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TITLE: RAMJET RESEARCH

AFOSR TASK 2308BW

Principal Investigators: Thomas A. Jackson
Mark R. Gruber

Propulsion Sciences and Advanced Concepts Division
Propulsion Directorate
Air Force Research Laboratory
Wright-Patterson AFB OH 45433

SUMMARY/OVERVIEW

This research task includes work in three primary focus areas: (1) multiphase flows relevant to fuel injection into very high-speed, oxidizing streams, (2) shock - boundary interactions within reactive media, and (3) multidisciplinary laser measurements for benchmarking modeling and simulation of high-speed, reacting flows. Within each of these areas there is a strong relevance to the scramjet propulsion system, and that relationship helps frame the context of our research. The focus of this abstract will be on the shock – boundary layer interactions in and around a recess in the walls that confine the supersonic core flow. A flow recess, or cavity, is an essential element of a scramjet flameholder. Its interaction with the core flow and the method of introducing fuel and in sustaining a stable, combustible mixture within the cavity are the subject of our research in this area. A joint computational-experimental study has revealed the cavity to be difficult to fuel uniformly in space and that the interchange with the core flow varies substantially in time.

TECHNICAL DISCUSSION

A cavity is a pervasive feature of scramjet combustion piloting devices. Its function is to decelerate a small portion of the high-speed core flow, establish a stable combustible mixture and hold flame. Ideally, it would perform this function insulated from the flow fluctuations of the core, interacting with the shock system like a locally thick boundary layer. It does not. Expansion fans and shocks dominate the mass exchange between cavity and core flow. Local stoichiometry varies widely in all three spatial dimensions and in time.

We have begun examining the flow around a model cavity-based flameholder in non-reacting and reacting, supersonic flows. Our initial work included a parametric assessment of the effects of cavity geometry (including length-to-depth ratio and aft wall angle) on global features such as drag, acoustic stability, and entrainment rate. More recently two-species Raman scattering has been used to map the fuel-air distribution around a wall cavity immersed in a Mach 2 flow with and without an imposed shock train. Wide spatial variations in local stoichiometry are observed. These experimental studies are complemented by computations based on a hybrid flow solver. The hybrid solver combines the strengths of a Reynolds-Averaged Navier Stokes (RANS) code with those of a Large Eddy Simulation (LES). These computations reveal significant temporal fluctuations within the recessed cavity exposed to a supersonic flow. The mass exchange with the core is highly oscillatory. One result is that fueling the cavity indirectly, through entrainment of both fuel and air from the core flow, may be more stable than direct fueling where the cavity stoichiometry varies temporally with variations in air entrainment.

The configuration of interest is a confined flow over a cavity located in one wall of a rectangular cross section. A facility nozzle accelerates the core flow to Mach 1.9. The flow enters a rectangular duct with a nominal aspect ratio of 3:1. Several duct heights downstream of the inlet the flow passes over a cavity. Cavities of various length-to-depth ratios have been evaluated. Cavity close-out surfaces angled 90 to 16 degrees to the core flow have been studied. Figure 1 illustrates the flow in cross-section of one such cavity. Depicted are the results of a RANS-based computation for flow over a cavity with no back-pressure and no fuel or fuel-simulant injected. The streamlines within the cavity are shown as well as the computed pressure field, represented by the gray-scale shading. Pressure measurements along the cavity walls match the computed field for all designs evaluated. This particular cavity establishes primary and corner recirculation zones. The shear layer separating core and cavity flow fields is steady in the computation.

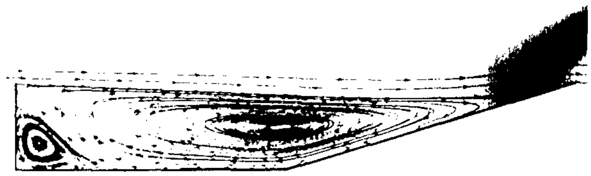

Figure 1. Mach 1.9 flow over a cavity – shadowgraph and RANS computation (1)

For fuel-air mixing studies gaseous fuel is injected into either the core flow and entrained into the cavity, or directly into the cavity. For injection into the core flow, only a single ethylene injector, angled at 15^{0} to the primary flow direction, is used.

This facility cannot sustain enough heat release to establish the desired pre-combustion shock system through combustion. Instead a back-pressure valve is used to create combustion-like pressure conditions over the cavity. Unobstructed, the flow over the cavity remains supersonic, representing the pre-ignition flow environment. Appropriately back-pressured to simulate different levels of combustion, the flow is subsonic in the mean at this condition. This flow represents the steady-state combusting environment within the scramjet operating at a flight Mach number of approximately 4. Figure 2 compares the static pressure along the wall of this facility at different levels of back-pressure with similar measurements taken on this geometry during full combustion testing in another facility. At increasing levels of heat release the pre-combustion shock system is pushed forward and peak pressures approach normal shock pressure rise. The cold-flow, back-pressured experiment replicates the wall pressure distribution of the combustion case.

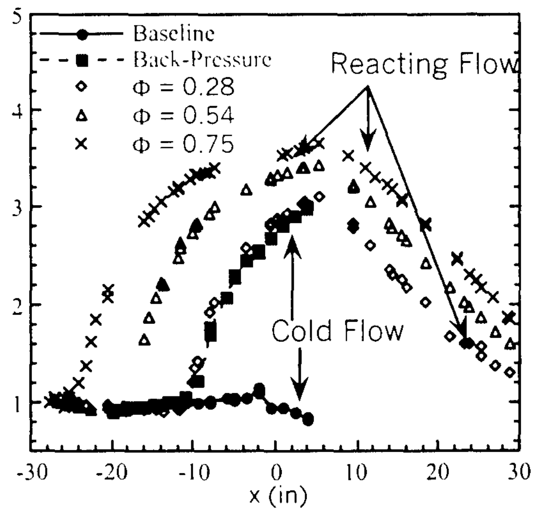

Figure 2. Static pressure distribution in cold and reacting flow

A Raman scattering system was configured to simultaneously measure ethylene and nitrogen concentrations. Ethylene was injected through the single injector upstream of the cavity at two injection pressures. The main air stream is the only source of nitrogen in the experiment.

Ratioing the two Raman measurements throughout the cavity established the spatial variation of the cavity stoichiometry. This was done with and without back-pressure applied to the core flow. Figure 3 is a sample of the results at a single axial position within the cavity (2). These results offer no insight into the temporal variations of the cavity stoichiometry – only the spatial distribution. At low fuel injection pressure, into either the supersonic (no back-pressure) or subsonic (back-pressured) core flows, the ethylene does not significantly penetrate the boundary layer and is entrained into the cavity. It is, however, slow to disperse in the transverse direction. At higher injection pressure the fuel penetrates the boundary layer of both core flows and fails to provide much fuel to the cavity. High pressure ethylene injected into the supersonic core flow sustains a very tightly bound fuel plume and begins to form vortical, kidney-shaped structures as it is transported downstream. While the trend of entrainment and injection pressure is predictable, it is noteworthy that the fuel dispersion differs substantially within the supersonic and subsonic core flows. Dispersion of fuel transverse to the main flow direction is slow in both situations.

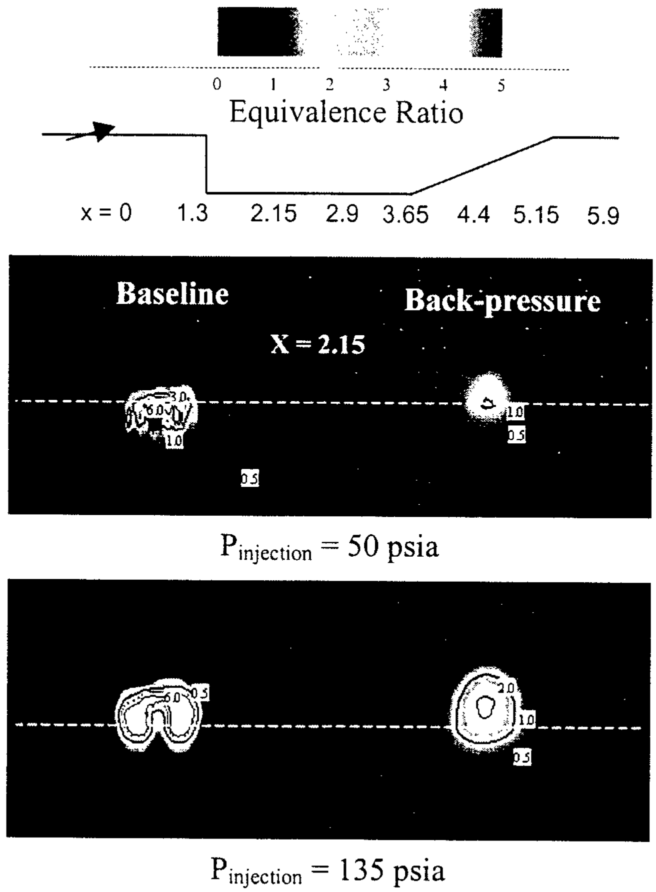

Figure 3. Local stoichiometry variations in cavity in a high-speed cross-flow using Raman scattering.

Temporal uniformity of cavity fueling has been investigated numerically. A Large Eddy Simulation (LES) flow solver has been patched into a hybrid solver with a RANS code and utilized to examine mass exchange between cavity and core flow. Coding details have been reported (3). Applied to the problem of continuously supplying a combustible mixture to the scramjet cavity through core flow entrainment and/or direct injection, this computational method is well suited. The supersonic flow in the constant-area duct up-stream of the cavity is well modeled with the RANS solver. In the cavity region the code reverts to the LES solver that can resolve details of the free-shear layer emanating from the forward step of the cavity. Figure 4 illustrates one frame of the periodic flow captured by the computation. The flow field is displayed as a numerical Schlieren image. When viewed as a series of images the flow is clearly not steady. Vorticies are formed and shed from the forward lip of the cavity suggesting mass exchange between cavity and core flows is highly periodic. This image is sharp contrast to that depicted in Figure 1 where the RANS solver fails to capture any instability in the shear layer over the cavity.

Two-species Raman scattering and the hybrid RANS-LES solver are powerful tools in studying the mass exchange between core and cavity-entrained flows in the confined supersonic flow characteristic of the scramjet propulsion system. Mixing entrained or direct-injected fuel in the

Figure 4. Numerical simulation of a supersonic core flow over a cavity. Result based on a hybrid LES-RANS computation.

transverse direction is slow. And, the unsteady nature of the exchange between core and cavity makes stabilization of the combustion process challenging with the cavity-based flame-holder. Our studies suggest better ways to fuel the cavity flame-holder and are leading us toward alternative ways to define a stable scramjet pilot.

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