Supersonic Combustion of Hydrogen Injected Perpendicular to a Ducted Vitiated Airstream

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Theme

REALIZATION of low engine cooling requirements without a sacrifice in performance in the design of supersonic combustion ramjets requires the ability to accurately predict the amount and distribution of the heat release produced in the combustor by a particular fuel injector arrangement. Because of the complexity of the flowfield produced by the transverse injection of fuel from wall injectors, analytical descriptions are difficult. Most results, therefore, describe the size of the mixing region and the degree and uniformity of the mixing by empirical correlations of data obtained in nonreacting experimental investigations.[1-5] To provide some information about the application of results for nonreacting flow to the problem of fuel injector arrangement in supersonic combustors, a supersonic combustion experiment has been conducted at the Langley Research Center. The experiment investigated how the mixing and reaction of hydrogen in a two-dimensional duct is affected by the number, size, and spacing of transverse wall injectors.

This paper presents some typical results of the experiment. In particular, pitot pressure and gas sample surveys at the duct exit and wall static pressure distributions are presented for two levels of injected equivalence ratio. A one-dimensional theory is used to deduce the amount of fuel reacted as an indication of the relative mixing performance of the various injector arrangements.

Contents

Ambient temperature hydrogen was injected transverse to a hot supersonic test gas from rows of equally spaced circular orifices positioned on opposite walls of a two-dimensional duct. A schematic of the duct section is shown in Fig. 1. The duct had a 20.7-cm long constant area section. The hydrogen injectors in each row were staggered with those of the opposing row. Tests were conducted for nine injector arrangements obtained by varying the injector diameter (d) for each of three injector spacings (s). Each arrangement was tested at nominal equivalence ratios (ϕ) of 0.5 and 1.0. The hot test gas was obtained from a burner to which hydrogen, oxygen, and air were supplied in proportions such that the test gas composition was 21% oxygen, 43% nitrogen, and 36% water by volume. The test gas was supplied to the duct through a Mach 2.70 nozzle at a nominal flow rate of 3.50 kg/sec and stagnation conditions of 2.76 MN/m^2 and 2200 K. Primary sources of data were wall static pressure distributions and pitot pressure and gas sample surveys of the duct exit flow.

Pitot pressure and gas composition profiles were measured using a nine probe rake positioned 5.3-cm downstream of the combustion duct exit. The gas composition was determined from a postrun analysis of the gas samples using a gas chromatograph. The gas samples were analyzed dry and the water content and local equivalence ratio (ϕ_l) were calculated from a mass balance assuming complete reaction of the hydrogen in the test gas burner. Figure 2 shows a comparison of pitot pressure and gas composition profiles on the horizontal centerline of the duct exit for two injector configurations operating at an equivalence ratio of 0.52. Note that the burner stagnation pressure was used to nondimensionalize the pitot pressures. The number of injectors (n) in each configuration is the total number on both walls of the duct. The profiles are symmetrical about the vertical centerline and show consistency in that the pitot pressures are lower in regions where the local equivalence ratio is higher. Comparison

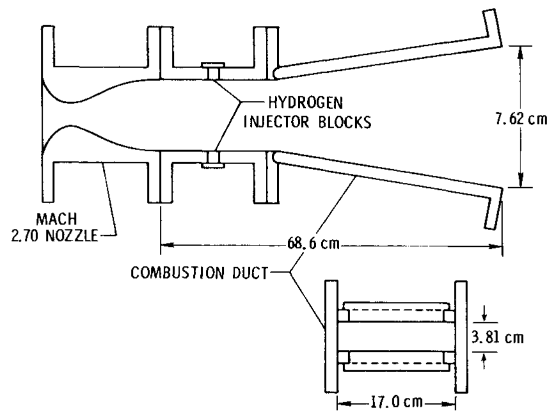

Fig. 1 Schematic of test apparatus.

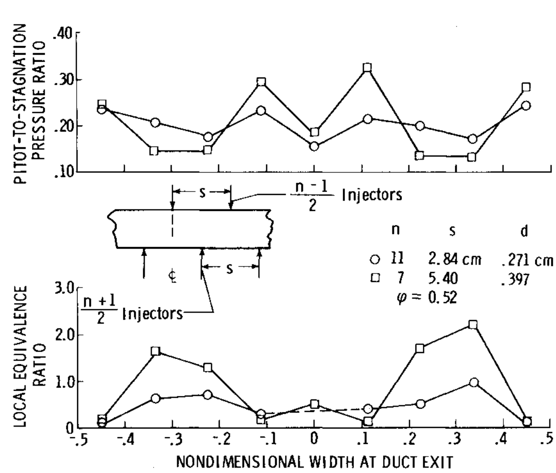

Fig. 2 Comparison of pitot pressure and gas composition profiles at duct exit.

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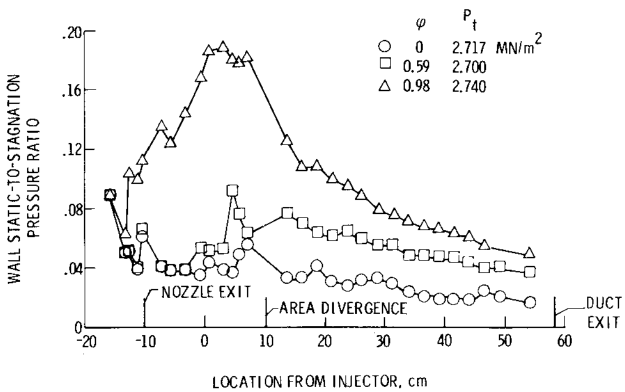

Fig. 3 Typical wall static pressure distributions for $n = 11$, $s/d = 7.94$.

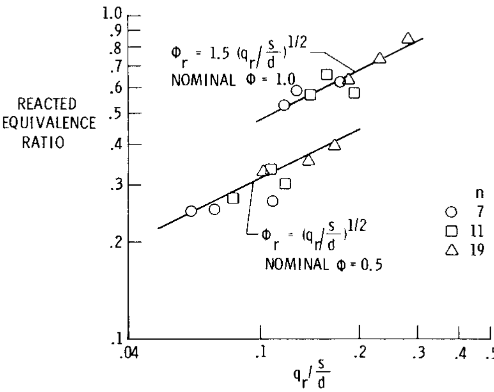

Fig. 4 Variation of reacted equivalence ratio with injector configuration.

of the pitot pressure profiles for the two cases indicates that a more uniform flow is obtained with an increase in the number of injectors and a decrease in the injector spacing-to-diameter ratio, (s/d). This trend has been observed for other injector configurations. A similar comparison of the local equivalence ratio profiles can be made. For the 11 injector case the mean of the data is near the bulk value of $\phi = 0.52$. In contrast, the much higher mean value of the 7 injector data suggests that the injected hydrogen penetrated well beyond the duct centerline resulting in regions of locally high hydrogen concentration. This effect was much more evident for the $\phi = 1.0$ cases which indicated a fuel rich core region that extended over about 70% of the duct height.

Typical static pressure distributions measured along the duct walls are presented in Fig. 3 for an 11 injector configuration with $s = 2.84$ cm and $d = 0.357$ cm. Distributions for equivalence ratios of 0.59 and 0.98 are shown in comparison with the pressure distribution for no injection. Typical of the high ϕ cases, the injected hydrogen causes blockage sufficient to separate the flow well upstream of the injectors and in some cases into the nozzle. Comparisons of pressure distributions for other injector configurations indicates a generally higher pressure level for injectors with lower values of s/d operating at higher values of injectant-to-mainstream dynamic pressure ratio (q_r). This trend of increasing level of wall static pressure suggests a greater amount of injected hydrogen has reacted at these conditions.

The amount of reaction, denoted by the value of the reacted equivalence ratio (ϕ_r), was used as an indicator of the relative performance of the various injector arrangements. Values of ϕ_r were determined by using a one-dimensional theory to perform a one-step calculation to match the measured static pressure at the duct exit. The change in momentum was accounted for by the wall pressure-area integral, determined from the static pressure data. Measured heat loss to the duct cooling water accounted for the energy change. The deduced values of ϕ_r were calculated for all nine injector configurations and are presented in Fig. 4 for two levels of injected equivalence ratio. Analysis of the values indicates a trend to correlate with the square root of the ratio of dynamic pressure ratio (q_r) to injector-spacing-to-diameter ratio (s/d), as indicated by the solid line through the data. Note that the level of reaction of the high equivalence ratio cases is about 1.5 times that of the low equivalence ratio cases at the same value of the correlating parameter.

The results of the experiment suggest the following conclusions. 1) Pitot pressure and gas sample surveys of the duct exit flow indicated good penetration of the hydrogen jets as evidenced by a large center core region of high equivalence ratio. The uniformity of this region as indicated by local equivalence ratio is apparently more a function of the injector spacing than injector size. 2) Duct wall static pressure distributions indicate that, in general, higher pressure levels are obtained for injector arrangements with smaller values of s/d and higher values of injection pressure. 3) Values of reacted equivalence ratiô, deduced from wall pressure-area integral using a one-dimensional theory, correlate with the square root of dynamic pressure ratio divided by spacing-to-diameter ratio.

References

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