Premixed flame-wall interaction and heat transfer characteristics in turbulent boundary layers: Insights based on Direct Numerical Simulations

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ABSTRACT

The walls of combustors need to be cooled for structural integrity because the burned gas temperature is often higher than the melting point of the combustor material. However, wall cooling has a significant impact on the fluid-dynamical transport processes in the near-wall region, and this interaction is usually referred to as flame-wall interaction (FWI). Flame quenching due to heat loss induced by cold walls leads to unburned reactants, which, in combination with heat losses to the wall, negatively affects the efficiency and pollutant emission performance of the engine. 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 micro-combustors and lightweight compact combustors for hybrid-electrical powertrain make FWI an inevitable event. Therefore, an improved physical understanding of the FWI mechanism is necessary to develop and design simultaneously efficient and environmentally friendly combustion devices.

FWI under turbulent conditions involves the intermittent passage of cold unburned and hot burned gases close to the wall. The heat flux at the wall is determined by contact with hot and cold gases and the proximity of the flame to the wall. In most practical combustion devices, the typical burned gas temperature remains about 1200-1800 K, whereas the wall temperature of the combustor is maintained in the range of 800-1000 K because of cooling so that structural integrity is maintained. A temperature change of the order of 400-800 K occurs within a thin layer of the order of 1.0 mm from the wall and thus gives rise to large heat flux magnitudes. This makes the analysis of FWI a challenging task due to the spatial resolution requirements. The only quantity, which can be measured reliably, is the wall heat flux, but this quantity is an indirect effect of the chemical processes taking place in the gaseous phase. Moreover, the transient effects associated with FWI (e.g., high wall flux for a short duration followed by reduced values of heat flux for a relatively long interval) makes the characterisation of the underlying combustion process extremely difficult. Thus, the near-wall region must be resolved sufficiently to obtain fundamental physical insights into premixed FWI. This resolution can be achieved utilising the recent advances of high-performance computing to conduct Direct Numerical Simulations (DNS) of premixed FWI where all the relevant length and timescales of the turbulence and combustion processes are resolved without any physical approximation. In the last two decades, the DNS of reacting flows has led to significant advancements in the physical understanding and modelling of turbulent combustion modelling. However, to date, most combustion DNS studies have been carried out in canonical configurations in the absence of no-slip wall boundary conditions but the advancements in high-performance computing have now made it possible to carry out DNS of premixed FWI.

This keynote lecture will focus on different aspects of turbulent fluid motion (e.g., wall functions for mean velocity and temperature) and scalar statistics (e.g. turbulent scalar flux, scalar variance and scalar dissipation rate) for the purpose of Reynolds Averaged Navier-Stokes (RANS) and Large Eddy Simulations (LES) modelling of premixed FWI based on interrogation of DNS data in a number of different flow configurations including oblique quenching of V-shaped premixed flames by an isothermal inert wall in a turbulent channel flow, and head-on quenching across a turbulent boundary layer on an inert isothermal flat plate. It will be shown that the flame configuration and the thermal wall boundary condition play significant roles in determining the statistical behaviours of Reynolds stresses, turbulent kinetic energy, and scalar fluxes, which have implications on the modelling of these quantities in the context of RANS and LES simulations. Moreover, it will be demonstrated that the existing mean

reaction rate closures do not adequately capture flame quenching in the near-wall region, and the existing modifications of these closures for the accurate representation of hydrocarbon-air premixed flame quenching may not be adequate for high hydrogen content fuels. The high flame speed for hydrogen-rich premixed flames can lead to flashback in turbulent boundary layers, which significantly affect local flame propagation rate, reactive scalar gradient statistics and turbulent kinetic energy transport. Detailed physical explanations will be offered for the influence of the flame on the near-wall heat and fluid flow based on physical insights extracted from DNS data and the associated modelling implications will be provided. Finally, the newly derived integral form of the energy conservation equation for the turbulent reacting flow boundary layer will be utilised in conjunction with DNS data to demonstrate that the wall heat flux magnitude for premixed FWI is intrinsically related to turbulent burning velocity. It will be shown that the measurement of wall heat flux can be utilised to predict the turbulent burning velocity in the case of premixed FWI within turbulent boundary layers.

SHORT BIOGRAPHY

Prof. Nilanjan Chakraborty is a professor of Fluid Dynamics and the lead member of the Fluid Dynamics and Thermal Systems research group (2011-), within the School of Engineering at Newcastle University. Previously, he was a senior lecturer (2008-2011) and a lecturer (2005-2008) at the University of Liverpool and a Mechanical Engineer of General Electric's Research and Development division before he pursued his PhD and Postdoctoral research at the University of Cambridge (2001-2005). His research interests include Direct Numerical Simulation (DNS) of turbulent combustion and multiphase flows, Large Eddy Simulation (LES) combustion modelling, natural convection of non-Newtonian fluids, Melting/Solidification related heat transfer problems in classical manufacturing (e.g., welding) and Laser aided manufacturing applications (e.g. Laser Surface Alloying). To date, his research has been funded by the Nuffield Foundation, Newton grant (NRCP1516/4/67), British Council and Engineering and Physical Sciences Research Council (EPSRC), UK. In 2005, he and his co-authors were awarded the prestigious Gaydon Prize for the most significant UK Contribution to the 30th International Symposium on Combustion. He was awarded the Hinshelwood Prize by the British Section of Combustion Institute for his contribution to combustion science in 2007. A paper co-authored by him was judged to be the most significant paper presented in the droplet combustion colloquium of the 32nd International Combustion Symposium. Prof. Chakraborty is one of the recipients of the prestigious Hind Rattan award 2015, which is one of the highest Indian awards given to people of Indian origin for outstanding contribution in their field of work by the Non-Resident Indian Welfare Society of India, an organisation under the umbrella of the Indian Government. In 2017, he received a short-term fellowship by the Japanese Society for the Promotion of Sciences (JSPS) for collaborative research on multiphase turbulent reacting flows at the University of Kyoto. He has been awarded a Guest Professorship at the University of Duisburg-Essen in 2018. He is a steering committee member of CoSeC (Computational Science Centre for Research Communities) and the UK Research Council's ExCALIBUR programme. He is also a Strategic Advisory Team member of the Computational Fluid Dynamics (CFD) part of EPSRC's e-infrastructure team. In 2021, he was elected as a Fellow of the Combustion Institute. To date, he published 290 papers in peer-reviewed journals and 171 conference publications. His citation record is given by an h-index of 43 (source Google Scholar).