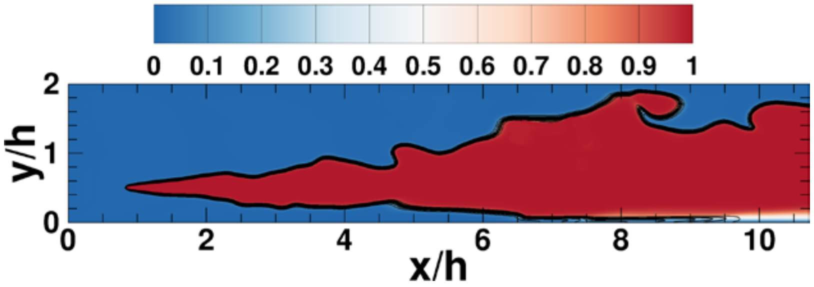
- V-flame is investigated in the $Re_\tau = 110$ channel flow with inert walls.
- The flame holder is placed in the log-layer region of the channel flow at $y^+ = 55$.
- The simulation is run for two flow through times after the initial transients have decayed.
- Progress variable is defined in terms of the fuel mass fraction.
- In the post-processing the data has been time averaged and then space averaged in the periodic (z) direction for Favre and Reynolds averaged quantities.

V-flame instantaneous behaviour

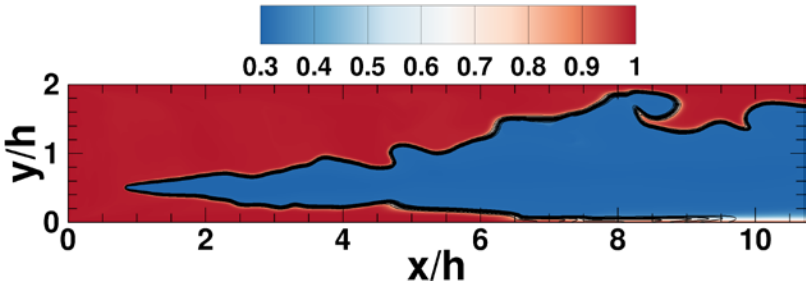
V-flame with isothermal walls



Q-criterion coloured by vorticity magnitude



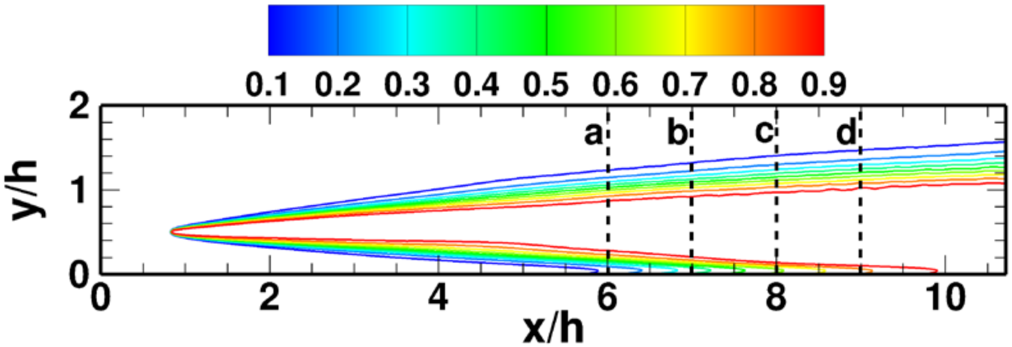
Temperature



Density

V-flame mean flow behaviour

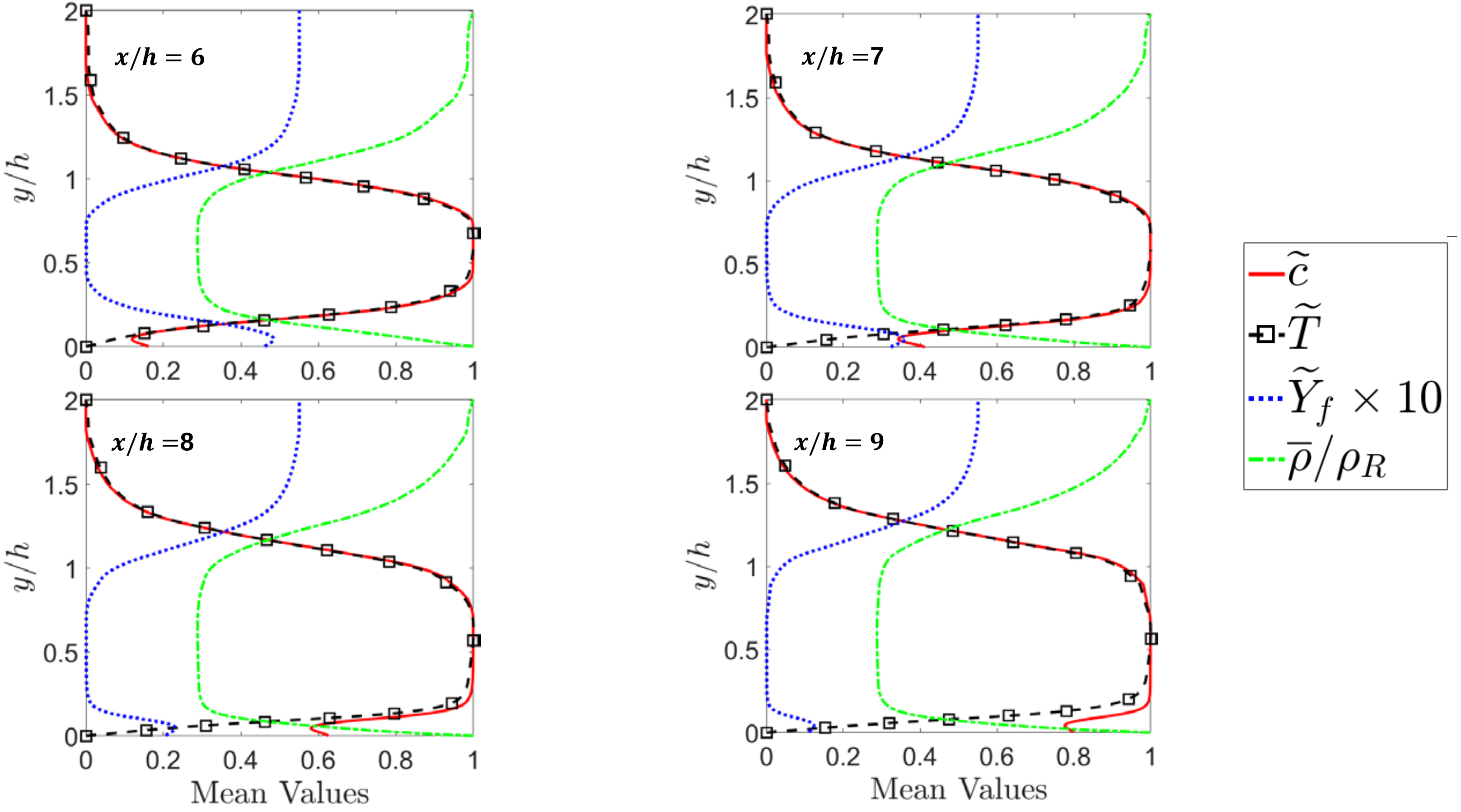
V-flame with isothermal walls



Favre Averaged Progress variable

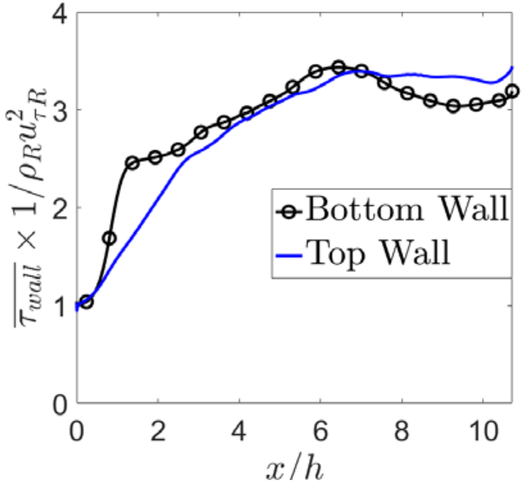
- Location $a = x/h = 6$
- Location $\mathrm{b} = x/h = 7$
- Location $\mathrm{c} = x/h = 8$
- Location $\mathrm{d} = x/h = 9$

V-flame mean flow behaviour

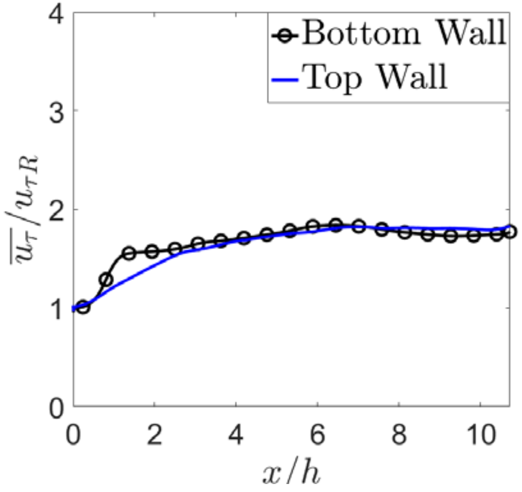


V-flame shear stress behaviour

Wall Shear Stress

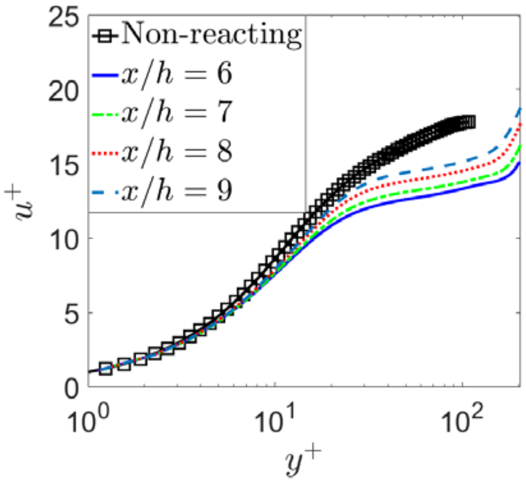


Wall Friction Velocity

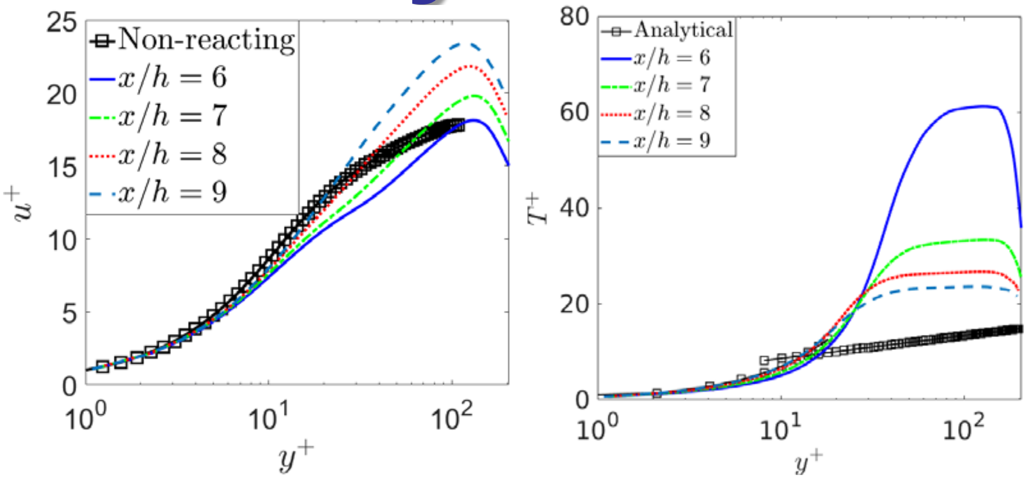


- Wall shear stresses increase in the stream-wise direction.
- Local flow acceleration due to the flame leads to steeper velocity gradients at the wall.

V-flame mean velocity behaviour



Top Wall

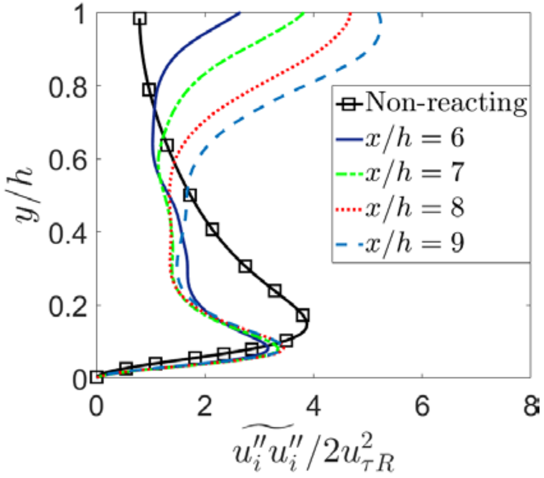


Bottom Wall

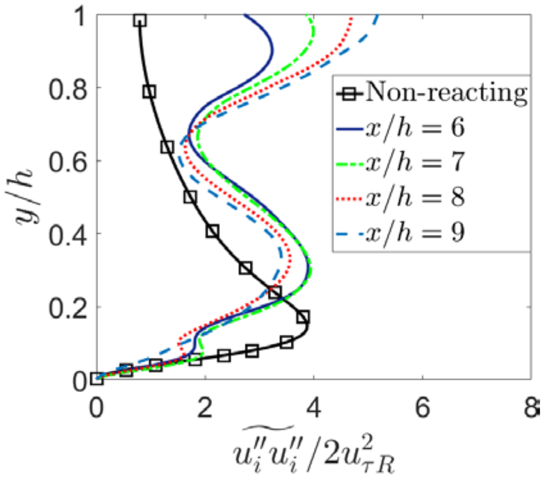
- The trend $y^+ = u^+$ is obeyed in the viscous sub-layer.
- $T^+ = (\tilde{T}/\overline{\Phi}_{wall}) \times u_\tau/S_L$
- The analytical function proposed by Kays & Crawford[1] for T^+ is not able to predict the correct behaviour in the log-layer region.

[1]**W.M. Kays, M.E. Crawford,** *Convective Heat and Mass Transfer*, 3rd edn, McGraw-Hill, New York (1993)

V-flame turbulent kinetic energy



Top Wall



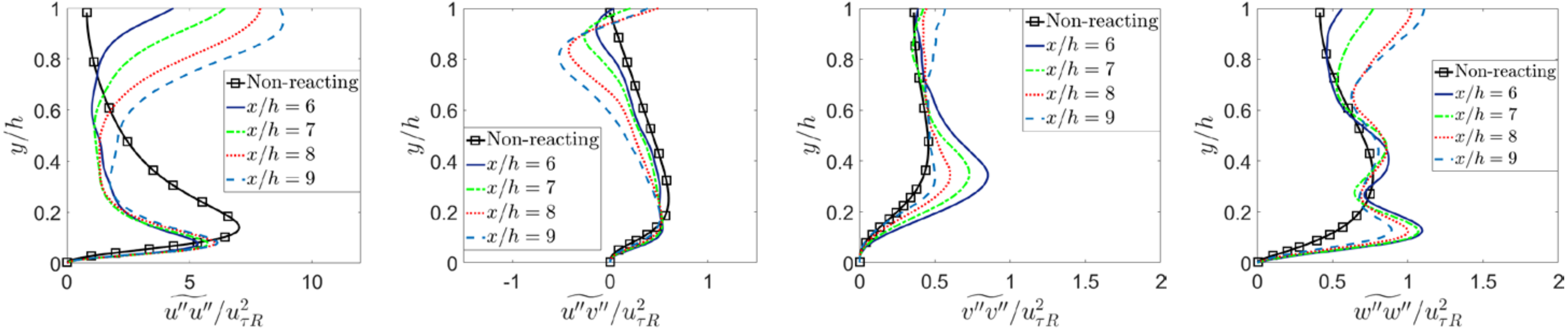
Bottom Wall

- Following Bruneaux et al.[1] the turbulence related quantities are normalised by u_{τ_R}.
- TKE profiles are similar to the non-reacting case near the top wall.
- On the bottom wall TKE is significantly altered by the existence of the flame.

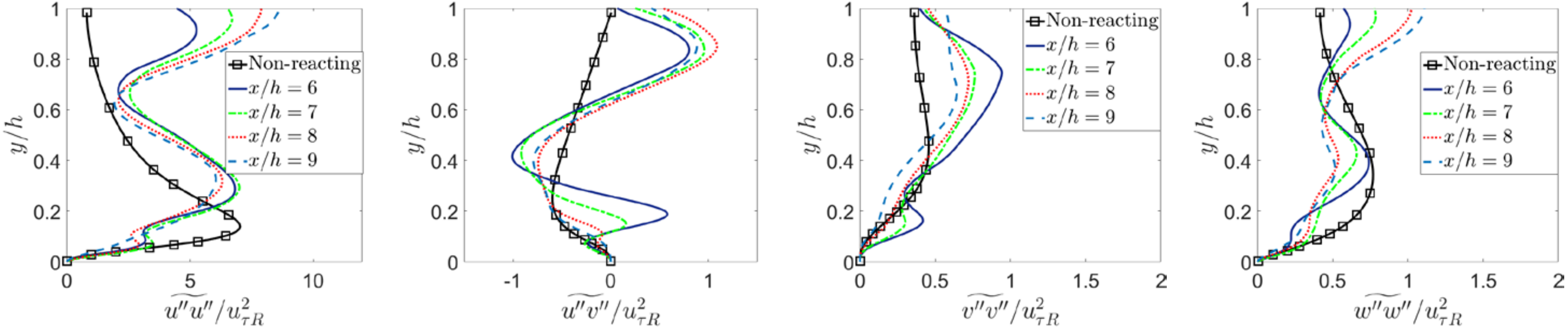
[1] **G. Bruneaux, K. Akselvoll, T.J. Poinsot, J.H. Ferziger,** *Combust. Flame*, 107 (1996), pp. 27-44

V-flame Reynolds stresses

Top Wall normalised by $u_{\tau R}$ values

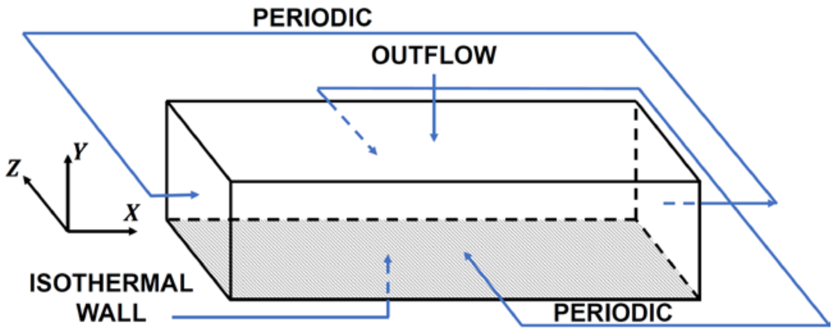


Bottom Wall normalised by $u_{\tau R}$ values



HOQ simulation

- HOQ is investigated in the $Re_\tau = 110$ periodic boundary layer with inert walls.



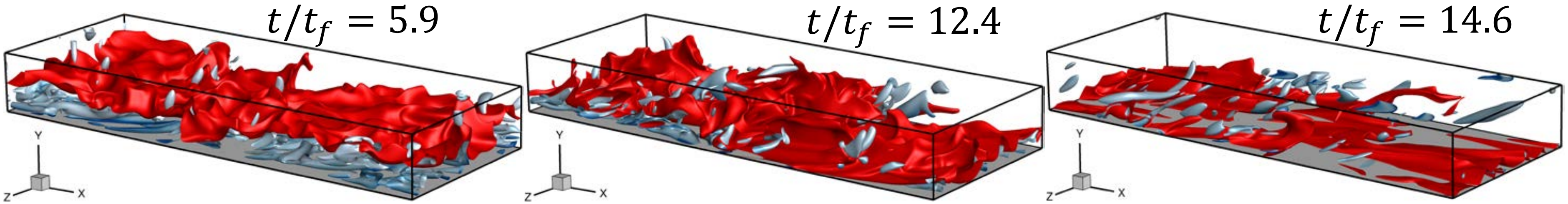
- Domain size $10.72h \times h \times 4h$ discretised on $1920 \times 180 \times 720$ (approx. 0.25 billion) grid points.

- The simulation is run until the flame has fully quenched.

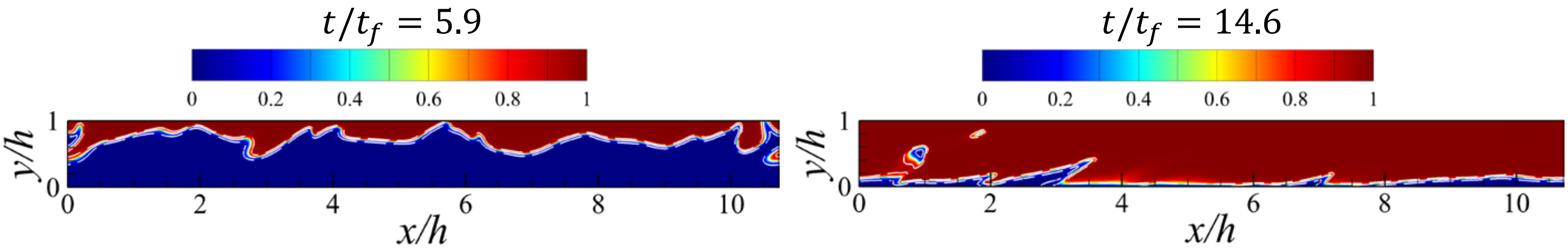
- Progress variable is defined in terms of the fuel mass fraction.

HOQ instantaneous behaviour

HOQ with an isothermal wall

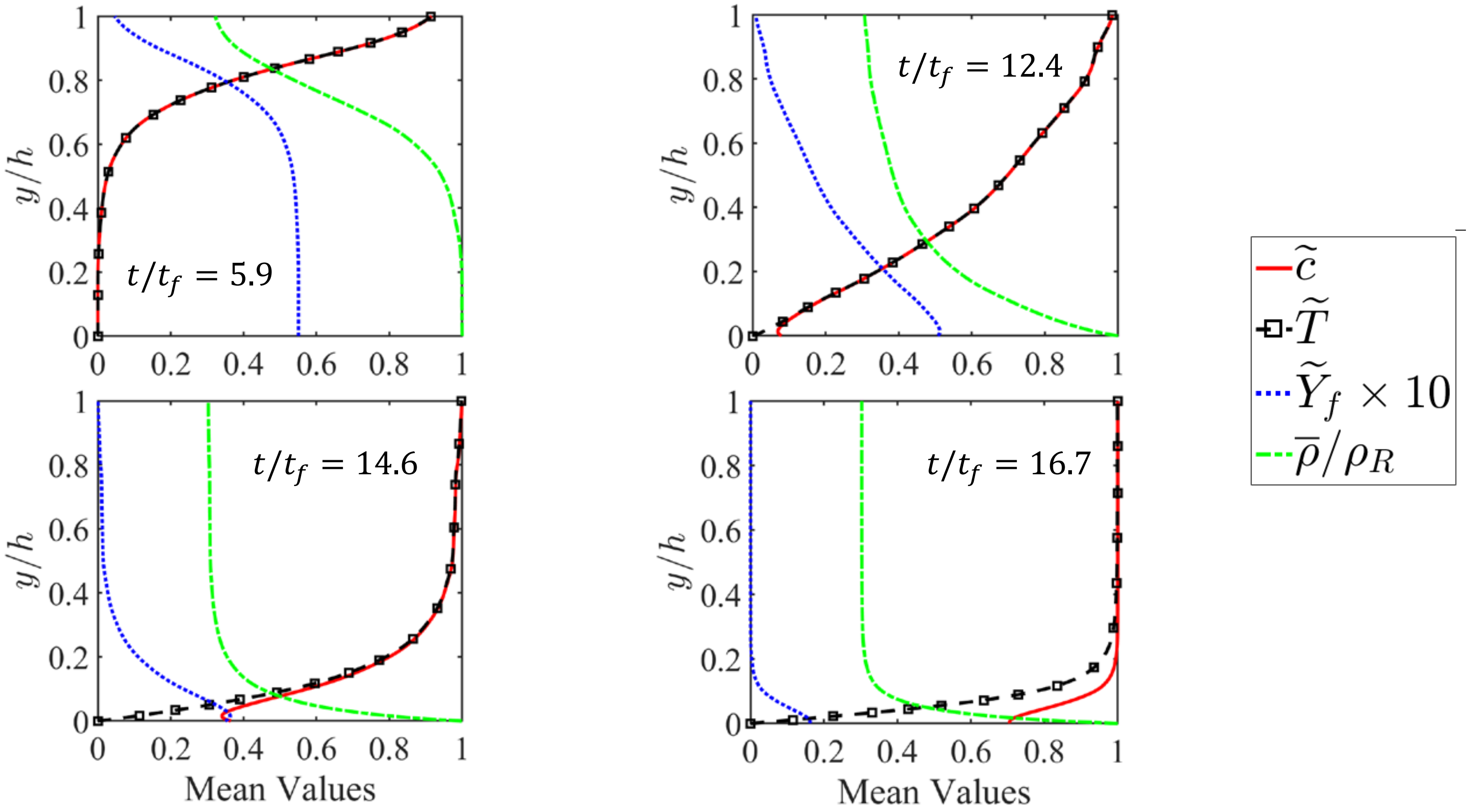


Q-criterion coloured by vorticity magnitude



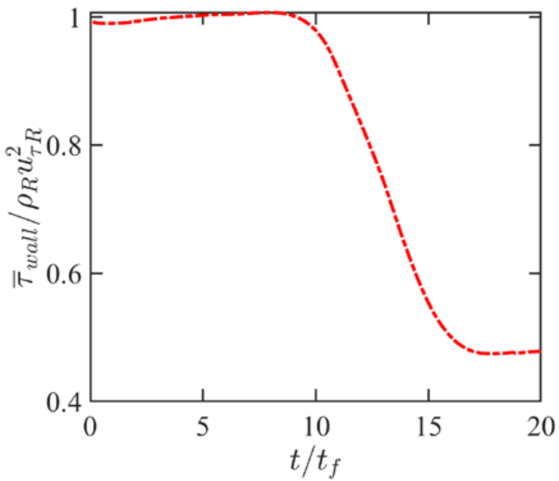
Temperature

HOQ mean flow behaviour

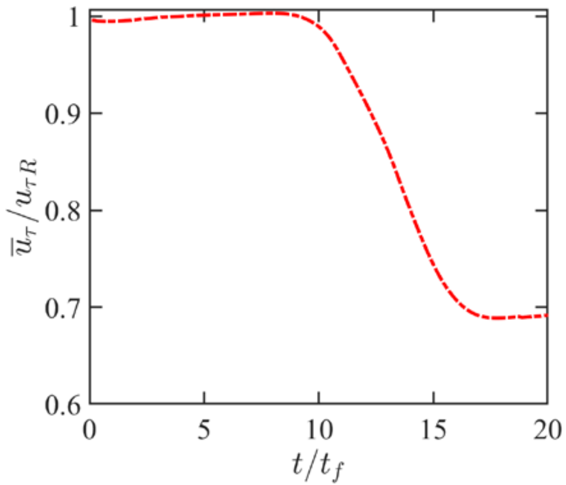


HOQ shear stress behaviour

Wall Shear Stress



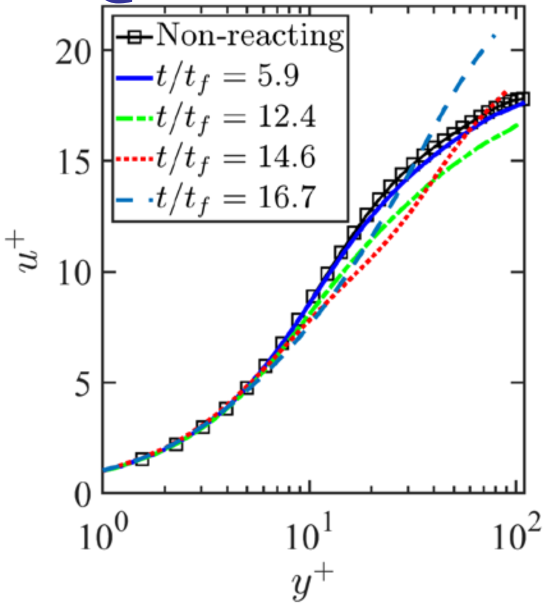
Wall Friction Velocity

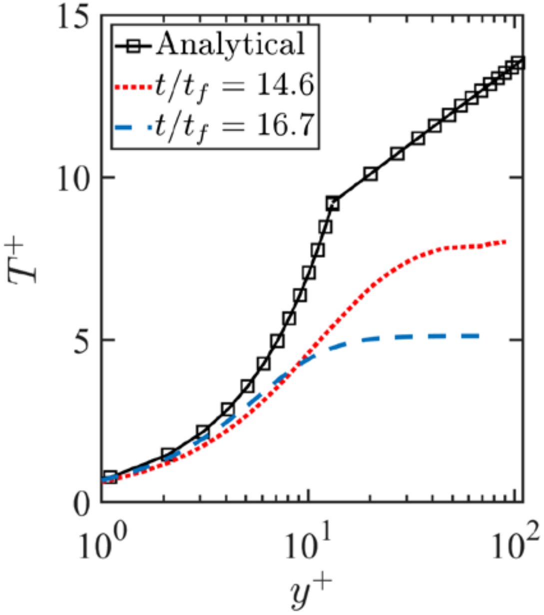


- Wall shear stress decreases with time as the flame interacts with the wall.

- During the flame-wall interaction u_τ decreases due to a decrease in the kinematic viscosity near the wall.

HOQ mean behaviour





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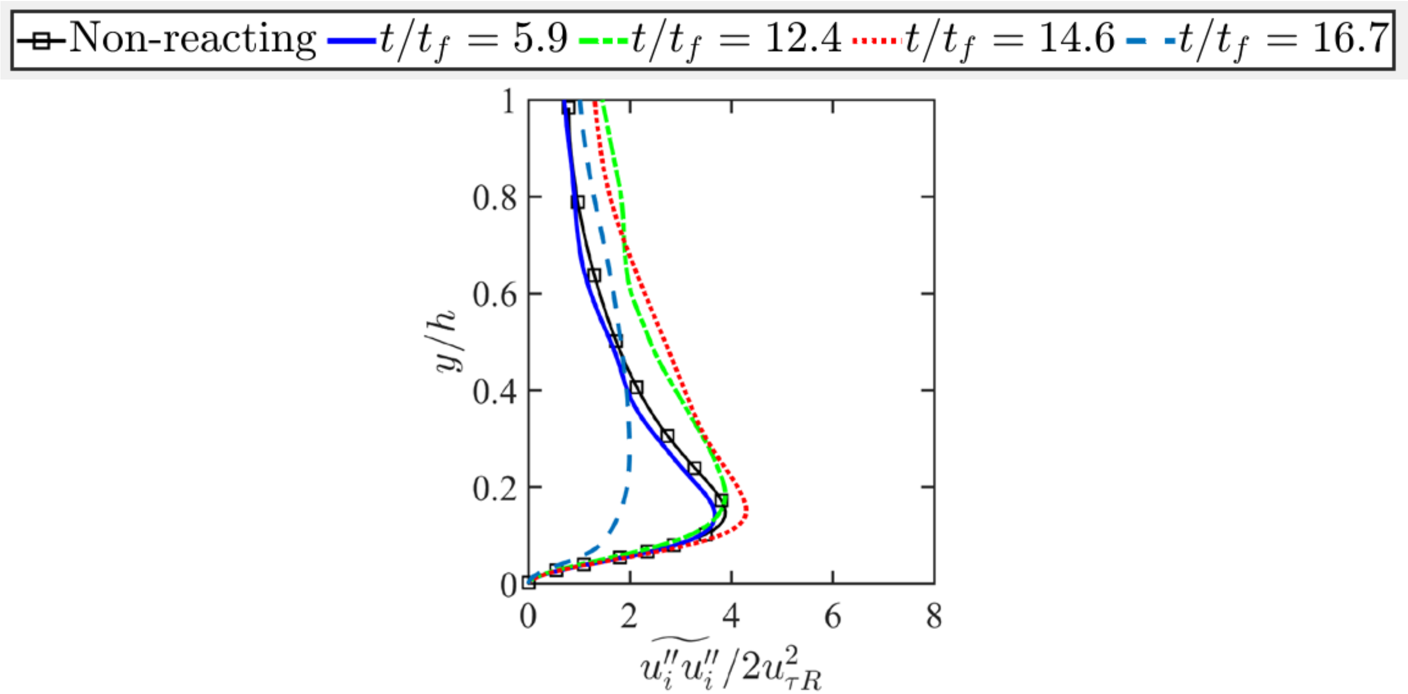
HOQ turbulent kinetic energy



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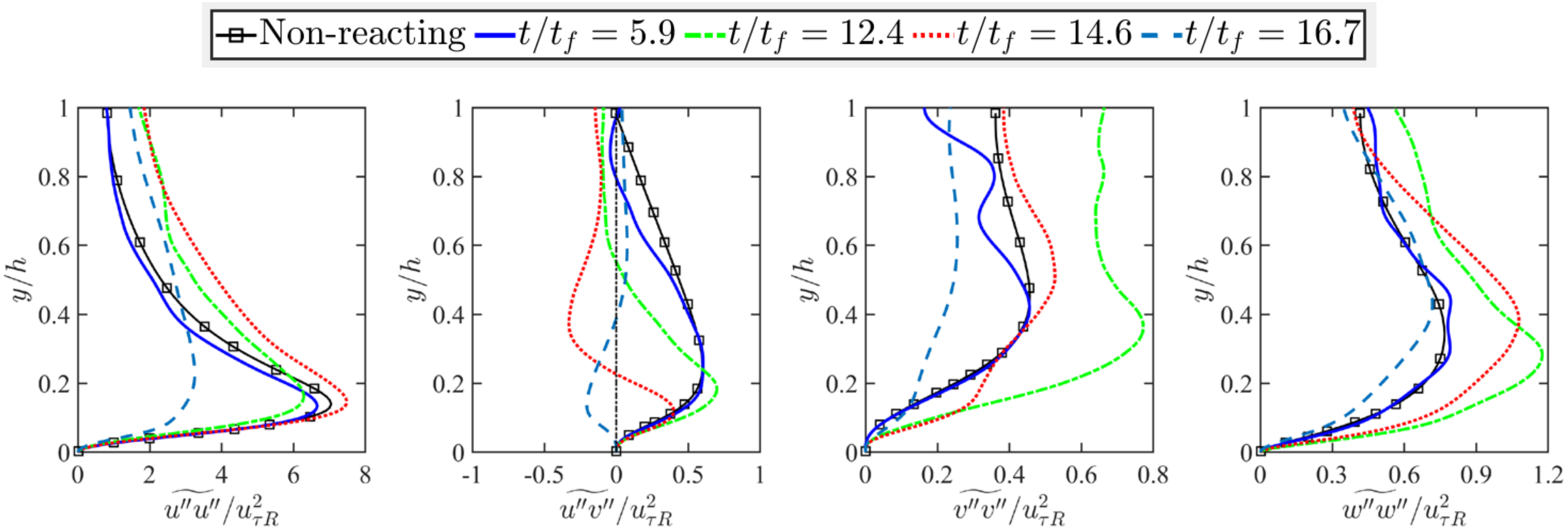
HOQ Reynolds stresses



Stresses normalised by $u_{\tau R}$ values

Summary and conclusions

- Isothermal wall boundary condition simulations for a V-flame and HOQ in a fully developed turbulent boundary layer at $Re_\tau = 110$ have been performed.

- It is found that the mean flame location and the quantities related to turbulence are altered by the change in the flame/flow configuration.

- It is also found that the mean behaviour of velocity and temperature is significantly affected by the flame/flow configuration.

- The standard formulations for near wall treatment in RANS and LES used for non-reacting flows have to be modified to account for flame-wall interaction in fully developed turbulent boundary layers.

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- HPC facility at Newcastle University (Rocket).

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