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Coherent anti-Stokes Raman spectroscopy of a premixed ethylene–air flame in a dual-mode scramjet

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As part of a broader effort to provide detailed measurements of turbulent flames in dual-mode scramjets, promote a deeper understanding of the relevant combustion physics, and aid appropriate computational model development, a high-subsonic cavity-stabilized premixed ethylene–air flame (typical of ramjet operation) is studied using coherent anti-Stokes Raman spectroscopy. This technique provides simultaneous measurements of temperature, separate O_2 temperature, and mole fraction of N_2, O_2, CO, CO_2, and C_2H_4. The experiments reveal a highly unsteady turbulent flame, approximately two-dimensional in the mean, which propagates downstream from the cavity and towards the observation wall. Measurements in the flame region reveal a flow that is largely divided into reactants (freestream fluid) and (nearly) equilibrium products, separated by flames that cannot be resolved by the CARS measurement volume, which is about 1 mm long. Mean and standard deviation of the resolved fluctuations of the temperature and mole fractions of species are quantified. The peak standard deviation in each profile across the flame occurs where the mean gradient is steepest, and is about 37% the difference between reactants (freestream) and products conditions. Several cases were investigated including limiting combustion cases near the lean fuel and low air temperature blowouts; in all cases the flame propagation angles are the same and distributions of suitably normalized mean and fluctuation parameters are similar at all locations and for all cases.

1. Introduction

Dual mode scramjet engines are being developed for use in hypersonic vehicles such as high-speed missiles, aircraft, and space launch systems. These engines may use hydrocarbon fuels, which are more easily stored and have higher energy per unit volume than liquid hydrogen. Design of these engines requires an understanding of the combustion processes, including flame holding, flame propagation, kinetic processes, and turbulence–chemistry interactions, as well as modelling tools that can predict them. In turn, a deep understanding of these processes requires detailed measurements of combustion-relevant parameters at temporal and length scales that capture the most important aspects of the physics, as well as complementary computational investigations employing state of the art modelling. The current work is part of a coordinated study involving several instrumentation techniques, including planar laser-induced fluorescence imaging (PLIF) [1,2], particle imaging velocimetry (PIV) [3], and a parallel computational effort employing large-eddy simulation/Reynolds-averaged Navier–Stokes modelling [4].

Detailed coherent anti-Stokes Raman spectroscopy (CARS) measurements are made in a cavity-stabilized premixed ethylene–air flame of a dual-mode scramjet combustor [5,6]. The technique is used to simultaneously measure temperature and mole fractions of N_2, O_2, CO_2, CO, and H_2. New calibration methods also enable simultaneous measurement of C_2H_4 from ethylene bands that appear in the spectra [7]. Ethylene was used as the fuel for this study because it can be measured, it has relatively simple chemistry compared to liquid hydrocarbon, it has favourable ignition properties, and is a substantial component in the gaseous products of thermally decomposed liquid hydrocarbons. An idealized dual-mode scramjet is studied for a case in which a shock train propagates from the combustor into the inlet isolator because of high combustor heat load; i.e., it is operated as a ramjet. The C_2H_4 is injected near the upstream end of the inlet isolator and, through

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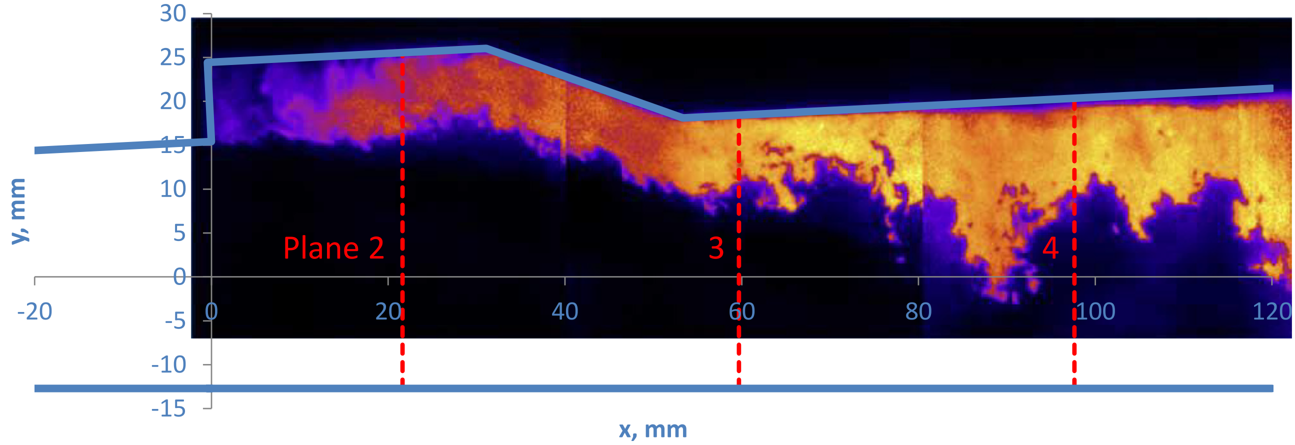

Fig. 1. Visualization of OH PLIF in the combustor, adapted from [1].

interactions with the shock train, is well-mixed with the air when it enters the combustor [8]. An approximately two-dimensional turbulent flame is stabilized at a cavity in the combustor. The flame is similar (via a transformation of coordinates) to the flat (in the mean) flame propagating into turbulent premixed reactants, and so comparison to other premixed turbulent flame experiments and numerical simulations may be possible, while the homogeneous nature of the reactants simplifies the analysis and interpretation of the results.

This work is the latest in a series of detailed investigations of important canonical scramjet flows conducted at the University of Virginia's using dual-pump CARS. The prior work, which followed on from CARS studies at NASA Langley Research Center and elsewhere [9–14], considered hydrogen-fuelled diffusion flames [15–17]. Beyrau et al. made dual-pump CARS measurements, including measurements of relative mole fraction of C_2H_4 and O_2 normalized to N_2, in a partially premixed C_2H_4 co-flowing jet flame on a slot burner [18]. The present work, and related publications, is the first to consider CARS studies of C_2H_4 combustion in a cavity stabilized premixed flame at scramjet-like flow conditions [5,6]. Related studies of simple hydrocarbon combustion in scramjet-like flows, using PLIF diagnostics, considered stratified or jet-in-crossflow combustion [19,20].

The cavity-stabilized flame (flow from left to right) is illustrated by Fig. 1, adapted from [1], which shows three, overlapping, single-laser-shot PLIF images of the OH radical on the symmetry plane of the model. (These particular images, in this highly turbulent flow, were selected so that they approximately match where they overlap.) Also shown is a coordinate system and the locations of CARS measurement planes. Since OH typically peaks on the hot side of the flame front and persists in the post-combustion products, it is a good indicator of flame propagation. The flame propagates outwards away from the cavity wall in the downstream direction. The boundary between combustion products and reactants is distinct, sharp and ragged. These images do not fully resolve the flame front; more recent OH-PLIF imaging, with a reduced field of view of 6.7 mm × 6.7 mm but approximately 50 µm spatial resolution, indicates that the flame front is as thin as 100 µm in places [2]. Thus the flame may be considered to have a thin, wrinkled flame or flamelet structure [21]. Spanwise OH-PLIF images show large unsteady structures similar in scale to those seen at the symmetry plane, although, as previously stated, the flame is approximately two-dimensional in the mean. Cantu et al. analysed their OH-PLIF images to obtain intermittency, defined as the fraction of time that OH is present at given point (i.e., image intensity exceeds some threshold value), and defined flame angle based on the 5% intermittency contour [1]. Good agreement was found in comparisons of flame angle with LES-RANS CFD calculations [4] analysed in the same way, and variation in flame angle between the nominal test case and cases near the low temperature and low equivalence ratio combustion blowout limits was small, from 10.3° to 11.6°. Non-combusting experiments were also reported where the shock train is stabilized to the same location in the inlet isolator as the baseline combusting case by use of the air throttle. NO was introduced into the cavity, and the propagation of NO out of the cavity was imaged with PLIF [22]. Qualitative similarity between the NO-PLIF and OH-PLIF images implied that propagation of the flame from the cavity is by the same mechanism as the propagation of NO, presumably the transport of mass by freestream turbulence generated in the shock train [1].

The current work builds on the previous [5] by presenting a more complete analysis of the CARS data. Contributions include a detailed database of mean and turbulent statistics of temperature and mole fractions of major species, useful for the development and validation of computational models, as well as findings in relation to cavity-stabilized flames in dual-mode scramjets. Additional contributions include methodologies and results for CARS techniques in the practically important regime of turbulent combustion where flame thickness is small relative to the length of the CARS volume.

2. Test flow and operating conditions

The experimental flow facility, model, and operating conditions have been described in detail by Rockwell et al. [8]. Air is electrically heated to a temperature that can be varied up to 1200 K, set to a pressure of 300 kPa ± 1%, and enters the model, shown in Figs. 1 and 2, through a Mach 2 convergent–divergent nozzle. The facility can operate at steady flow conditions for many hours and is ideal for optical techniques that require many detailed measurements at stable conditions, such as CARS. Fuel is introduced at the upstream end of the inlet isolator, symmetrically, from two rows of three surface-normal, diameter 1.25 mm, sonic injectors on both the top (observation) and bottom (cavity) walls. Following the isolator, the flow enters the combustor, which is a 2.9° diverging duct with a cavity flameholder on one wall, an extender consisting of a constant area duct (which contains the "thermal" throat), and an extender which is further length of diverging duct. The duct width is constant at 38.1 mm. When operated at nominal fuelling conditions, a shock train moves into the isolator with its leading edge just downstream of the isolator fuel injectors, and