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SOME EFFECTS OF COMBUSTION ON TURBULENT MIXING

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Introduction

Mixing and reacting compressible and turbulent flows play an important role in supersonic combustion propulsion systems. A question that has arisen in the past is whether combustion affects turbulent mixing of the fuel and air streams. This question was considered by Cohen and Guile[1] in an investigation of coaxial hydrogen injection into vitiated air and nitrogen. They did not find an effect of chemical reaction on mixing rates for the conditions of their experiments. Beach[2] also studied coaxial hydrogen injection into air and nitrogen. His calculations indicated that the nonreacting nitrogen and hydrogen streams had a higher rate of mixing. No concentration measurements were made in this study, however, so no definite conclusions about relative mixing rates could be drawn. There have also been related studies of turbulent diffusion flames at low subsonic speeds. These studies, which produced conflicting evidence on the effect of combustion on mixing, have been summarized by Chigier and Strokin[3]. Chigier and Strokin also made detailed measurements in a round methane jet issuing into stagnant room temperature air. They found that near the nozzle, the diffusion coefficient (m^2/sec) in the flame was much less than for the corresponding cold jet. Farther downstream this condition was reversed, with the diffusion coefficient for the flame becoming larger.

The present study is concerned with mixing and combustion of near-sonic central hydrogen jets and coaxial supersonic air or nitrogen streams. Results of concentration measurements in these flows are presented.

Experimental Apparatus

The experiments were conducted in the Ceramic-Heated Tunnel[4] at NASA Langley Research Center. In this facility the test gas, air or nitrogen, is heated to a maximum stagnation temperature of 2220K by passing it through a heated zirconia pebble bed. The test gas is then accelerated to Mach 1.98 in a stainless-steel, water-cooled nozzle with exit diameter 6.53 cm. The exit static pressure is 1.0 atm.

A hydrogen injector was mounted along the nozzle axis, as shown in Figure 1. This injector is made from Inconel tubing 1.59 cm O.D. and 0.89 mm wall thickness. The injector also has a converging nozzle insert, so that the ratio of fuel jet to base diameter, d_J/d_B, is 0.60. Hydrogen entered the system at ambient temperature, and was heated as it cooled the injector walls. The hydrogen mass flow rate was measured by means of a calibrated orifice plate in the hydrogen supply line. The air and hydrogen jets exhausted into quiescent atmospheric air. For these flow conditions and the geometry shown in Figure 1, the free stream air velocity, U_e, was 1440 m/sec. Hydrogen mass flow rates of 4 and 7 gm/sec were used in the experiments. These gave jet to free stream mass flux ratios, $\rho_J U_J/\rho_e U_e$, of 0.15 and 0.27, respectively. The respective velocity ratios U_J/U_e were approximately 1.1 and 1.0.

The gas sampling probe is an 18° half-wedge, water-cooled, 4.76 cm wide, and 1.03 cm maximum thickness. Gas samples were withdrawn through nine ports, each 0.508 mm diameter. These ports are on one face of the wedge, in a row perpendicular to the flow direction, 1.59 cm from the leading edge. They are equally spaced at 2.38 mm. A discussion of the use of this type of probe is given in reference 5. The gas samples were analyzed using a gas chromatograph.

Comparison of the mixing of the H_2-air and H_2-N_2 flows was made on the basis of the mean mass fraction of hydrogen atoms, C_H. This quantity gives a measure of the amount of hydrogen present at a point, whether or not chemical reaction has taken place. The gas chromatograph analysis gave the mole fractions of H_2, O_2, and N_2 in the gas sample. To compute the corresponding mole fraction of H_2O, it was assumed that nitrogen diffused at the same rate as oxygen. By this assumption, the number of nitrogen and oxygen atoms at a point were in the same proportion as in air. The number of oxygen atoms computed in this way from the N_2 mole fraction, minus the number from the O_2 mole fraction, was the number that had gone into the formation of water.

Results

Figure 2 shows the variation of $C_{H,O}/C_{H,J}$ with x/d_J. Here $C_{H,O}$ is the value of C_H on the centerline, $C_{H,J} = 1$ is the value of C_H at the hydrogen jet exit, and x is the axial distance from the hydrogen jet exit. For both hydrogen flow rates, and for either air or N_2 as the free stream, $C_{H,O}/C_{H,J}$ was closely proportional to $(x/d_J)^{-1}$. Also, $C_{H,O}/C_{H,J}$ was larger for the burning hydrogen-air flows. Similar behavior was found by Chigier and Strokin[3]. The data at $\dot{m}_J = 4$ gm/sec and $x/d_J = 3.3$ did not follow these trends, however. A definite explanation for this has not been found. It may also be noted that the values of $C_{H,O}/C_{H,J}$ scale almost exactly with $\dot{m}_J$ for these data.

In Figure 3 the variation of the nondimensional width of the mixing region, $r_{0.5}/r_J$, is shown. Here, $r_{0.5}$ the distance from the axis at which $C_H/C_{H,0} = 0.5$, and $r_J = 0.5\ d_J$. The relative values of $r_{0.5}/r_J$ for combustion and no combustion are influenced by density differences, as well as by possible mixing rate differences. Thus, conclusions about relative mixing cannot be drawn directly from the data of Figure 3. Because of the lack of temperature measurements it was not possible to construct accurate mass-averaged profiles.

Figure 4 shows that the data for $C_H/C_{H,0}$ are well-described by a Gaussian profile when plotted against $r/r_{0.5}$. Essentially the same behavior was found for $\dot{m}_J = 7$ gm/sec.

Flow field calculations were made to aid interpretation of the experimental data. These calculations used the time-average conservation equations for mass, momentum, energy, chemical species, mean-square fluctuation of mass fraction of O_2 and H_2, turbulence kinetic energy, and turbulence dissipation rate in the boundary-layer approximation. The correlations that appear in these equations were modeled as described by Launder and Spalding[6,7]. A reaction rate model for turbulent diffusion flames was also used[8]. These calculations were made for the same initial conditions as in the experiments, but with an infinitesimally thin injector wall. The numerical solution used a finite-difference method based on that of Patankar and Spalding[9].

The calculated results for $C_{H,0}/C_{H,J}$ were similar to the experimental results shown in Figure 2. Also, the calculated values of $r_{0.5}/r_J$ were larger with combustion. However, the turbulent mass transport coefficient (kg/m sec) and the mean density at $r_{0.5}$ were everywhere larger with no combustion. The turbulent diffusion coefficient (m^2/sec) with combustion was smaller near the injector, but then became larger a few injector diameters away. This latter behavior was also observed in the free jet experiments of Chigier and Strokin[3]. Finally, the calculations showed larger turbulence kinetic energy with combustion, except very close to the injector. Similar results were also observed by Chigier and Strokin[3].

These calculated results, plus the experimental results of Chigier and Strokin[3], suggest the following interpretation of the data of Figures 2 and 3. The turbulent diffusion coefficient (m^2/sec) becomes larger with combustion within a small distance from the hydrogen nozzle. The lower density of the flow with combustion produces lower mass transport coefficients (kg/m sec), however, leading to the results shown in Figure 2. Also, the lower density of the flow with combustion seems responsible for the larger values of $r_{0.5}/r_J$ with combustion shown in Figure 3.

Figures 5 and 6 provide additional information about the present experiments. Radial profiles of mole fractions at x/d_J of 13.3 and 26.7 for $\dot{m}_J$ = 4 gm/sec are shown in Figure 5. Flame contours are shown in Figure 6, based on the locations where the mean mole fractions of H_2 and O_2 are in stoichiometric proportions.

Summary

The present experiments for mixing and combustion of near-sonic central hydrogen jets with coaxial supersonic air or nitrogen streams have shown larger concentrations of hydrogen near the axis when there was combustion. Results of present flow field calculations, and of low-speed free jet experiments[3], suggest that this behavior was caused primarily by lower density in the burning case producing lower turbulent mass transport coefficients (kg/m sec).

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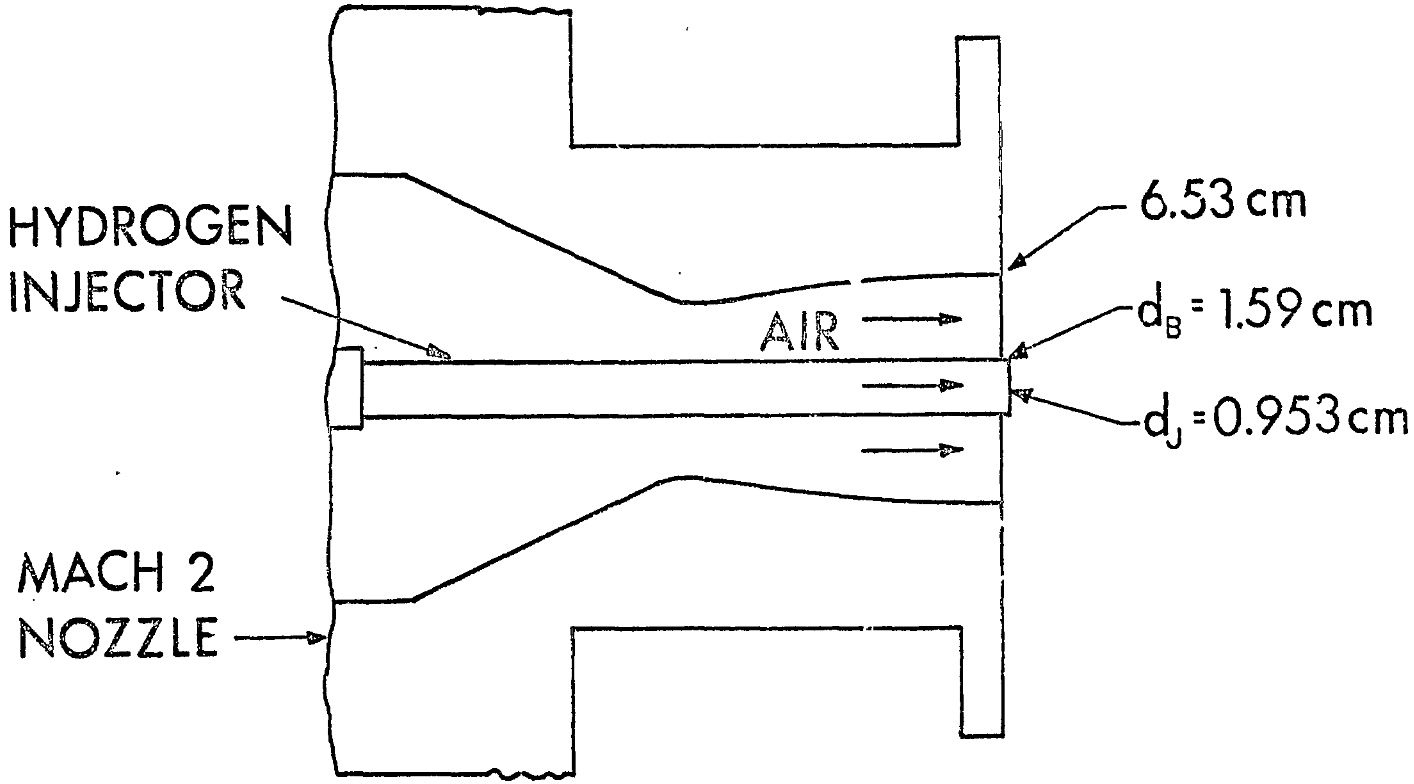
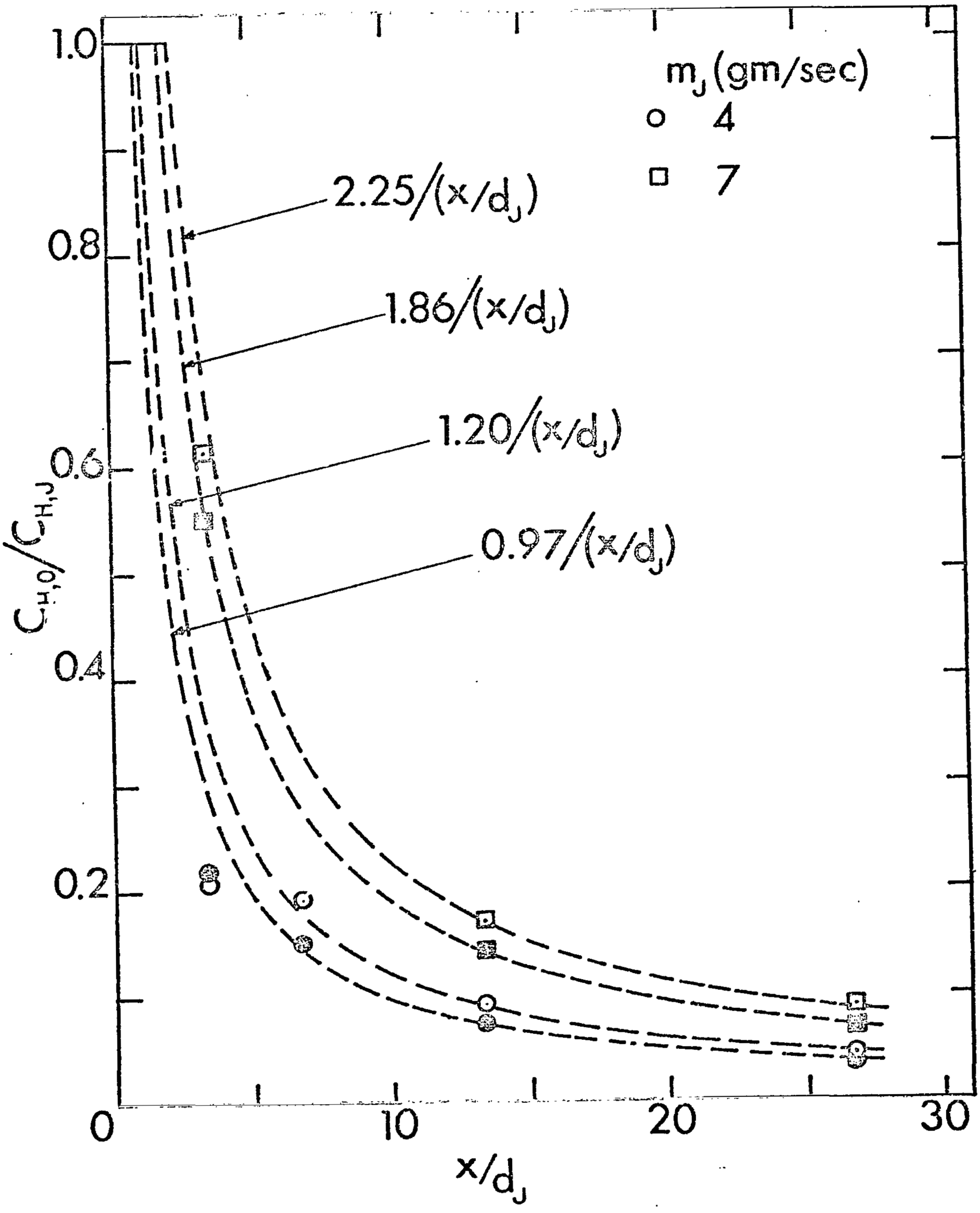
List of Figures

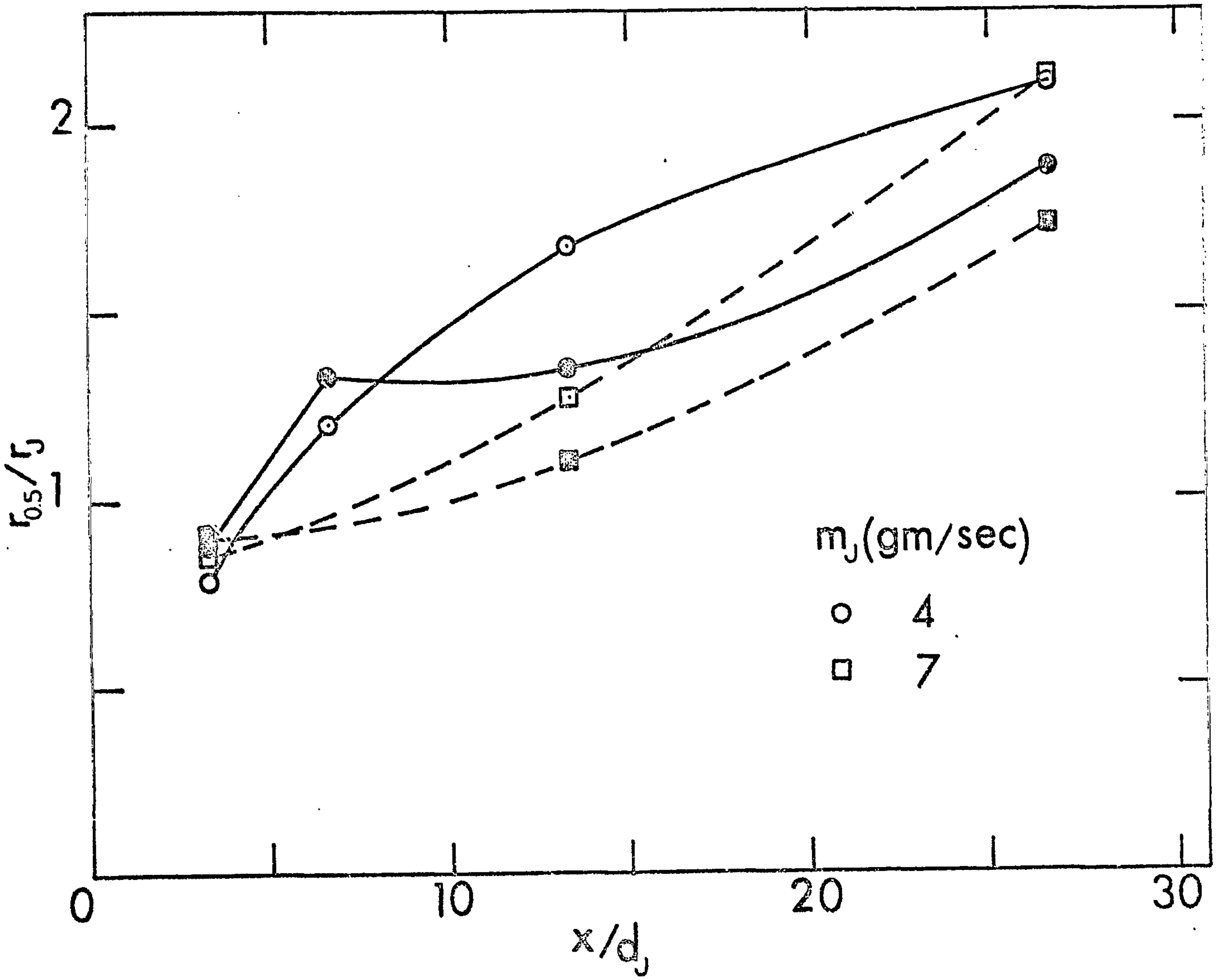
BAINGERT - FIG. 1



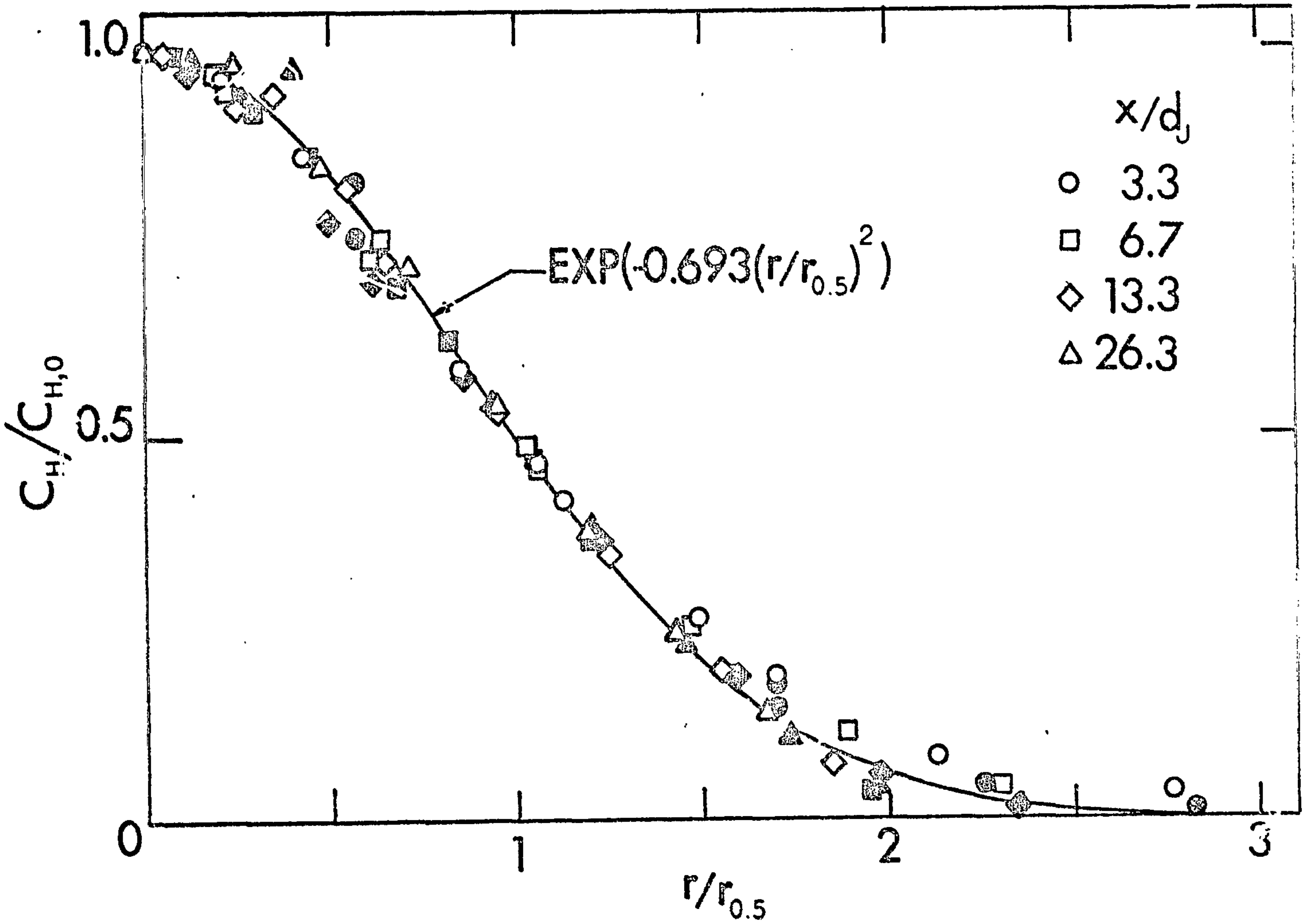
BAIGERT - FIG. 2



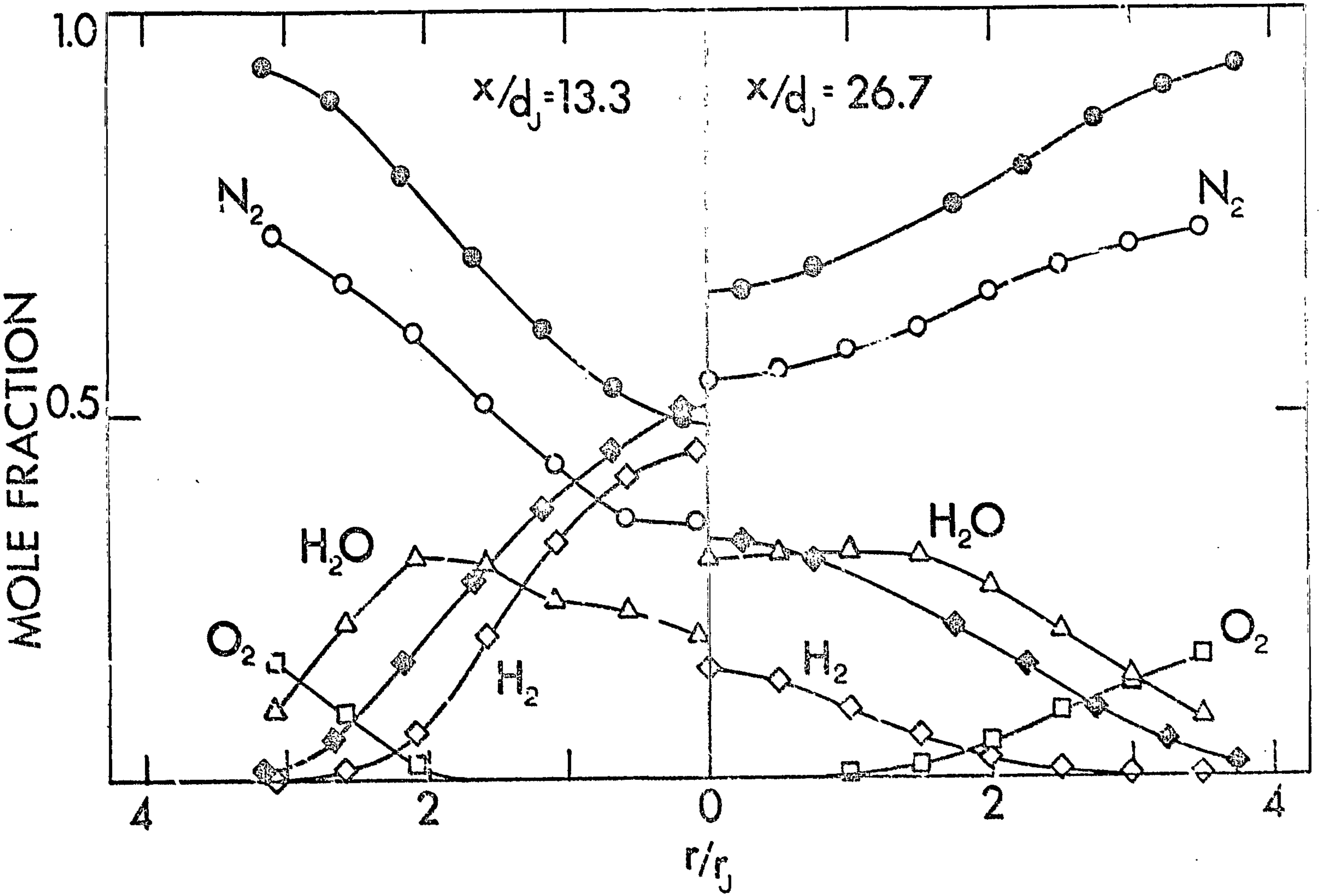
BANGERT - FIG. 3



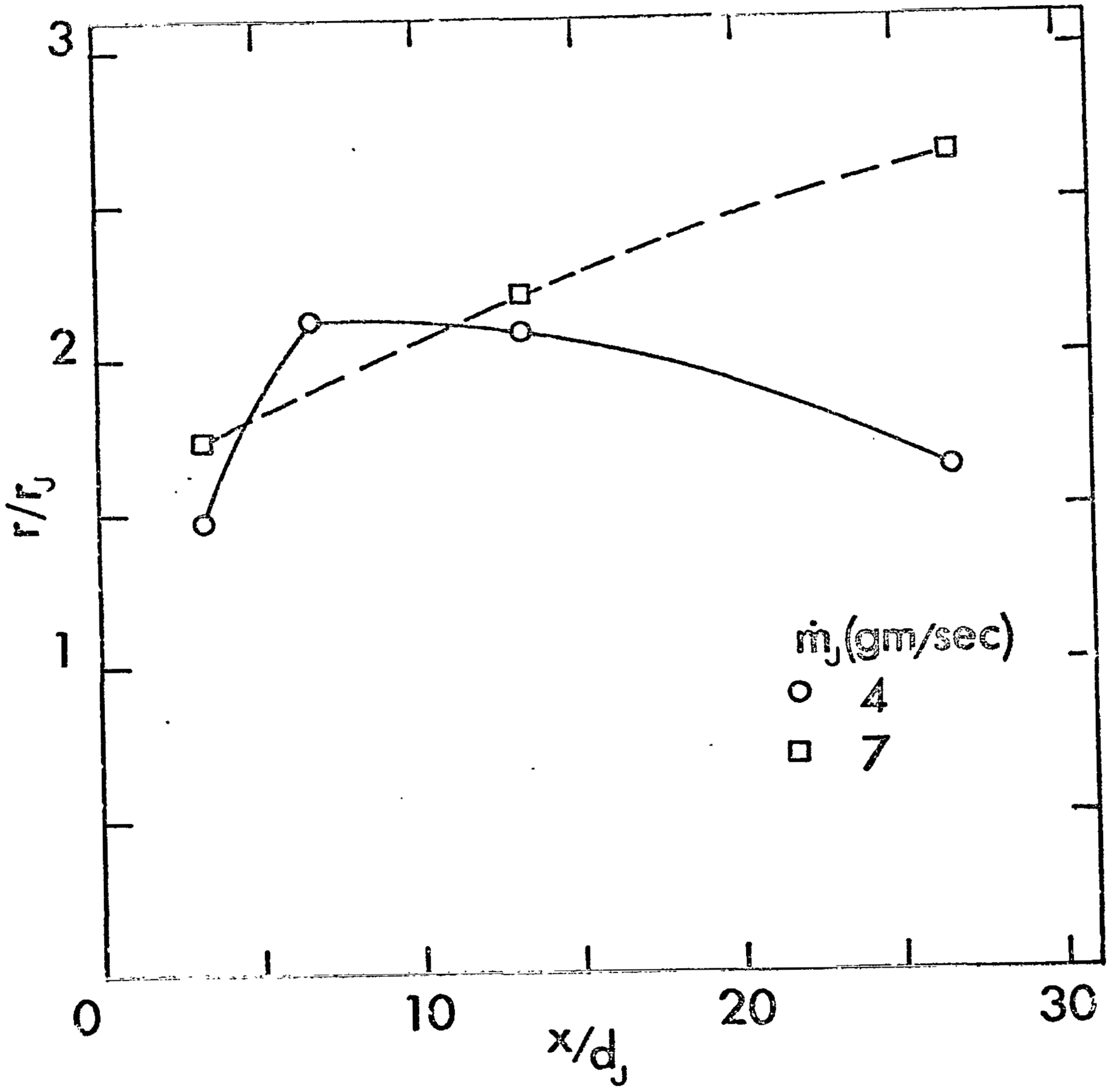
BANGERT - FIG. 4



Bangert - Fig. 5



BANGERT - FIG. 6



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