UNIVERSITY OF Southampton

Engineering and the Environment

Aeronautics, Astronautics and Computational Engineering

Simulation of spray combustion for aero-nautical gas turbines

UTC for Computational Engineering

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Advanced modelling for combustor design

Development of high-performance low-emission aero-combustors depends upon deep understanding and also accurate prediction of combustion processes. Accurate computational simulation tools reduce the need for costly and time-consuming prototype testing. More importantly, numerical predictions can provide highly-detailed information – and therefore understanding – necessary for innovative design. In the case of combustor design, however, current simulation technology has very limited predictive ability.

Engine performance is strongly affected by spray-combustion interactions since they may promote pockets of fuel-rich mixture – where pollutants form – or fuel-lean zones – where local extinction may occur, promoting combustion instability. The objective of this study is to extend Rolls Royce spray combustion capabilities by developing models for spray-combustion interaction.

Spray modelling challenges

A central challenge to modelling combustion in aero-gas turbines is describing the fuel spray, and accounting for its influence on the combustion process. Established spray combustion models fail to account for some important effects: Fuel droplets experience rapidly varying temperatures as they fly through the combustor, and the usual model assumption that the droplets 'see' an averaged temperature can lead to significant errors in the evaporation rate (pannel1). Conversely, the properties of the spray (droplet diameters, number densities, velocities) also vary throughout the combustor in an unsteady manner, and it is important to account for their effects on the combustion processes – these contributions of spray inhomogeneity are neither understood or modelled at present. This study both investigates these fundamental spray-combustion processes (panel 1), and develops the predictive models underpinned by this new fundamental understanding (panel 2).

1) Fundamentals of spray-combustion interactions

High-fidelity Direct Numerical Simulations (DNS) of spray combustion are employed as a tool for studying the small-scale interactions occurring in droplet combustion, and which are not resolved in design calculations.

The DNS studies reveal relationships between spray properties (such as droplet number density, diameter and temperature distributions) and the large-scale combustion dynamics to be described by practical engineering models. These insights are being used to develop new engineering models which account for the influence of spray interactions on flame propagation. The simulations employ full multispecies chemistry and solve the compressible Navier-Stokes equations with high accuracy. The spray is represented by a point source model in which various mass and heat transfer models can be easily employed. The simulation configuration is shown schematically in Fig. 1.

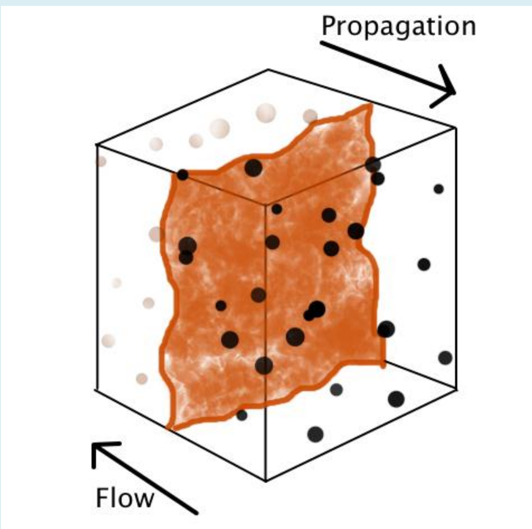

Figure 1: Schematic diagram of DNS configuration, showing a flame sheet propagating in to a turbulent spray.

A zero-dimensional test case has also been employed, in which droplets are subjected to stochastic fluctuations of the 'seen' temperature and composition. Results in Fig. 2 indicate that fluctuations may modify the evaporation rate by an order of magnitude, depending on the local composition distribution, and that these effects should be included in engineering models.

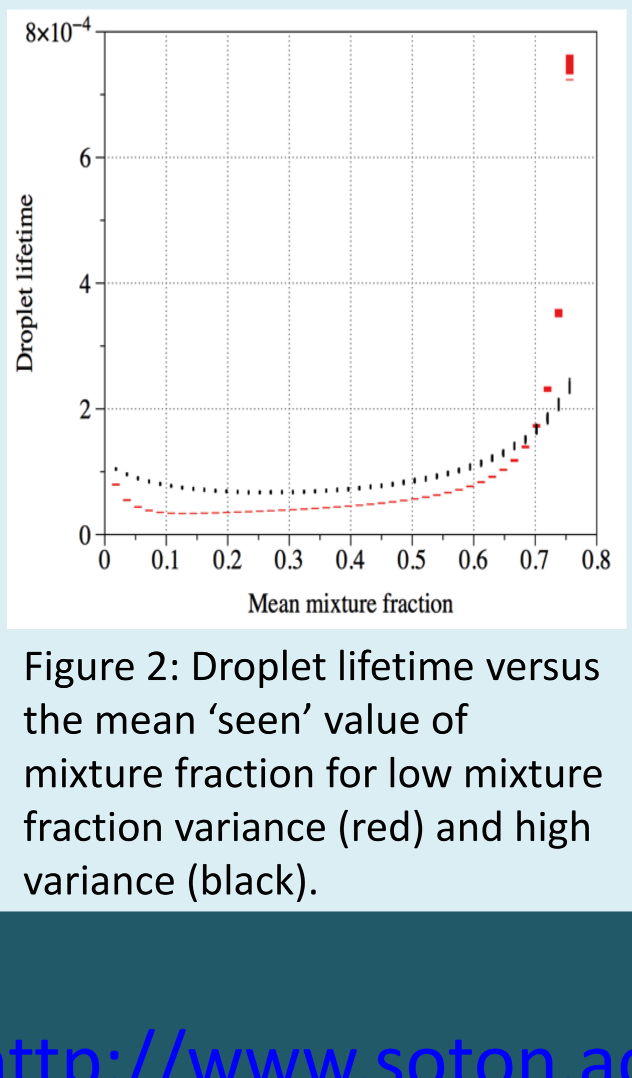

Figure 2: Droplet lifetime versus the mean 'seen' value of mixture fraction for low mixture fraction variance (red) and high variance (black).

2) Large Eddy Simulation (PRECISE –UNS)

Large Eddy Simulation resolves the energy containing scales of a flow and it can accurately predict the swirling flow-fields in gas turbine combustors by applying a spatial filter to the Navier-Stokes equations. Hence processes such as spray combustion which take place on length scales below the filter size must be modelled. The predictive ability of such models needs to be validated against observation; for this we use the well-characterised spray combustion experiments from Sydney[1]. Currently the mixture fraction field is reproduced as shown in Fig. 3. The simulation uses a Flamelet Generated Manifold (FGM) combustion model and a two-way coupled Lagrangian spray.

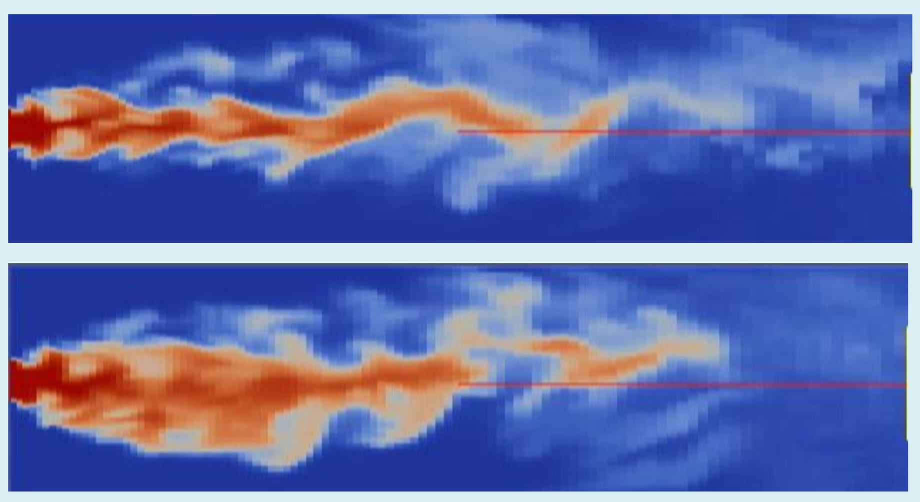

Figure 3: Cross section of the mixture fraction field from a 3-dimensional LES of spray, at two different times.

Future work will proceed with the implementation of the methods described in Bilger[2] which include the effects of fluctuations in the seen composition and temperature. We will look towards new flamelet based methods, tabulated on both gas phase and spray parameters as a means of including spray-combustion interactions in the combustion model in an efficient way. Once the spray combustion model is well validated, the resulting set of improved computational tools will be used to study global phenomena of importance in gas turbine engines, such as spatial and temporal variations in spray properties, heat release and emission levels.

1. *A. Masri and J. Gounder, Turbulent spray flames of acetone and ethanol approaching extinction, Combustion Science and Technology, vol. 182, no. 4-6, pp. 702-715, 2010.*
2. *R. W. Bilger, A mixture fraction framework for the theory and modeling of droplets and sprays, Combustion and Flame, vol. 158, no. 2, pp. 191-202, 2011.*

Research funded by EPSRC EP/1004564/1. The authors gratefully acknowledge additional support from Rolls-Royce plc.

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