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An Analytical and Experimental Study of Supersonic Combustion of Hydrogen in Vitiated Air Stream

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Theme

EXPERIMENTAL data on the diffusive mixing and reaction of hydrogen and air at high temperatures are needed for the design of the supersonic combustion ram jet engine. While there are some experimental data in the literature on the turbulent diffusion of a light gas, such as hydrogen, into a high-velocity stream, very little experimental information exists on reacting flows. The objective of the present work is to provide such data and develop numerical techniques for the analysis.

In the experiment the Mach number in the main stream was 2.4, static temperature 1260°K, and static pressure atmospheric. Hydrogen was injected at sonic velocity and at matched static pressure. The analysis is based on a numerical solution of the boundary-layer equations in which the turbulent transport terms are computed by using the concept of eddy viscosity. The chemical reaction is incorporated in the analysis using the equilibrium assumption.

Contents

In the experiment the high-temperature gas stream was produced by burning hydrogen-nitrogen gas mixture with liquid oxygen at high pressure. Each component was regulated so that the desired total temperature in the products was achieved with an oxygen content of about 21% by volume. In addition to the reacting tests, the nonreacting mixing tests were conducted in which the gas products contained no oxygen and only a small fraction of hydrogen. In this way, it was possible to study the mixing process independently of combustion under approximately the same conditions.[1]

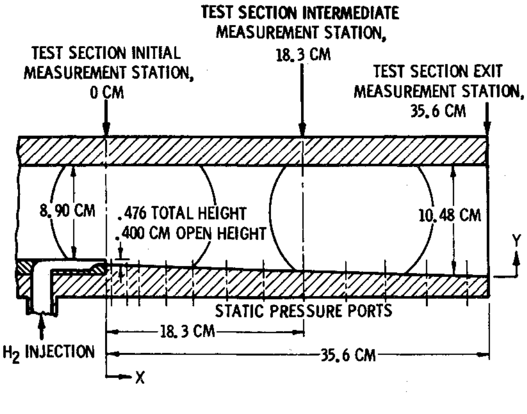

Fig. 1 Test section showing hydrogen injection step, location of static pressure ports and measurement stations.

The test section dimensions are given in Fig. 1. The width of the flow passage, normal to the plane of the drawing was constant and equal to 5.1 cm. Short run durations of the order of 2–3 sec were used because there was no provision for elaborate cooling of the hardware. Consequently, in traversing the flowfield, only one experimental point could be obtained per run. To reduce variations in pressure and total temperature measurements due to lack of run-reproductability, they were normalized by using, respectively, measured gas generator pressure P_{ref} and calculated equilibrium gas generator temperature T_{ref}.

Complete traverse of the flowfield was made at the test section exit plane. In addition, some pitot pressure and total temperature measurements were obtained at the injector exit plane and at an intermediate station 18.3 cm downstream of the injector.

Two water cooled sampling probes were used in the experiment. One of the probes was also instrumented to measure the static pressure on the surface of the conical tip. The conical tips had 40° and 30° total included angles and sample port diameters of 0.142 cm. The sampled gases were collected in small containers and analyzed on a mass spectrometer on a dry basis. The water vapor content of the sample was determined from the difference of the two mass flow rates: one was measured at a point where gas temperature was high enough so that all of the water was in the vapor phase, and the other was measured downstream of the cooled section of the sample line where the water vapor was condensed except for the small amount corresponding to the vapor pressure. Probes were also instrumented with a small thermocouple several centimeters downstream of the tip. In addition to bare wire thermocouple measurements the stream total temperature was deduced from this temperature measurement and the estimated amount of heat transfer to the cooling water jacket upstream of the thermocouple.

The composition profile for the reacting case is shown in Fig. 2. The measured freestream composition was in good agreement

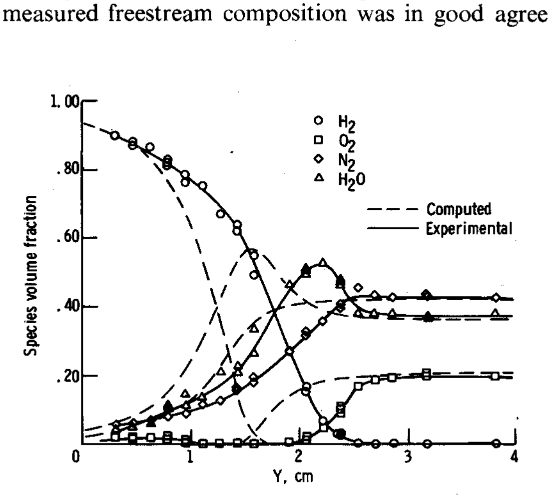

Fig. 2 Composition profile $X = 35.6$ cm, hydrogen-vitiated air. Calculated composition of vitiated air, H_2-0, O_2-0.203, N_2-0.438, H_2O-0.359.

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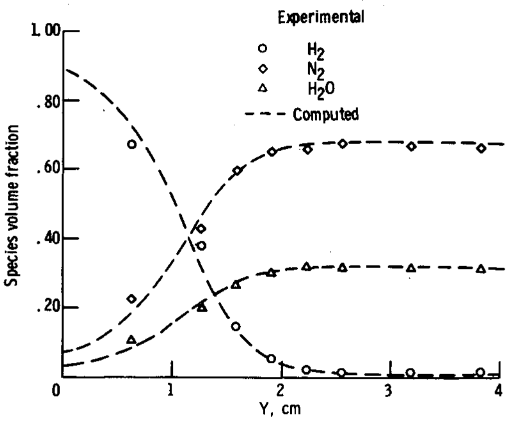

Fig. 3 Composition profile for mixing case $X = 35.6$ cm, hydrogen-inert gas.

with the theoretical composition from gas generator performance calculations. The increase in water vapor fraction above the freestream value in the region around $y = 2.2$ cm is attributed to the chemical reaction. The small amount of oxygen present in the hydrogen rich region is attributed to the diffusion process upstream of the ignition point. The composition profile for the nonreacting case is presented in Fig. 3. The water vapor fraction in this figure was deduced by assuming that the ratio of volume fractions of water vapor and nitrogen is constant. The mixing boundaries for reacting and nonreacting cases based on 1% deviation from the freestream water vapor volume fraction are, respectively, 2.1 cm and 2.3 cm, corresponding to the spreading angles of 2.9° and 3.9°.

Pitot pressure measurements are presented in Fig. 4. As noted in the figure, some fluctuation in pitot pressures was observed in the combustion region. Most of the total temperature measurements, Fig. 5, were obtained using iridium–iridium/40% rhodium bare wire thermocouples. The flagged point for $y =$ 1.9 cm at the test section exit was obtained by using a tungsten–tungsten/26% rhodium thermocouple. It should be noted that the indicated temperature for this point could be in error because of oxidation of the thermocouple surface. However, examination of gas composition in Fig. 2 indicates that only a small amount of oxygen is likely to be present at this position. The total temperature values deduced from the sampling probe thermocouple measurements were in general agreement with values from Fig. 5.

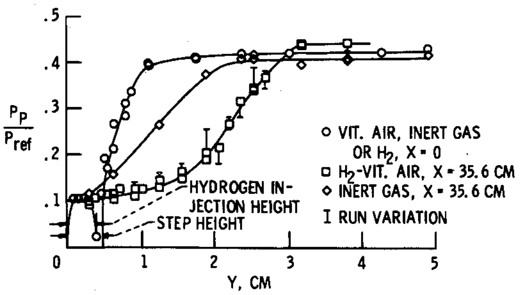

Fig. 4 Pitot pressure profiles. Vitiated air, $P_{ref} = 17.1 \times 10^5$ N/m^2; inert gas, $P_{ref} = 18.5 \times 10^5$ N/m^2.

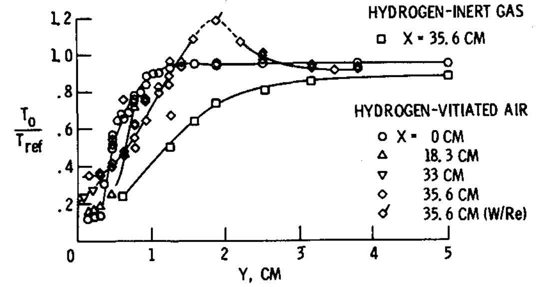

Fig. 5 Total temperature ratios from thermocouple measurements. Vitiated air, $T_{ref} = 2380°K$; inert gas, $T_{ref} = 2276°K$.

However, the results obtained from one sampling probe indicate that the heat-transfer coefficient in the flame region was somewhat lower than obtained from calibration.

The analytic results were obtained by a numerical solution of time-average boundary-layer equations in streamline coordinates. The procedure is a simplification of a more general method described in Ref. 2. In the numerical solution, in order to be able to resolve the laminar sublayer, a variable grid in the normal direction had to be used. The initial velocity and temperature profiles were obtained from measurements just downstream of the injector. On the hydrogen side the flow was assumed to be uniform.

Some flow deceleration between entrance and the exit of the test section was observed in the experiment due to the boundary-layer buildup. In the analysis for the reacting case this change is assumed to take place linearly.

The turbulent viscosity is based on the Herring-Mellor model. In the initial region, prior to merging of the developing turbulent boundary layer ($y = 0$, wall) and the free shear layer, Herring-Mellor model is assumed in the boundary layer, molecular viscosity in the undisturbed hydrogen jet, and Herring-Mellor outer boundary-layer viscosity in the free shear layer. In the downstream region, the viscosity is determined as in the turbulent boundary layer. The chemical equilibrium was formulated similarly as in Ref. 3.

For the pure mixing case, the agreement between experimental and computed composition, as shown in Fig. 2, is quite good. However the agreement is less satisfactory for the reacting case. The main difference is that the experimental profiles appear to be shifted away from the wall. This could be explained by the fact that in the experiment the rate of reaction depends strongly on temperature, and hence, ignition occurs in the lean mixture region, where the static temperature is high. The equilibrium assumption in the calculation, however, causes the peak in water vapor and related consumption of reactants to occur near the stoichiometric plane, which also corresponds to the maximum temperature plane.

References

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