Experimental Measurements in Supersonic Reacting ($F+H_2$) Mixing Layers

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Theme

AN experimental approach involving spectroscopic and fluid mechanical diagnostics is used to study the development of the mixing reaction zone between parallel streams of H_2 and F, in N_2 diluent. A dual arc heated facility is used to provide independent temperature control for each reactant. Measurements of temperature, velocity and HF population (in vibrational levels $0 \leqq v \leqq 5$) within the reaction zone are obtained for various flow parameters and injector geometries. The data indicate the effects of operating parameters upon over-all mixing and chemical reaction rates. The results also indicate regimes of laminar, transitional, and turbulent mixing for a plane parallel reactive flow configuration with thick initial boundary layers.

Contents

The experiments were carried out in a facility in which hydrogen and fluorine (each diluted in nitrogen) could be separately heated by arcs. These flows were then expanded through contiguous rectangular Mach no. 4 nozzles to form a supersonic two-dimensional reacting mixing layer between parallel jets of F/N_2 and H_2/N_2. The mole fraction of N_2 diluent in each jet was typically 90%. The atomic fluorine was obtained by arc heating of SF_6/N_2 mixtures to stagnation temperatures of about 2400°K. The exit pressures of the hydrogen and fluorine jets were carefully matched to each other as well as to the surrounding cavity pressure in order to maintain a parallel flow geometry.** The H_2/N_2 stream was operated either unheated or heated to a stagnation temperature of about 2000°K. The ratio of the exit freestream velocities of the hydrogen and fluorine jets varied from 3 to about unity depending upon whether the hydrogen jet was unheated or heated. Tests were made for the parallel flow system at pressures ranging from 1 to 13 torr, two hydrogen jet temperatures, and several values of the H_2/F molar flow rate ratio. The paper also contains a brief discussion of preliminary results obtained with an injector in which pure hydrogen was ejected as an underexpanded jet into parallel supersonic streams of F/N_2 on either side.

Spectra of HF infrared chemiluminescence from the mixing layer were obtained at a number of locations. These data resulted in the determination of temperature and HF population profiles (for vibrational quantum states 1–5) at various downstream locations. The population of HF in the $v = 0$ ground state was obtained from absorption-gain measurements using a low-pressure H_2/F_2 burner as a probing light source. The experimental and analytical details are described in the paper.

In addition to the chemiluminescence and absorption measurements, an infrared scanner was used to quantitatively map the 1.8–3.2 μ radiation from the entire flowfield. This device was especially useful in determining the rate of spread of the mixing layer and for visualizing the amount of vibrationally excited HF within the layer. Pitot probe surveys were also made at several axial stations. These, together with the spectroscopic temperature measurements, were used to determine the velocity.

For measurements in which the exit pressures of the fluorine and hydrogen jets were matched, infrared scanner records indicated that the reaction zone spread nearly equally into both jets. Variation in the total temperature of the hydrogen jet from 300°K to 2000°K did not produce a significant change in either the rate of spread of the mixing layer or the amount of vibrationally excited HF within the zone. This weak observed dependence upon hydrogen jet stagnation temperature is due in part to the important influence of nozzle wall boundary layers and combustion heat release upon the temperature within the reaction zone.

A particularly significant result of the parallel flow measurements was the observation that the width of the reaction zone and the concentration of the various vibrational levels of HF correlated well with the product of exit pressure (P_e) and downstream distance (X), i.e., with the Reynolds number. Figure 1 shows the dependence of the width (at half-maximum intensity) of the reaction zone ΔY as a function of the downstream distance

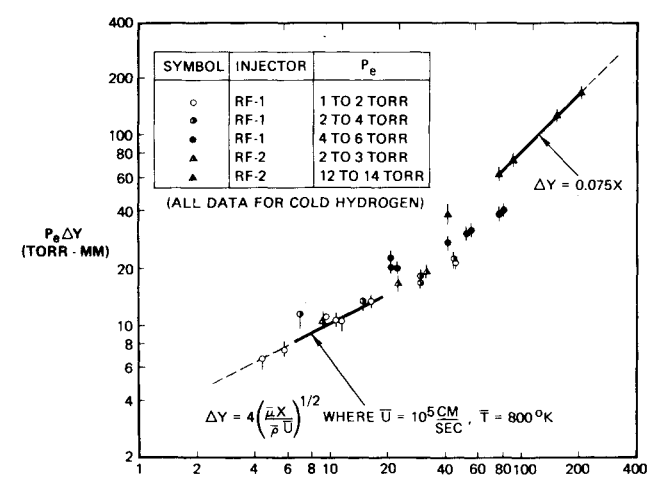

Fig. 1 Mixing layer width (ΔY) vs downstream distance (X) in ($P_e Y$, $P_e X$) coordinates (P_e = nozzle exit static pressure). Results for two different plane-parallel injector configurations and exit pressures between 1 and 13 torr are shown.

Presented as Paper 73-640 at the AIAA 6th Fluid and Plasma Dynamics Conference, Palm Springs, Calif., July 16–18, 1973; synoptic received August 13, 1973; revision received March 4, 1974. Full paper available from AIAA Library, 750 Third Avenue, New York, N.Y. 10017. Price: Microfiche, $1.00; hard copy, $5.00. **Order must be accompanied by remittance.** The work reported herein was supported by the Air Force Special Weapons Center, Kirtland Air Force Base, N. Mex., under Contract F29601-72-C-0021. The authors wish to thank G. S. Bell, R. H. Herrett, R. C. Hilyard, F. N. Mastrup, R. C. Sorenson, and A. S. Whiteman for significant contributions to the program.

Index category: Reactive Flows.

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** As a result of the heat release due to chemical reaction, the static pressure is not strictly uniform across the mixing layer. Measurement of the oblique shock angle outside the reaction zone, which was about 15°, leads to an estimate of $\Delta p/p \approx 0.1$ for the relative pressure increase within the mixing layer. (A 15° shock angle is attributable to an equivalent flow deflection angle of 1° at $M = 4$.)

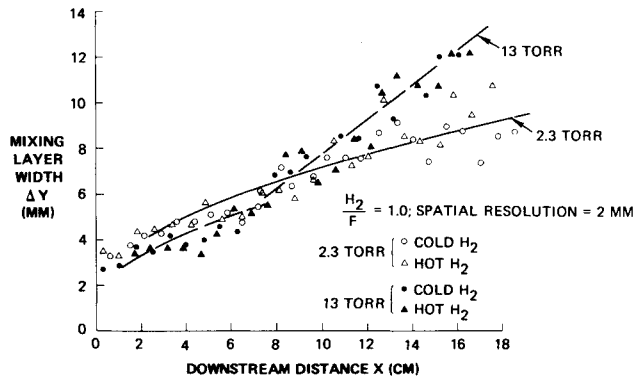

Fig. 2 Mixing layer width vs downstream distance at 2.3 and 13 torr, for mixing of plane-parallel jets.

in $(P_e\Delta Y, P_eX)$ coordinates. For low values of P_eX, the results obtained with different injectors and at exit pressures of from 1 to 13 torr are seen to exhibit a density and X dependence typical of laminar mixing. At high values of P_eX, the dependence of ΔY upon X is linear, as is expected for a turbulent mixing layer. The absolute magnitude of the mixing layer widths in the laminar and turbulent regimes is also consistent with available data.[1,2] The scatter of the data in the intermediate region is attributed to the dependence of the location of transition upon the thickness of the initial wall boundary layer. The data for a single injector shown in Fig. 2 indicates that transition occurred at a point about 7 cm downstream of the exit at 13 torr, and remained laminar throughout the observed flowfield at 2.3 torr. The transition distance observed at 13 torr is about 300 θ, where θ is the combined width of the hydrogen and fluorine nozzle boundary-layer momentum thicknesses. This result is qualitatively consistent with measurements in subsonic mixing layers[3] and flat plate wakes[4] where transition occurs at about 100 θ, and also with experimental and theoretical evidence[5] that the transition distance for the wake of a flat plate at $M = 6$ is about 1000 θ.

Pitot probe surveys were taken at the nozzle exit plane at several downstream stations. Total shear layer widths measured in this way were substantially larger initially than those indicated by the half-intensity points of the reaction zone observed by the IR scanner. At $P_e = 6$ torr for example, the sum of the fluorine and hydrogen nozzle boundary-layer widths was about 7 mm,

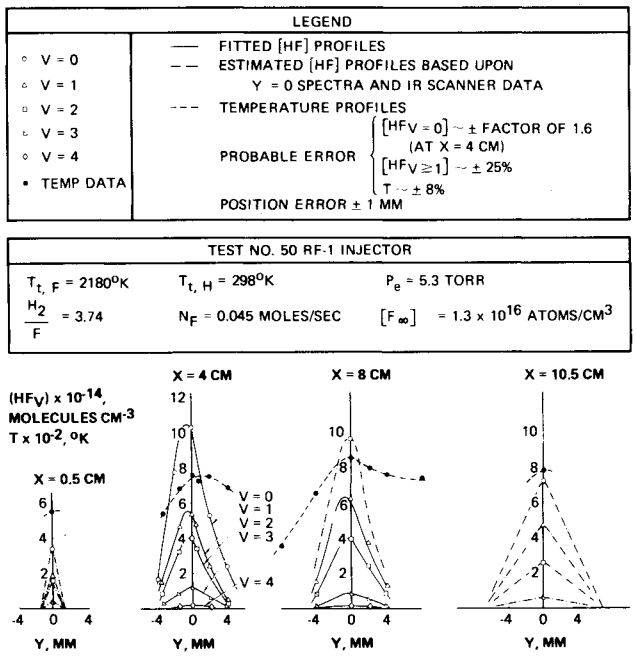

Fig. 3 HF population in vibrational level V ($[HF_v]$) and temperature as functions of Y at $X = 0.5$, 4, 8, and 10.5 cm.

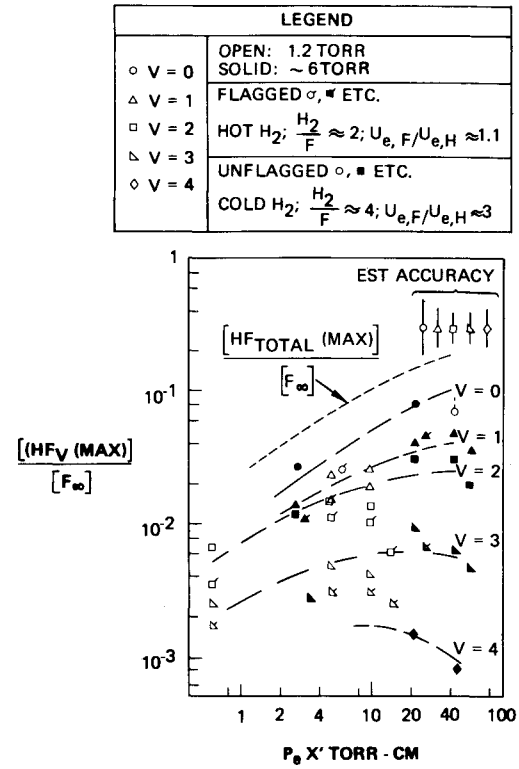

Fig. 4 Maximum HF concentration in the reaction zone (normalized by freestream fluorine concentration $[F_\infty]$) as a function of P_eX. Data corresponding to two exit pressures and two hydrogen temperatures are combined in this graph.

or about one-third nozzle width. At $P_e \approx 1$ torr the boundary layer in the fluorine nozzle completely filled the nozzle.

Figure 3 illustrates spectroscopically obtained temperature and concentration profiles of HF (in vibrational levels between 0 and 4) at various downstream locations, for one of several operating conditions. Figure 4 shows the maximum value of the HF concentration in specific vibrational levels (normalized by the freestream fluorine concentration $[F_\infty]$) plotted as a function of the P_eX variable. When presented in this form, that data obtained at 1 and 5 torr and with both heated and unheated hydrogen fall approximately on same family of curves. All the data in Fig. 4 correspond to the laminar mixing regime. The data indicate that the total amount of HF on the centerline is less than 10% of $[F_\infty]$ at $P_eX \leqq 10$ torr-cm, and therefore that the reaction zone has not approached the diffusion-controlled "thin flame" limit. In the thin flame limit, the ratio of the product concentration in the flame sheet to the freestream concentration of the least abundant reactant (F, in this case) approaches a value of about $\frac{1}{2}$. The present result is shown to be consistent with estimated values of the Damkohler number (the ratio of characteristic flow and chemical reaction times) under these flow conditions.

References

[1] Pai, S. I., *Viscous Flow Theory,* Van Nostrand, Princeton, N.J., 1956, pp. 189–193.

[2] Brown, G. and Roshko, A., "The Effects of Density Differences on the Turbulent Mixing Layers," presented at the AGARD Fluid Dynamics Panel Meeting, London, Sept. 13–15, 1971 (an updated version is to be published in *Journal of Fluid Mechanics,* 1974).

[3] Bradshaw, P., "The Effect of Initial Conditions on the Development of a Free Shear Layer," *Journal of Fluid Mechanics,* Vol. 26, Pt. 2, 1966, pp. 225–236.

[4] Ko, D. R. S., Kubota, T., and Lees, L., "Finite Disturbance Effect on the Stability of a Laminar Incompressible Wake Behind a Flat Plate," *Journal of Fluid Mechanics,* Vol. 40, Pt. 2, 1970, pp. 315–341.

[5] Ko, D. R. S., "Integral Theory of the Instability of Laminar Compressible Wakes Behind Slender Bodies," *AIAA Journal,* Vol. 9, No. 9, Sept. 1971, pp. 1777–1784.