Case Study 2

1. Title of Case Study: Fundamental investigation and modelling of turbulent premixed flame-wall interaction

2. Grant Reference Number: EP/K025163/1

3. One sentence summary: Direct Numerical Simulations (DNS) of turbulent premixed flame-wall interaction have been carried out for different configurations, and the physical insights obtained from DNS data have been utilised to develop high-fidelity models, which will play a pivotal role in the design-cycle of next-generation Internal Combustion (IC) engines, gas turbines and micro-combustors.

4. One paragraph summary: Three-dimensional compressible simple and detailed chemistry Direct Numerical Simulations (DNS) of turbulent premixed flame-wall interaction (FWI) have been carried out for (i) head-on quenching of statistically planar flames and (ii) oblique quenching of turbulent V-flame. This DNS data has, in turn, been used for obtaining fundamental physical insights into the behaviour of the mean reaction rate, and the transports of turbulent kinetic energy, scalar variance, scalar flux, Flame Surface Density (FSD) and Scalar Dissipation Rate (SDR) in the near-wall region, which was rare in existing literature until now. The near-wall behaviour of the unclosed terms in the turbulent kinetic energy, scalar variance, scalar flux, FSD and SDR transport have been obtained by explicitly averaging/ filtering the DNS data, and the physical understanding obtained from DNS data is utilised to develop high-fidelity models for Reynolds Averaged Navier-Stokes (RANS), and Large Eddy Simulations (LES). The fundamental understanding of FWI and its modelling will provide robust and cost-effective Computational Fluid Dynamics (CFD) based design tools for reliable, fuel-economic and low-emission combustion devices.

5. Key outputs in bullet points:

- Statistical behaviour of wall heat flux, and flame quenching distance for premixed flame quenching by isothermal inert walls, which are of pivotal importance in the design of IC engines and micro-combustors.
- Fundamental physical insights into the statistical behaviours of turbulent kinetic energy, turbulent scalar flux, scalar variance, scalar dissipation rate, and FSD in the vicinity of the wall during wall induced flame quenching. Until recently, this information has been lacking in existing literature.
- Collaboration with UK and International colleagues (see section 7 below) who are interested in this research and in using this data.
- Until now the project has given rise to 6 high-quality journal papers and 9 international conference proceedings
- So far, a PhD student and four Masters students have benefitted from this project (e.g. received extensive training in combustion theory and modelling, high-performance computing etc.)

6. Main body text

In most combustors, the cooling of walls is necessary because the burned gas temperature is often higher than the melting point of the combustor material. This cooling has a significant impact on the combustion processes in the near-wall region and on the life span of the combustor itself, and this interaction is often referred to as flame-wall interaction (FWI). In IC engines, flame quenching by cold walls leads to unburned hydrocarbons, which, in combination with heat losses to the wall, negatively affects the efficiency and pollutant emission performance. Furthermore, flame propagation in the low-velocity region of the wall boundary layer may lead to a flashback from the combustion chamber to the mixing zone in a gas turbine. The increasing demands for lightweight and micro-combustors make FWI an inevitable event in these applications. Therefore, a thorough physical understanding of the FWI mechanism is necessary in order to develop and design more energy-efficient and environmentally friendly combustion devices. It is difficult to get detailed information of FWI with experimental measurements because of small length-scales. In this project, the advancement of high-performance computing (HPC) has been utilised analyse FWI for turbulent premixed flames using Direct Numerical Simulations (DNS) (simulations carried out on ARCHER and N8 using SENGA/SENGA2) without any recourse to physical approximation, and therefore bypassing the above limitations. In this project, DNS of premixed flames have been carried out to analyse FWI in (i) head-on quenching (HOQ, where the mean flame propagation is normal to the wall) of statistically planar flames without any mean shear (see Fig. 1); (ii) oblique quenching of a rod-stabilised V-flame (see Fig. 2), as these configurations incorporate all the generic types of FWI. The DNS data has provided important physical insights into the enstrophy (i.e. rotational kinetic energy) transport [1], wall heat flux and flame quenching distance [2], and flow topology distribution [3] in the near-wall region at various stages of flame quenching. Moreover, the DNS data has been explicitly Reynolds-averaged/LES filtered to obtain the unclosed terms in the turbulent kinetic energy [4], Flame Surface Density (FSD) [5], Scalar Dissipation Rate (SDR) [1,6,7], turbulent scalar flux and scalar variance [8], and to compare the performances of existing models. Furthermore, the mean reaction rate closures by FSD and SDR have been modified so that they account for the reduction of burning rate in the near-wall region due to wall-induced flame quenching [2,5,6]. The aforementioned information was not reported in the existing literature until now despite applications in IC engines and gas turbines, and the proposed project will address this important gap in the knowledge-base of turbulent reacting flows. Furthermore, fundamental physical insights and modelling information extracted from this research will provide the foundation for robust and cost-effective Computational Fluid Dynamics based design tools for reliable, fuel-economic and low-emission combustion devices for the future.

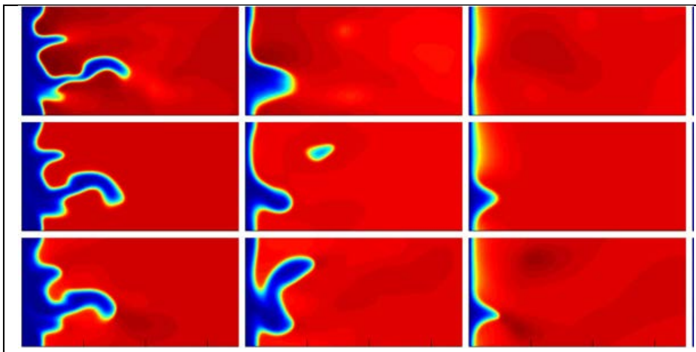

Fig. 1: Instantaneous non-dimensional temperature field (red-high and blue-low) for head-on quenching of statistically planar flames for $Le = 0.8$ (1st row), 1.0 (2nd row) and 1.2 (3rd row) at different times (e.g. time increases from left to right for a given row).

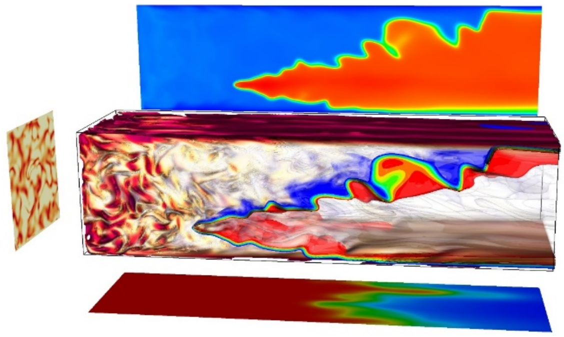

Fig. 2: The instantaneous distribution of vorticity magnitude (background: red-high and white-low) and temperature (isosurface and side view, red-high and blue-low) and fuel mass fraction (lower wall view, red-high and blue-low).

References

1. J. Lai, N. Chakraborty, A. Lipatnikov, Eur. J. Mech. Fluids/B., http://dx.doi.org/10.1016/j.euromechflu.2016.10.013.
2. J. Lai, N. Chakraborty (2016) Flow Turb. Combust., 96, 279-308.
3. J. Lai, N. Chakraborty, Proc. 8th Eur. Combust. Meeting 2017, Dubrovnik, Croatia.
4. J. Lai, N. Chakraborty, Proc. 7th Eur. Combust. Meeting 2015, Budapest, Hungary.
5. J. Sellmann, J. Lai, N. Chakraborty, A.M. Kempf, Proc. Combust. Inst., 36, http://dx.doi.org/10.1016/j.proci.2016.07.114
6. J. Lai, N. Chakraborty (2016) Combust. Sci. Technol., 188,1440-1471.
7. J. Lai, N. Chakraborty (2016) Combust. Sci. Technol., 188, 250-276.
8. J. Lai, N. Chakraborty (2016) Combust. Sci. Technol., 188,1925-1950.

7. Names of key academics and any collaborators:

Key academic: Prof. Nilanjan Chakraborty (nilanjan.chakraborty@ncl.ac.uk), Newcastle University, UK
Collaborators: Prof. R. Stewart Cant (rsc10@eng.cam.ac.uk), Cambridge University Engineering Department, UK
Prof. Andreas M Kempf (andreas.kempf@uni-due.de) , University of Duisburg, Germany
Prof. Markus Klein (markus.klein@unibw.de), Universitat der Bundeswehr Munchen, Neubiberg, Germany
Dr. Andrei Lipatnikov (andrei.lipatnikov@chalmers.se) , Chalmers University, Sweden
Prof. Lipo Wang (lipo.wang@sjtu.edu.cn) , Shanghai Jiao'Tong University, China

8. Sources of significant sponsorship (if applicable):

N/A

9. Who should we contact for more information?

Mr. Jiawei Lai (j.lai@ncl.ac.uk), Newcastle University, UK
Prof. Nilanjan Chakraborty (nilanjan.chakraborty@ncl.ac.uk) , Newcastle University, UK

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

Yes