Mixing Enhancement and Flameholding in Supersonic Combustors using a Pylon-Cavity Flameholder

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Abstract

The primary goal of a supersonic combustion ramjet (Scramjet) engine is to produce higher thrust for hypersonic flights. This is achieved by increasing the specific enthalpy of the fluid and then converting it into kinetic energy, which implies that the thrust produced depends hugely on the heat release that takes place within the combustor. However, the heat release itself depends on the combustion process. The three factors that influence supersonic combustion and are critical in developing a scramjet engine are mixing, ignition, and flameholding. The high flow velocity within the combustor due to supersonic/hypersonic flight conditions causes less residence time for the fuel and air to get well mixed. This makes it difficult to have a continuous heat release or flameholding in supersonic flow conditions. Therefore, over the years various researchers have investigated different fuel injection and flameholding strategies using concepts such as wall-based injection and in-stream injection to enhance the mixing and combustion performance. The fundamental objective of both of these concepts is to create relatively low-velocity recirculation zones within the combustor and thereby increase the residence time for the fuel-air mixing and facilitate stable combustion. These zones also act as a continuous source of reactive radicals that can sustain the combustion process. Though there are various advantages for both of these concepts, the higher drag penalties, cooling requirements, and complexity in an in-stream injector make the wall-based injector more interesting for the present investigations.

The current study follows a combined experimental and numerical approach to investigate the mixing enhancement and the combustion performance of a pylon-cavity flameholder with wall-based fuel injector. A compressible real gas steady Reynolds-averaged Navier-Stokes (RANS) equations are solved by coupled, implicit, second-order upwind solver with Menter's Shear Stress Transport (SST) $\kappa - \omega$ turbulence closure. An inflow Mach number of 2.2 with a stagnation pressure and temperature of 4 bar and 300 K, respectively, is maintained for all the non-reactive flow simulations, whereas an inlet stagnation temperature of 1771.2 K is used for the reactive flow simulations. A sonic H_2 fuel injection at 2.5 bar and 250 K is used for all the test cases, and a detailed H_2-air chemical kinetic scheme (Jachimowski) is used for the reactive flows. The numerical schemes used for the non-reactive flow conditions are validated experimentally with steady wall pressure data, Schlieren imaging, 2D-velocity vector field from particle image velocimetry (2D-PIV) measurements, and 2D-fuel mass fraction distribution obtained from acetone tracer

planar laser induced fluorescence (Tracer-PLIF) measurements. Due to safety considerations, He is used as a surrogate fuel for H_2 in non-reactive experiments. The numerical schemes for the reactive flow cases are validated using the standard benchmark problems from the literature.

In order to optimize the flameholder performance and understand the fundamental mechanisms involved, the overall objectives of the current study are divided into primary and secondary objectives. The studies coming under the primary objective aims to enhance the mixing and combustion performance of the flameholder by varying the fuel injection parameters and the geometrical features of the pylon. The mixing performance parameters used in these investigations are mixing efficiency, combustion efficiency, total pressure loss, flammable plume area, and fuel jet penetration height. The fundamental mechanisms involved are deliberated in detail to arrive at an optimum pylon-cavity flameholder configuration suitable for Scramjet applications with H_2 as fuel. The secondary objectives are formulated to increase the confidence in the methodology adopted for these investigations and evaluate the correctness of the results obtained.

The three studies under primary objectives explore various parametric investigations on fuel injection location, fuel injection angle, and pylon geometry variations. Study 1 investigates seven different fuel injection location cases (A-G) to identify the suitable locations that can enhance the mixing performance of the flameholder under non-reactive flow conditions. The results show that the fuel injection locations C, E, and F within the cavity give better mixing capability than the locations outside the cavity due to the interaction of the fuel jet with the cavity induced counter-rotating vortex pair (CCVP) III. Study 2 investigates the effect of fuel injection angle on mixing performance using the cavity locations with 90° and 45° injection angles under non-reactive flow conditions. Though 45° injection can provide a marginally better mixing performance than 90° injection, the poor fuel jet penetration capability of the earlier makes the transverse fuel injection the preferred fuel injection strategy. Using the optimum configuration from non-reactive investigations, Study 3 focuses on the effect of pylon geometry variations in enhancing the mixing and flameholding capability of the flameholder under reactive flow conditions. Here, four different pylon geometries, P0, P1, P2, & P3, and the associated pylon-cavity induced vortex structures are investigated. The interaction between the fuel jet vortex pair (FJVP) with these geometry induced vortex structures enhance the reactant mixture formation within the flameholder aiding flame stabilization. Four different flame holding locations L1, L2, L3, & L4 are identified in this study. The flameholding mechanism at L1 location solely depends on the mixing effectiveness and the reactant mixture formation due to K-H instability. The flame stabilization at locations L2, L3, and L4 are due to local reactant mixture formation and highly influenced by the hot gas combustion products recirculation within the cavity. P2 configuration is found to give a significant enhancement in the combustion performance among other configurations. This is due to the crucial role of FJVP interaction with the pylon-cavity induced vortex structure II which not only enhances the reactant mixture formation, but also aid in the lateral distribution of the mixture within the cavity of P2.

In supersonic combustion research it is common to use non-reactive simulations to ascertain the mixing characteristics and flameholder capability to reduce the complexity of simulations and computational costs. Also, He is used as a surrogate fuel of H_2 for experimental studies. In view of this, the Study 4 under secondary objectives investigate the suitability of using a non-reactive flow simulation in evaluating the mixing performance (as in studies 1 & 2) and flameholding capability of a supersonic combustor flameholder. The results show that the non-reactive flow studies can predict the qualitative trends in the mixing performance parameters that are not sensitive to combustion properties whereas, it is not always suitable for predicting the flame stabilization locations. Since He is used as a surrogate fuel for the present experimental validation of non-reactive flow simulations, its suitability as a surrogate fuel for H_2 in H_2-air non-reactive supersonic mixing studies is investigated in Study 5. The results show that the difference in the molecular physical properties between the two gases plays a vital role in the near-field mixing predictions. It is observed that He is not suitable for micro-level mixing studies due to significant discrepancy between the parameters predicted in the near-field mixing region compared to H_2. However, it is possible to closely predict the trend in global mixing performance parameters as in the H_2 case.