Mixing Enhancement of Low Pressure Supersonic $F + H_2$ Streams by Means of Fluid Injection

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In an earlier study by the authors,[1] an experimental investigation was conducted of mixing between supersonic chemically-reacting $F + H_2$ streams at low pressure. Two nitrogen streams, one heated containing atomic fluorine (F) and the other unheated containing molecular hydrogen (H_2), were fed to contiguous supersonic nozzles having a Mach number of four. A classical mixing-reaction zone is formed between the two streams. Spatially-resolved infrared-scanner measurements of the excited-state hydrogen fluoride population (HF*) in the reaction zone were made from 1- to 13 torr static pressure. At low pressure, the mixing zone was laminar and even at high pressure (~10 torr) transition occurred only several cm downstream. These results are summarized in Fig. 1[1] where a similarity parameter, the product of the pressure P_e and the reaction-zone width $\Delta Y_{1/2}$ is shown to undergo a laminar, transitional, and turbulent-like development as a function of the downstream-distance/pressure product P_eX. For values of $P_eX > 100$ torr cm, the mixing layer width $\Delta Y_{1/2}$ grows linearly in X, being independent of pressure, and thus, far more rapidly than the data for $P_eX << 100$ torr cm which exhibit a laminar-like growth law, $X^{1/2}$, having an inverse pressure dependence $P_e^{-1/2}$.

Further, it was observed in this earlier work that there was a marked increase in HF* production in the turbulent mixing regime as compared to the laminar regime.[1]

The results just discussed raise a basic question of how faster mixing, and hence greater production, can be achieved in the low pressure ($P_eX << 100$) regime observed in Fig. 1. In an attempt to answer this question, an investigation has been conducted on enhancement of mixing and chemical reaction in the mixing layer described. The concept[2] pursued in this investigation was one of introducing three-dimensional disturbances between otherwise parallel streams of reactants. This was done by injecting small amounts of inert gas through discrete orifices directed at 90° to the main streams. A sketch of the nozzles and the tube containing these orifices is shown in Fig. 2.

The design considerations for choosing hole size, spacing, and injection pressure were the following: jet penetration height be variable from zero to order δ^*, the boundary-layer displacement thickness; the orifice spacing be large enough compared to δ^* so that distinct disturbance regions are produced; and, total mass flow through the holes be small compared to the primary nozzle flows so that only small perturbations to the overall pressure and concentration fields will occur. As shown in Fig. 2, the injection device contained eight 0.009-in. diameter holes equally spaced at 0.020-in. (L) on alternate sides of the tube. This arrangement provided values of $2L/\delta^*$ ranging from about 4 to 8 for the disturbance spacing over the range of operating conditions.

The device discussed here artificially speeds up the mixing between streams to produce a fast turbulent-like mixing and effect more complete combustion. The degree of enhancement of mixing and of excited-state species production by the device is shown in Figs. 3 and 4 at two static pressure levels with and without injection. The data were obtained with an IR scanning instrument which provides a two-dimensional mapping of vibrationally-excited molecular concentrations. The

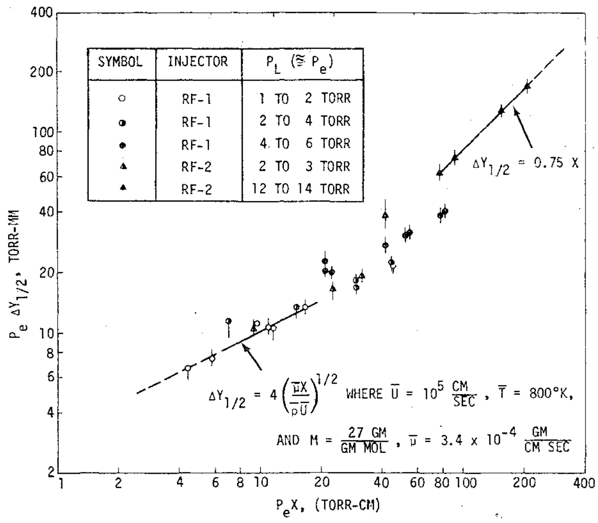

Fig. 1 Composite plot of RF-1 and RF-2 mixing layer width data, plotted as $P_e\Delta Y_{1/2}$ vs P_eX. (All data refer to test in which the H_2 jet was not heated.)

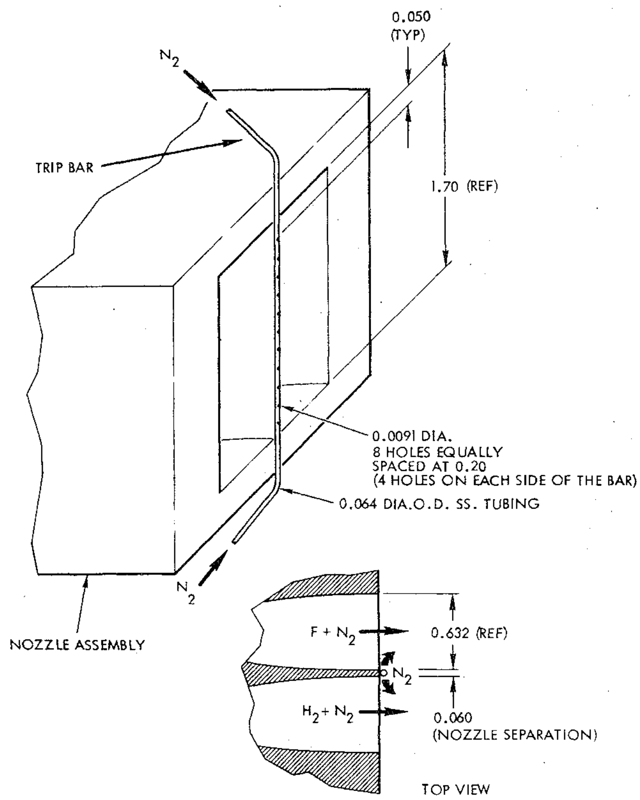

Fig. 2 Fluid injection trip bar installation on large nozzle. Note: All dimensions in inches.

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Index categories: Reactive Flows; Viscous Nonboundary-Layer Flows.

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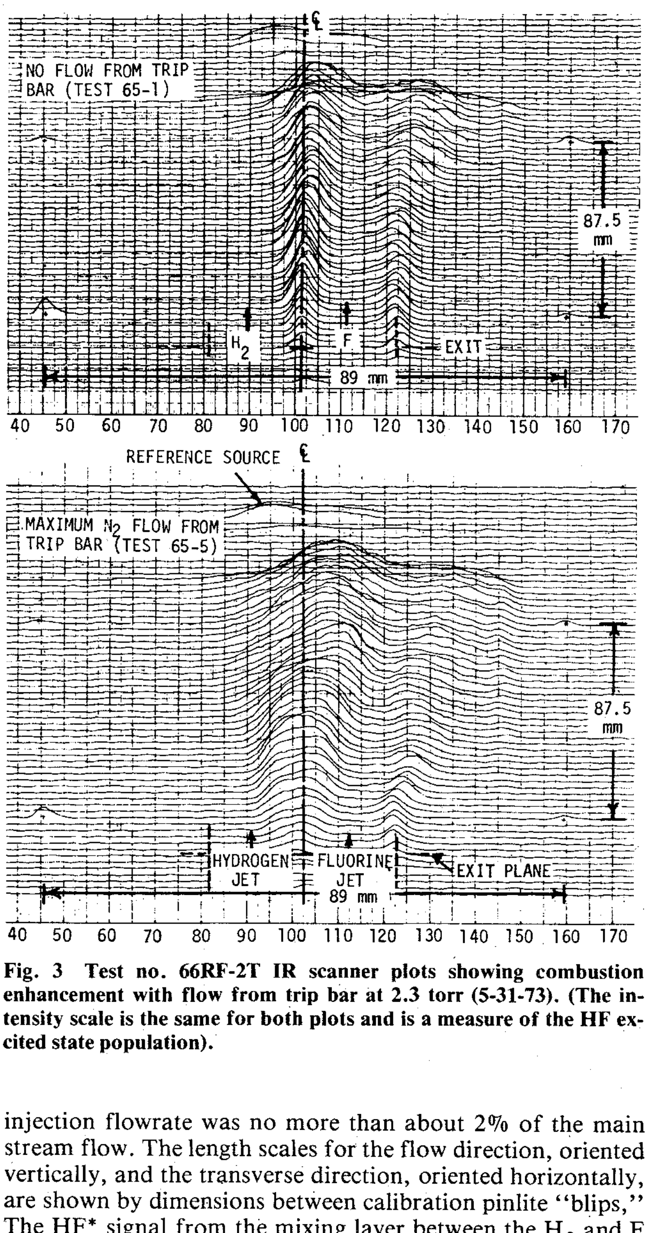

Fig. 3 Test no. 66RF-2T IR scanner plots showing combustion enhancement with flow from trip bar at 2.3 torr (5-31-73). (The intensity scale is the same for both plots and is a measure of the HF excited state population).

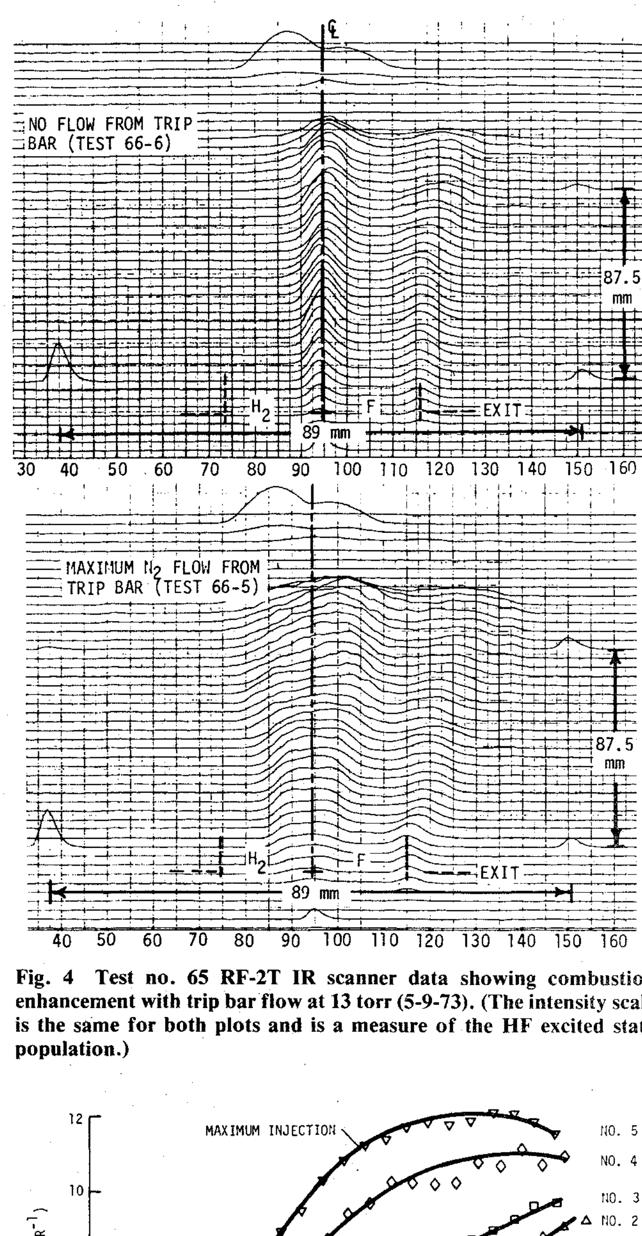

Fig. 4 Test no. 65 RF-2T IR scanner data showing combustion enhancement with trip bar flow at 13 torr (5-9-73). (The intensity scale is the same for both plots and is a measure of the HF excited state population.)

injection flowrate was no more than about 2% of the main stream flow. The length scales for the flow direction, oriented vertically, and the transverse direction, oriented horizontally, are shown by dimensions between calibration pinlite "blips," The HF* signal from the mixing layer between the H_2 and F nozzles starts at the nozzle exit plane. The signal intensity is given by the vertical displacement of the traces. Because of a recirculation pattern, some H_2-F combustion occurs on the outside or free shear layer side of the F stream.

With the fluid injection turned on, the mixing-reaction zone width is observed to increase by about a factor of two without a noticeable change in peak signal. Faster, turbulent-like mixing is caused by injection of the small fluid sprays in a way which is currently not understood.

When the number-density profiles are integrated and plotted as a function of downstream distance X, a measure of enhancement can be made by comparing the results to the no-injection case. In Fig. 5, it is observed that enhancement increases monotonically with injection rate at 13 torr. N_{eff} is the local radiance in the mixing layer. Similar results are achieved at 2 torr. The maximum enhancement achieved with this device is observed to be a factor of 2 at $X=10$ cm for HF combustion.

In summary, the following remarks can be made: 1) A technique has been discovered which can enhance the mixing at low pressure when mixing is normally slow. 2) The technique affords convenience in operation and effectiveness because it can be controlled remotely. 3) The technique appears to provide a low pressure-loss means of enhancing the mixing. 4) Further work needs to be directed toward understanding the fluid-injection-trip phenomena, especially the

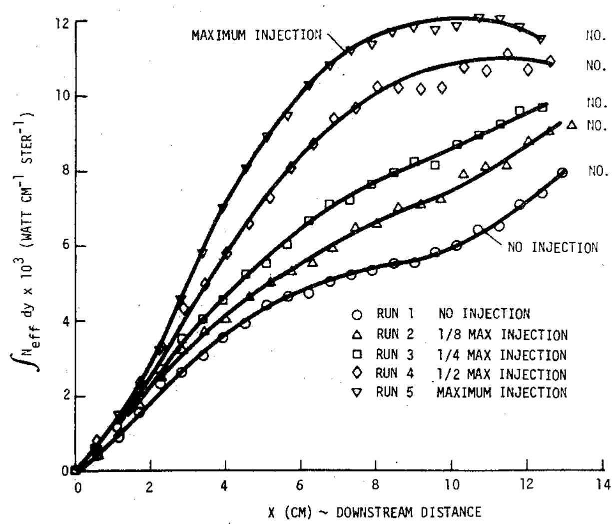

Fig. 5 Integrated radiance of the mixing layer $\int N_{\text{eff}}\, dy$ vs X for tripped and untripped parallel flows, 13 torr (from Test 65, May 9, 1973.)

feature of scaling such quantities as hole size, spacing, and flowrates.

References

[1] Shackleford, W.L., Witte, A.B., Broadwell, J.E., Trost, J.E., and Jacobs, T.A., "Experimental Studies of Chemically Reactive ($F+H_2$) Flow in Supersonic Free Jet Mixing Layers," AIAA Paper 73-640, Palm Springs, Calif., 1973; also found in abbreviated form as

synoptic, "Experimental Measurements in Supersonic Reacting ($F+H_2$) Mixing Layers," *AIAA Journal,* Vol. 12, Aug. 1974, pp. 1009-1010.

[2]Witte, A.B. and Broadwell, J.E., "Chemical Laser Cavity Combustion Enhancement Device," TRW Patent Disclosure No. 74-164, June 7, 1974.

Liquid Bipropellant Ignition and Combustion in an Instrumented Drop-Weight Tester

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Introduction

THE Olin-Mathieson drop-weight tester has become a standard tool for the evaluation of the impact sensitivity of propellants and explosives.[1] Its mode of operation is simple; a small quantity of the material to be tested is subjected to the impact of a known weight dropped from a measured height. The energy required to produce ignition of the material in half the attempts (50% point) is a measure of the material's impact sensitivity. The device, refined by the addition of a pressure cell, also has been used to record the pressure-time history of the ignition and high-pressure combustion of liquid monopropellants and explosives.[2] By means of a minor modification, the use of the pressure cell has now been extended to the investigation of a two-phase nonhypergolic bipropellant system, liquid hydrocarbons and nitric acid.

Experimental

The apparatus used in these experiments was a Technoproducts Olin-Mathieson drop-weight tester incorporating the special pressure cell (Fig. 1) originally designed for monitoring the combustion of liquid explosives and monopropellants. Its operation is as follows. Two† Viton O-rings are placed in the bottom of the sample cup; then small quantities (normally 30 microliters total) of the fuel and oxidizer are carefully syringe-injected into the space in the bottom of the cup (encircled by the O-rings). A stainless steel diaphragm and vented piston are inserted onto the O-rings, and the sample cup assembly is placed into the pressure-cell body. The retainer ball and cap are added, and the cap is torqued to 7 in. – lb The assembled pressure cell is then placed in the drop-weight tester. Ignition energy is supplied by the impact on the retainer ball of a known weight dropped from a measured height above the ball. The sample pressure is imparted to the force transducer by means of the pistons and hydraulic fluid. The transducer output is displayed on a triggered oscilloscope and photographed. Because of the compressibility of the fluid coupling up to 50% of the impact energy is absorbed by the cell, and the minimum ignition energies obtained with this device are significantly higher than those obtained with the conventional rigid cell.

A typical pressure trace is shown in Fig. 2. Time measurement was arbitrarily begun when the impact pressure spike would have returned to zero pressure if no combustion had occurred. A blank (nonreactive) experiment was always run for baseline calibration.

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Index categories: Combustion in Heterogeneous Media; Fuels and Propellants, Properties of.

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†While the standard procedure calls for only one Buna O-ring, Viton was used because of its greater compatibility with nitric acid; two were required to give reproducible ignition. This is the only required modification of the standard apparatus.

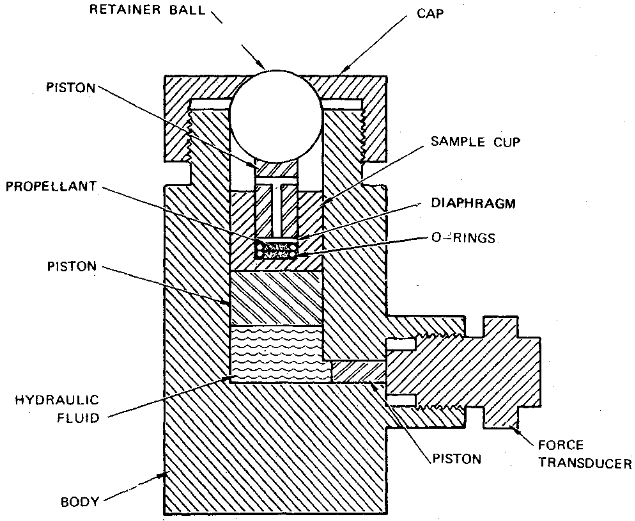

Fig. 1 Technoproducts Olin-Mathieson drop-weight tester pressure cell.

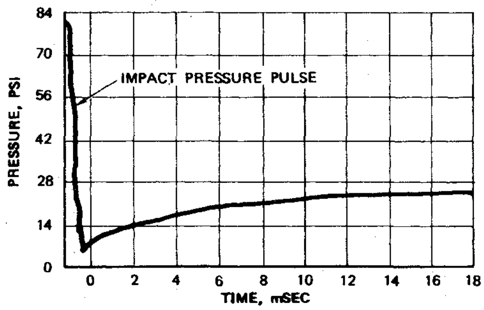

Fig. 2 Typical pressure trace.

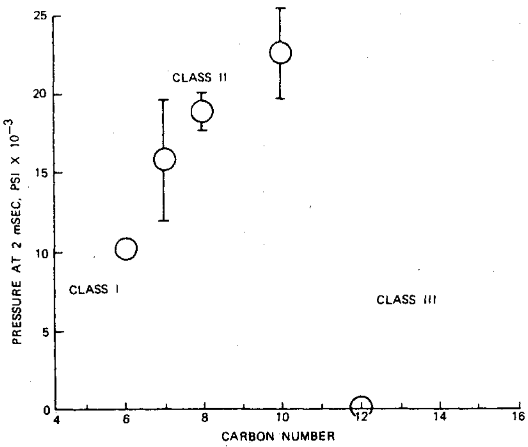

Fig. 3 Effect of carbon number on pressurization rate for n-alkane/nitric acid combustion (O/F volume ratio = 1:1).

Results and Discussion

The pressure cell was used to examine the reactions of a series of normal alkane (C_5 to C_{16}) fuels with 90% nitric acid oxidizer at three different oxidizer/fuel (O/F) ratios. Volume ratios of 4:1, 2:1, and 1:1 were employed for the following n-alkanes: 1) n-pentane, C_5H_{12}; 2) n-hexane, C_6H_{14}; 3) n-heptane, C_7H_{16}; 4) n-octane, C_8H_{18}; 5) n-decane, $C_{10}H_{22}$; 6) n-dodecane, $C_{12}H_{26}$; and 7) n-hexadecane, $C_{16}H_{34}$. An impact energy of 250 kg-cm was used throughout. The results are summarized in Table 1. The pressure 2 msec after the im-