Case Study

1. Title of Case Study: Flame-Wall Interaction of Premixed Combustion in Turbulent Boundary Layers.

2. Grant Reference Number: EP/P022286/1, EP/R029369/1

3. One sentence summary: Flame-wall interaction of premixed combustion in fully developed turbulent boundary layers is investigated using three-dimensional Direct Numerical Simulations

4. One paragraph summary: The treatment of near-wall turbulence for non-reacting flows remains a challenging problem and quite often becomes the limiting factor in flow prediction in practical applications. In reacting flows, the fundamental understanding remains even more limited and the modelling of such complex flows is currently in a rudimentary stage. In addition, as the flame approaches the wall, flame elements interact with the walls leading to high wall heat fluxes. The cooled combustor walls introduce a temperature gradient between the flame and the walls which in turn promotes flame quenching in the vicinity of the walls. This modifies the characteristic behaviour of the flame and the underlying turbulence. In practice, limited information is known about the effects and behaviour of turbulence during flame-wall interaction (FWI). Although extensive research has been directed to non-reacting turbulent boundary layers, this has limited relevance in turbulent reacting flows within boundary layers, due to thermal expansion effects present during the combustion process, effectively leading to significant modifications in the velocity and temperature distributions. The fundamental understanding of the physical mechanisms of premixed FWI is crucial for the development of computationally efficient turbulence and reaction rate closures, which can play a pivotal role in the design and optimisation of the new generation of combustion chambers for power generation and automotive sectors. In this spirit the influence of flow configuration has been investigated in fully developed turbulent boundary layers.

5. Key outputs in bullet points:

Knowledge: Understanding of the behaviour of turbulence in the boundary layer during flame-wall interaction of premixed flames has been investigated for the first time.

Skill: The project has trained a PhD student in advanced computing with Fortran and a Research Associate went on to get a permananet academic job (i.e. lectureship).

Dissemination: The following articles have been presented and published:

1. I. Konstantinou, U. Ahmed, M. Klein, N. Chakraborty. Near-wall behaviour of turbulence in flame-wall interaction of premixed turbulent combustion in boundary layers. In: 9th European Combustion Meeting (ECM 2019). 2019, Lisboa, Portugal.
2. I. Konstantinou, U. Ahmed, N. Chakraborty. Influence of fuel Lewis number on flame-wall interaction for impinging turbulent premixed flames. In: 27th International Colloquium on Dynamics of Explosions and Reactive Systems. 2019, Beijing, China.
3. U. Ahmed, M. Klein, N. Chakraborty. Oblique flame-wall interaction in premixed turbulent combustion under isothermal and adiabatic wall boundary conditions. In: 27th International Colloquium on Dynamics of Explosions and Reactive Systems. 2019, Beijing, China.
4. I. Konstantinou, U. Ahmed, N. Chakraborty, M. Klein. Statistics of turbulence during head-on quenching of premixed turbulent combustion in boundary layers. International Workshop on Clean Combustion: Principles and Applications Darmstadt, Germany, September 25-26th, 2019.
5. U. Ahmed, N. Chakraborty, M. Klein. Scalar gradient and strain rate statistics in oblique premixed flame-wall interaction witin turbulent boundary layers. International Workshop on Clean Combustion: Principles and Applications Darmstadt, Germany, September 25-26th, 2019.

6. Main body text:

The fundamental understanding of the physical mechanisms of premixed flame-wall interaction (FWI) is important for the development of computationally efficient turbulence and reaction rate closures, which can play a pivitol role in the design and optimisation of the new generation of combustion chanbers for power genertation and transport sectors. Flames usually quench very close to the wall and in the case of fully developed turbulent boundary layers the scale separtation in turbulence structures makes the fundamental investigation of FWI very challenging in experiemtnal studies. Furthermore, the flame elements approaching the walls increase the heat flux experienced by the combustor walls which can severly reduce the life span of the combustor and can lead to the failure of the equipment due to thermal fatigue cased by high wall heat fluxes. In this case the turbulence structure is altered by the walls and the interaction of flame elements with the walls leads to the modification of the underlying turbulence and combustion processes. The treatment of turbulence for non-reacting flows is still a difficult problem and can be a limiting factor in flow prediction of practical applications. In this spirit, FWI has been investigated under isothermal inert wall boundary conditions, by performing Direct Numerical Simulation (DNS) of oblique quenching of a V-flame in a fully developed channel flow configuration and head-on quenching (HOQ) of a statistically planar flame in a fully developed turbulent boundary layer. The V-flame configuration is representative of bluff body stabilised flames in gas turbine engines and industrial furnaces, and is an inherently statistically stationary configuration. In contrast, the HOQ configuration is inherently unsteady in nature. By interrogating the DNS data from the HOQ configuration one can eliminate the fluid mechanical effects introduced by the presence of the V-flame holder. This can essentially lead to the development of Reynolds Averaged Navier-Stokes (RANS) models capable of accounting for the near-wall turbulence in conjunction with the flame quenching zone, which is generally inside the viscous sublayer. Figure 1 shows the instantaneous 3D views of the V-flame configuration along with the Favre mean progress variable. It can be seen that the flame interacts with the wall downstream of the flame holder and the flame brush is stretched along the wall. Figure 2 shows the HOQ configuration at different times during different stages of the FWI. The instantaneous non-dimensional temperature along with the contours of the instantaneous progress variable are also shown in Fig. 2.

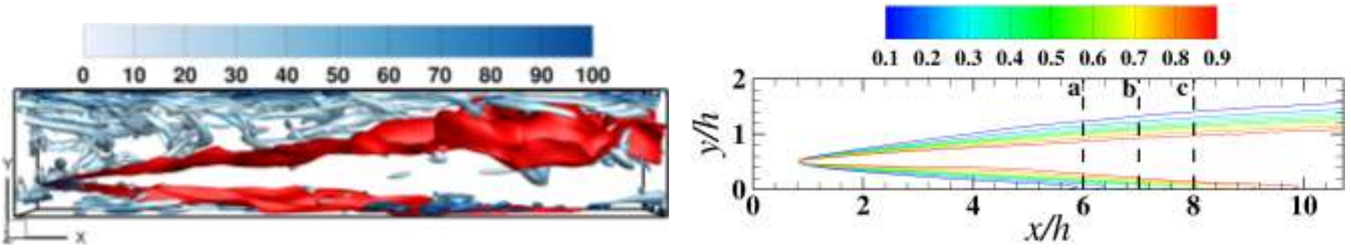

Fig. 1: V-flame case with Isothermal walls boundary conditions. Figure on the left shows the iso-surface coloured in red represents $c = 0.5$. The isosurfaces coloured in blue represent the Q-criterion coloured by vorticity magnitude. Figure on the right shows the contours of Favre mean reaction progress variable, $\tilde{c}$.

The aforementioned simulation databases have been explicitly Reynolds-averaged or filtered for the purpose of extraction of unclosed terms in the context of Reynolds Averaged Navier-Stokes (RANS) and Large Eddy Simulations (LES).This exercise, in turn, has been utilised to analyse the statistical behaviours of the unclosed terms and assess the performances of their models. This model assessement enables modification of the existing models of turbulent boundary layer analysis (e.g. wall functions of velocity and temperature) for the analysis of turbulent premixed FWI and also development of new models, wherever necessary based on the physical insights extracted from DNS data.

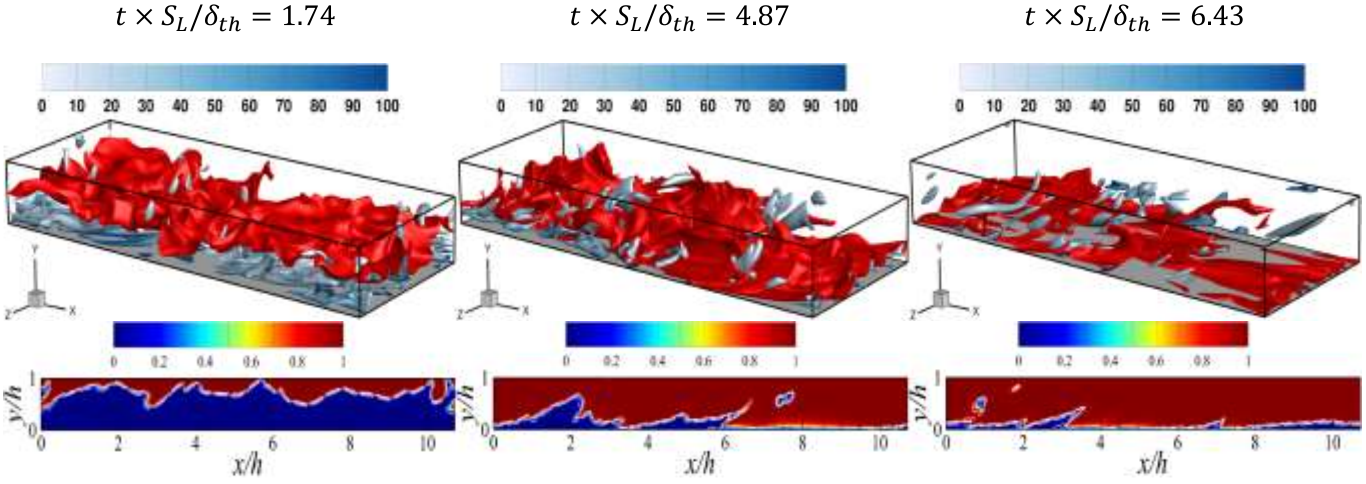
$t \times S_L/\delta_{th} = 1.74$ $t \times S_L/\delta_{th} = 4.87$ $t \times S_L/\delta_{th} = 6.43$

Fig. 2: Instantaneous view of $c = 0.5$ isosurface (coloured in red) (top). Contour lines of reaction progress variable, $c = 0.1$, 0.5, 0.9 in white superimposed on the instantaneous temperature field (bottom).

7. Names of key academics and any collaborators:
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8. Sources of significant sponsorship (if applicable): Not applicable

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10. Please indicate if you would like this case study to be included on the Consortium's ARCHER web-page. yes