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A Preliminary Study of Supersonic Combustion in a Vitiated Airstream Using Transverse Injection

By

Hiroshi TSUJI, Tadao TAKENO, and Akira YOSHIDA

Summary: An experimental investigation was conducted on the combustion of gaseous fuels injected normal to a supersonic airstream. City gas, ethylene and methane were injected transversely at sonic velocity from a circular injector in a flat plate (simulating the combustion chamber wall of a scramjet engine) into a Mach 1.10 vitiated airstream at an air total temperature of 1700°K and total pressure of about 2 atmospheres. Photographic observations of the flame shape were made to compare the edge of the luminous flame zone with the nonreacting jet penetration. The total pressure and the temperature surveys were made to examine the complex combustion flow field in the vertical and horizontal planes. As a result of the investigation, it was found that the edge of the luminous flame zone was correlated well with the nonreacting jet penetration. There was a relatively large recirculation region immediately downstream of the fuel jet, and the supersonic flow field with fuel injection was influenced only a little by the heat release.

1. INTRODUCTION

Recently the development of supersonic commercial transports has roused the interest of the technical world in the possibility of future hypersonic aeroplanes or hypersonic vehicles.

For the propulsion systems of hypersonic vehicles, chemical rockets and airbreathing ramjets, namely, subsonic combustion ramjets and supersonic combustion ramjets (scramjets), may be considered to be available. Airbreathing ramjet propulsion systems have many advantages in comparison with any chemical rocket known today, such as a large specific impulse and weight savings. Cycle analyses show that in the flight regime between Mach 5 or 6 and 10, supersonic combustion ramjet engines will be more efficient than conventional subsonic combustion ramjets [*1*]. Above Mach 10, the only airbreathing propulsion systems currently thought feasible employ supersonic combustion. Also, throughout the supersonic and hypersonic flight regime, supersonic combustion on exterior vehicle surfaces offers a relatively simple means of generating large side forces for control of current missiles and future hypersonic vehicles. Therefore, the process of adding energy to supersonic airstream by combustion is of great interest in the development of future hypersonic cruise and boost vehicle.

In fact, in the past decade many researches have been made for reusable Earth-to-Orbit launch systems employing airbreathing first stage and sustainers for a future hypersonic cruising vehicle, and various types of scramjet engine having potentially attractive operating characteristics have been suggested. At the same time, several test models of scramjet engine have been manufactured for trial [*2*].

The different types of scramjet engine are distinguished on the basis of the combustion process used [*3*], [*4*]. The first type of combustion suggested is based on combustion through a shock wave [*5*]. The air and a gaseous fuel are premixed at supersonic speeds, and the temperature and pressure of the combustible mixture are then raised through a shock wave; a detonation type of combustion is produced. In this combustion process, however, the pressure loss due to a shock wave is significant. The second is to use a pilot flame to stabilize a premixed flame in a supersonic flow. This is a promising means in order to extend the operation of a supersonic combustion ramjet to a low flight Mach number, where spontaneous ignition of the fuel-air mixture will not occur because of low static temperature and pressure [*6*], [*7*]. The third is to employ diffusion flames. In this process, the airstream is decelerated gradually to a lower Mach number (supersonic) in the inlet of a scramjet in order to increase the static temperature and pressure of the air. Subsequently, the fuel is injected at high velocity and mixes rapidly with the airstream. If the temperature and pressure of the mixture are sufficiently high, ignition occurs spontaneously and the time for combustion is very short. In this case, the heat release is controlled by the mixing process [*8*]–[*10*]. The supersonic combustion controlled by mixing can be utilized throughout a wide range of Mach numbers without making the engine geometry variable, because the mixing process depends mainly on the fuel-injection scheme. The third type in these three combustion processes suggested appears, therefore, to be the most promising for the scramjet engine.

Thus, recently, the studies of the supersonic combustion employing diffusion flames have been undertaken extensively. But many practical problems are still remained to be explored. One of these problems is the method how the fuel is injected to obtain the uniform fuel distribution in the combustor without a significant total pressure loss and flow disturbances.

The fuel-injection schemes under consideration at present are broadly classified into four groups:

(1) Slot injection; the fuel is injected parallel to the combustion chamber wall through the open face of a rearward facing step.

(2) Distributed injection; the fuel is injected from the porous wall of the combustion chamber.

(3) Transverse injection; the fuel is injected transversely across the main stream through a discrete opening in the wall.

(4) Downstream injection; the fuel is injected parallel to the main stream from a downstream jet or a strut located in the main stream.

The first three groups are generally called as "wall injection" and distinguished from the last.

In the scramjet combustor, many factors, such as pressure gradients and the amount of nonuniformity in the fuel distribution, which are affected mainly by the fuel-injection scheme, may influence the ignition and combustion. Moreover, for a practical combustor design, we must consider the structural simplicity and cooling characteristics of each fuel-injection scheme. By taking these problems into consideration, among these four schemes the transverse injection appears to be the most promising means of adding fuel to a supersonic airstream and simultaneously promoting rapid mixing.

In the past decade, the particular flow field produced by the transverse injection of the secondary fluid has been treated in the investigations on the thrust vector control of solid propellant rockets. Many theoretical and experimental studies have been made to elucidate the complex interaction occurring between the secondary fluid and the primary flow in the rocket nozzle and to estimate the thrust augmentation and the side force [*11*], [*12*].

Recently this particular flow field has become to be investigated in the scramjet-oriented studies. In the practical scramjet combustor, the fuel jet structure in the vicinity of the injection opening controls the jet penetration, and the turbulent mixing of the injected fuel with the supersonic airstream controls the supersonic combustion. Thus, in theoretical treatment, the analysis was aimed primarily at the jet penetration and the shock wave structure in proximity to the injector, and many attempts were made to determine the jet penetration and the Mach disc height using various analytical models. To solve these jet interaction problems theoretically, we must know the pressure distribution on the common boundaries of the jet and airstream. Therefore, various physical and mathematical models, such as the Newtonian drag model, the isentropic flow model and the effective back pressure model, were employed [*13*], [*14*]. It was concluded that the last was the physically and mathematically consistent concept and that it provided the most excellent agreement with measured flow field properties. On the other hand, Schetz et al. investigated experimentally the structure of the secondary underexpanded jet issuing transversely through a surface into a supersonic airstream, and measured the location of the Mach disc as a criterion of the penetration by means of schlieren photographs [*15*], [*16*]. They developed an approximate description of the penetration process based on the notation of an effective back pressure and showed this description to be in good agreement with experiments for the case of both sonic and supersonic injection. This type of investigation has proved useful in the preliminary design of scramjet fuel-injection schemes, but the optimization of the fuel-injection schemes also requires a knowledge of the downstream mixing region. By means of concentration measurements, Povinelli et al. made a study of the mixing of helium injected normal to a supersonic airstream from a single port [7]. Rogers also measured in detail the injectant volume fraction in the mixing region, and determined the three-dimensional mass flux profiles which showed the downstream penetration and spreading of a transverse jet [*18*]. In these investigations, it was found that the penetration depends mainly on the ratio of jet dynamic pressure to free-stream dynamic pressure (i.e., the ratio of jet momentum flux to free-stream momentum flux) and injection Mach number, and that the penetration increases at downstream location. Wagner et al. investigated the interaction between adjacent jets from multiport injector and compared the performance of the multiport injector with that of the single port on the basis of the total pressure recovery and the fuel distribution, in order to apply it to the practical scramjet engine combustor [*19*].

Studies reviewed above were made in the cold airstream, and therefore, without combustion. On the other hand, several studies have been also made on the combustion and the jet and main stream interaction caused by the transverse injection of a combustible gas into a high temperature supersonic airstream. Edelman et al. investigated the mixing and combustion characteristics of multiphase fuels in a Mach 2 supersonic combustion wind tunnel, being prompted by the requirements of short combustors using storable, high energy fuels, and established the feasibility of ignition and efficient combustion of these fuels over wide ranges of simulated flight conditions [*20*]. Bier et al. measured the ignition temperature by injecting gaseous hydrogen and methane transversely into a Mach 2 supersonic air free-jet heated by a plasma burner and investigated the influences of combustion on the flow field by schlieren method and direct photography, and recently by concentration measurements [*21*]–[*23*]. It was shown that for a Mach 2 airstream and hydrogen injection, the lowest static air temperature at which stable combustion was observed is about 700°C, whereas the corresponding value for methane injection is about 1300°C. It appears, however, that in these experiments the combustion flow field was too complicated to be elucidated, because the supersonic airstream mixed with the ambient quiescent air and the combustion mainly occurred in this mixing region. Thayer III investigated the two-dimensional flow field with and without chemical heat release. In this experiment, a gaseous fuel or an inert gas was injected from a converging slot nozzle of an instrumented flat plate wind tunnel model perpendicular to a supersonic airstream [*24*]. It was found that injection caused the extensive separation of the turbulent boundary layer upstream of the slot, and that the resulting upstream recirculation region was fuel-rich, where ignition occurred at sufficiently high hydrogen and air temperature.

The main requirements of a scramjet are to stabilize the flame in a supersonic airstream and to make the time for combustion very short. Moreover, to design an efficient combustor of a supersonic combustion ramjet, the mixing and combustion of the injected fuel should be elucidated. As for mixing, data have been accumulated in aforementioned investigations, whereas a few papers on flow field with combustion have been published.

The object of the present study is to investigate experimentally the structure of the flame established in a supersonic airstream by the transverse injection of gaseous fuels. The effects of different fuels and the ratio of jet total pressure to free-stream total pressure on the flame shape were studied by the visual and photographic observations. The observed flame shape was compared with the jet penetration estimated by the empirical formula proposed in reference [*17*]. The distributions of the total pressure and the temperature in the combustion flow field were measured in detail in order to examine the aerodynamical and thermal structure of the flame.

In the experiments reported herein, the high temperature vitiated airstream was produced by burning the lean mixture of city gas and air at high pressure. The hot

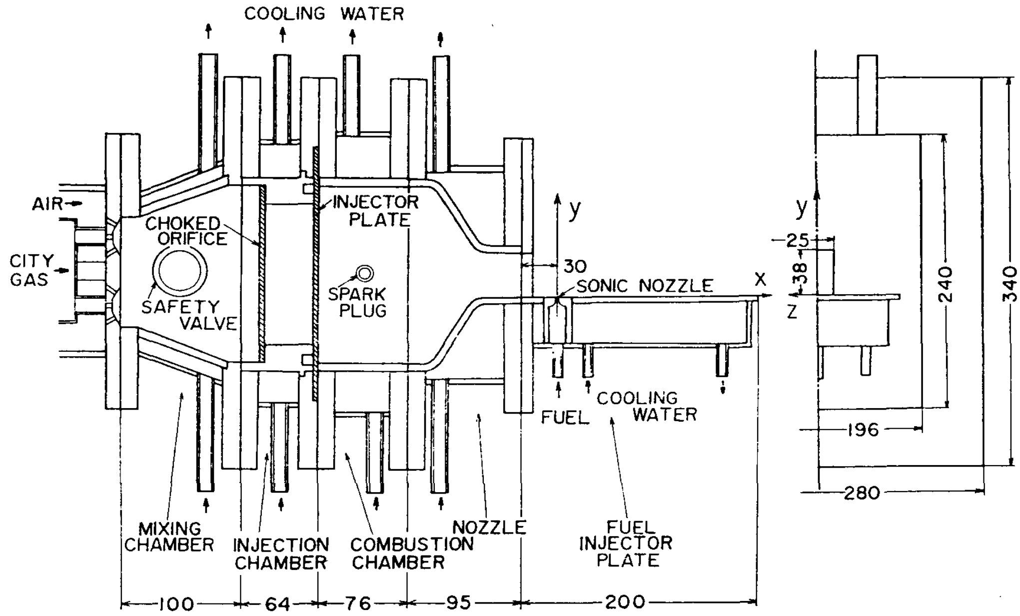


FIG. 1. Experimental apparatus. Dimensions are in millimeters.

burnt gas with oxygen expanded through a two-dimensional Laval nozzle to the atmospheric pressure, and the Mach number at the nozzle exit was 1.10. The supersonic combustion was produced by the underexpanded jets of methane, ethylene and city gas issuing from a single port of a flat plate model perpendicular to this supersonic vitiated airstream.

2. Experimental Apparatus

The experimental apparatus used in the present study is shown in Figure 1. The experimental work was carried out in a Mach 1.10 vitiated airstream supplied by the gas generator. The rectangular water cooled flat plate model with a round sonic nozzle as a fuel injection port was used.

The gas generator was composed of four parts, namely, a mixing chamber, an injection chamber, a combustion chamber and a nozzle, and all of them were water cooled. The air and the city gas were continuously supplied by each compressor and their flow rates were metered separately by the calibrated orifices installed in their respective feed lines. The city gas and air were introduced into the mixing chamber, impinging on each other, and then were mixed throughly. The city gas-air mixture entered the injection chamber through a choked orifice, which was installed so as to prevent the flash back of the flame into the mixing chamber. The city gas-air mixture of an equivalence ratio of 0.6 was injected into the combustion chamber through the perforated injector plate with 45 injector orifices of 5 mm in diameter, and uniform velocity and temperature profiles were obtained in the combustion chamber. The internal cross section of the combustion chamber was 95 mm $\times$154 mm and its length was 76 mm. The temperature and pressure in the com-

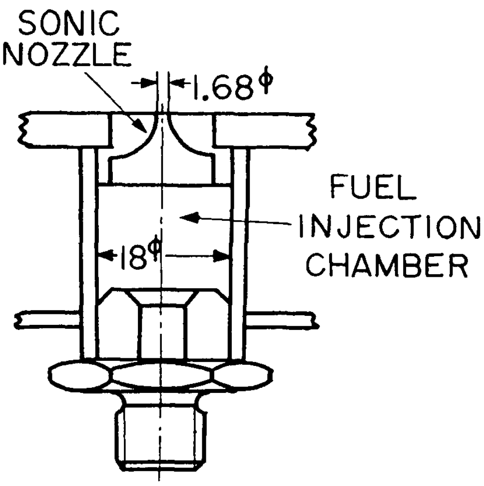


FIG. 2. Cross sectional view of sonic nozzle. Dimensions are in millimeters.

bustion chamber were measured by a Pt/Pt-Rh 13% thermocouple and a Bourdon gauge, respectively. The two-dimensional contoured nozzle with a 25 mm×38 mm exit cross section was designed to supply the uniform vitiated airstream of Mach number of 1.10 at the atmospheric pressure.

The flat plate model was 200 mm in length, and a sonic nozzle of 1.68 mm in diameter was flush-mounted perpendicular to the plate surface and was located 30 mm from the plate leading edge. Details of the nozzle are shown in Figure 2. The jet total pressure was measured in the fuel injection chamber of the flat plate model by means of a Bourdon gauge.

In the present study, city gas, methane and ethylene were used as injection fuels. City gas was supplied by a gas compressor, whereas methane and ethylene were supplied by fuel cylinders, respectively, through a high capacity regulator which was used to control injection pressures.

Two similar total pressure probes which were not water-cooled were designed to measure the profiles of the total pressure in the flow field with and without fuel injection. The first probe, designated as Probe I, was made of platinum tube of 1.2 mm i.d. and 2.0 mm o.d. This probe was used as the reference probe and was used only in the experiments without fuel injection because of the catalytic effect of the platinum tube. The second probe, designated as Probe II, was made of quartz tube and had an outside diameter of 1.5 mm and an inside diameter of 1.0 mm. Probe II could be used in the combustion flow field and is shown in Figure 3. The measured total pressure was recorded on the $X-Y$ recorder using a pressure transducer.

The temperature profiles in the flow field were measured by a total temperature probe and an exposed-junction thermocouple. The total temperature probe had a platinum sheath of 3.2 mm o.d., and a Pt/Pt-Rh 13% thermocouple of a wire diameter of 0.53 mm was installed in the sheath. Because of the low spacial resolution owing to the relatively large sheath diameter, this probe could be used only in the experiments without fuel injection. The exposed-junction thermocouple of

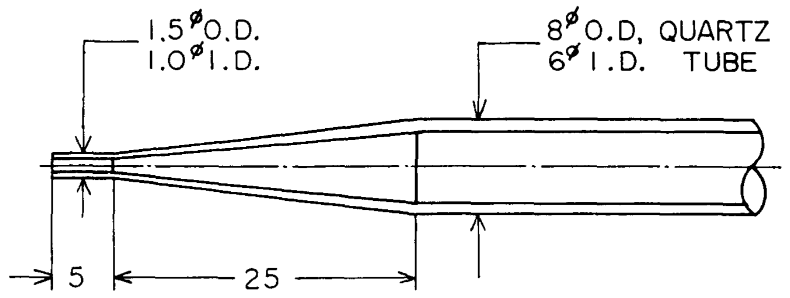


FIG. 3. Total pressure probe II. Dimensions are in millimeters.

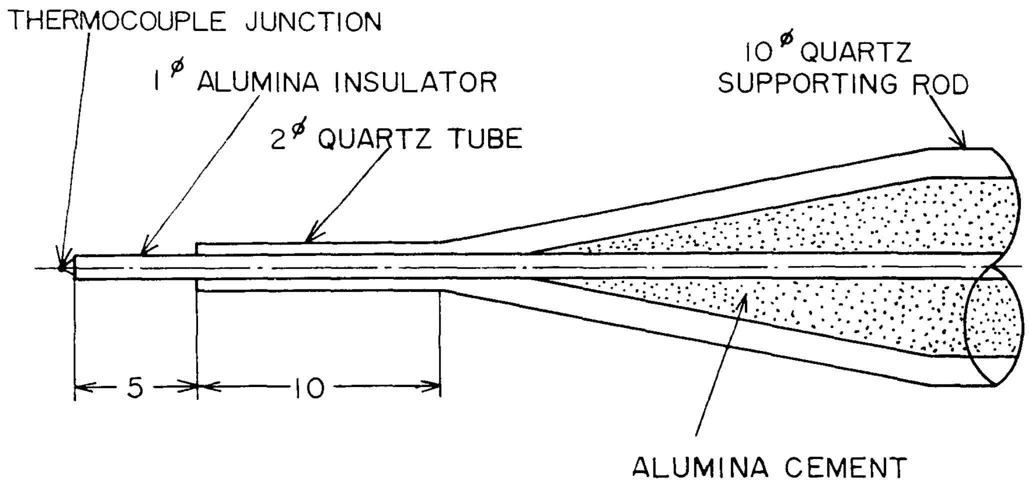


FIG. 4. Exposed-junction thermocouple. Dimensions are in millimeters.

a wire diameter of 0.3 mm had a quartz supporting rod of 10 mm o.d., and was used to measure the temperature profiles in the combustion flow field. The exposed-junction thermocouple is shown in Figure 4.

The total pressure probe and the total temperature probe or the exposed-junction thermocouple were mounted on an automatically operated traversing mechanism.

3. Experimental Procedure

Runs were sequenced for a five minute duration with steady state vitiated airstream from the gas generator established for 4 minutes or longer. After the vitiated airstream became steady, the fuel was injected from an underexpanded nozzle. At each of the downstream stations, two or three vertical or horizontal surveys of the flow field were made for each run to measure the profiles of the total pressure and the temperature. The vertical surveys were made along the jet center line stepwise from the plate surface upward, while the horizontal surveys were made continuously.

4. Data Reduction and Accuracy

The total pressure and temperature data at each survey point were reduced to yield values of Mach number and static temperature, except for the case of fuel injection. Mach number and static temperature were computed, assuming that the gas was perfect and using the equations for one-dimensional isentropic flow. For the case of fuel injection, Mach number and static temperature could not be determined, because the gas analysis was not made in the present study and the molecular weight and the specific heat of gaseous mixture in the combustion flow field could not be estimated.

The flow rates of air and city gas, the equivalence ratio of the city gas-air mixture in the gas generator and the static temperature of the vitiated airstream were reproducible within $\pm 1\%$.

The Mach number of the supersonic vitiated airstream at the fuel injection station varied about $\pm 1.5\%$ from run to run. The vertical and the horizontal Mach number profiles at the fuel injection station proved to be uniform within $\pm 0.5\%$ in the 30 mm (height) $\times$ 18 mm (width) core section.

Temperatures indicated by the thermocouple probe were reproducible within $\pm 1\%$ when care was taken to insure the integrity of wire, junction and alumina insulator. For vertical surveys, readings were taken after the junction temperature had stabilized, and for horizontal surveys, the thermocouple probe was moved with the actuator mechanism so slowly that the response time for the thermocouple proble to the temperature changes was assumed to be negligible.

The quartz total pressure probe was calibrated with the platinum total pressure probe in the high temperature vitiated airstream over the Mach number range of the present study.

5. Experimental Results and Discussion

5-1. *Flow Field of the Vitiated Airstream*

The schematic diagram showing the coordinate system is presented in Figure 5. In this figure, x, y, and z are the downstream distance from the fuel injector port, the normal distance from the plate surface, and the lateral distance from the center line of the injector respectively. The structure of the flow field on the flat plate without fuel injection is shown in Figure 6. All distances were normalized by the throat diameter d_j of the fuel injector port. Figures 6–a and 6–b show vertical profiles of Mach number obtained on the flow center line and horizontal profiles obtained at two vertical locations, respectively. The Mach number profiles proved to be almost uniform in the core section which becomes narrower at the downstream location. At an x/d_j of 35.7, it is shown that the mixing region between the supersonic airstream and the ambient still air extends to the flow center line, and at further downstream the uniform supersonic region can not be noticeable, that is, the entire flow field becomes subsonic. The uniform supersonic region is schematically shown in Figure 5. The vertical and horizontal profiles of the total tem-

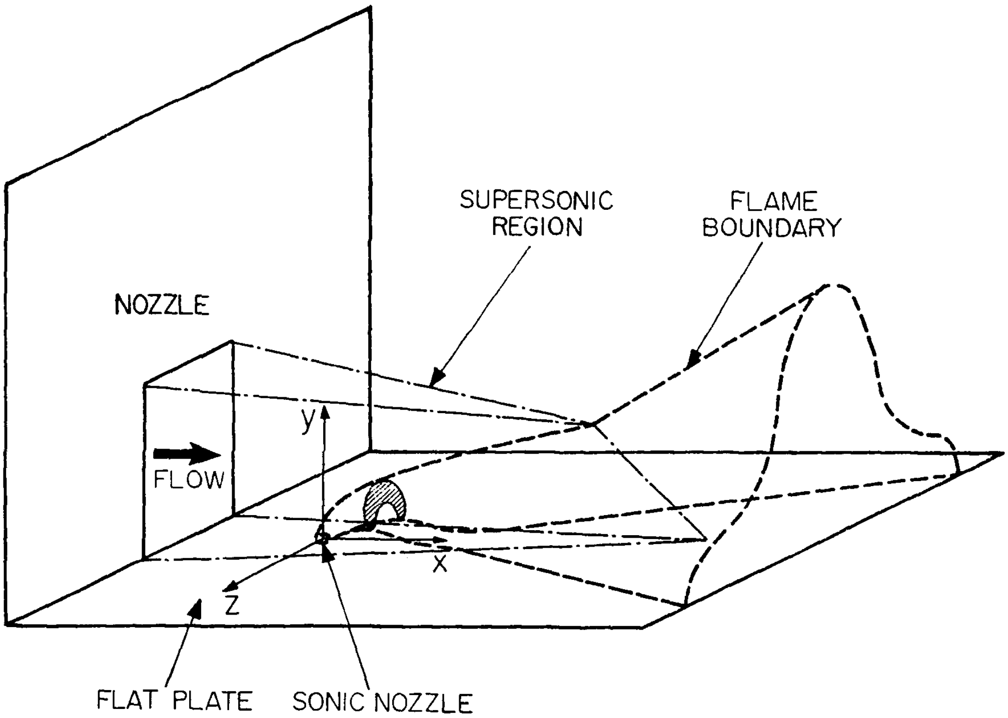


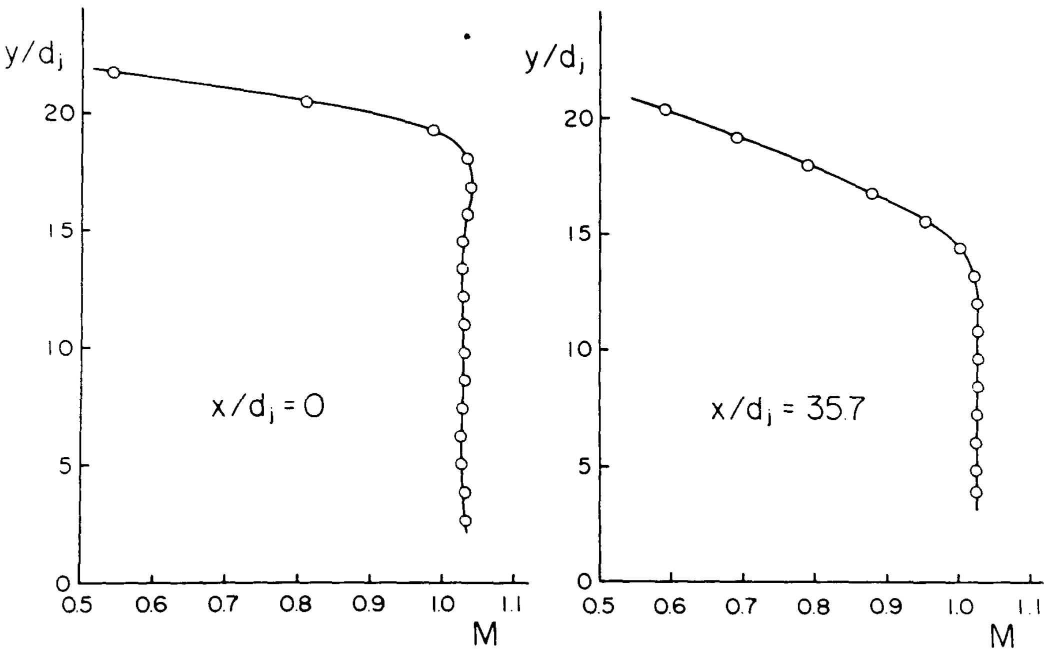
FIG. 5. Schematic representation of combustion flow field showing coordinate system.

perature T_0 are presented in Figures 6–c and 6–d, respectively. The total temperature profiles are not so uniform even in the core section as the Mach number profiles, and this is thought to be due to the lack of uniformity of the combustion in the gas generator. There is no uniform temperature region at an x/d_j greater than 35.7.

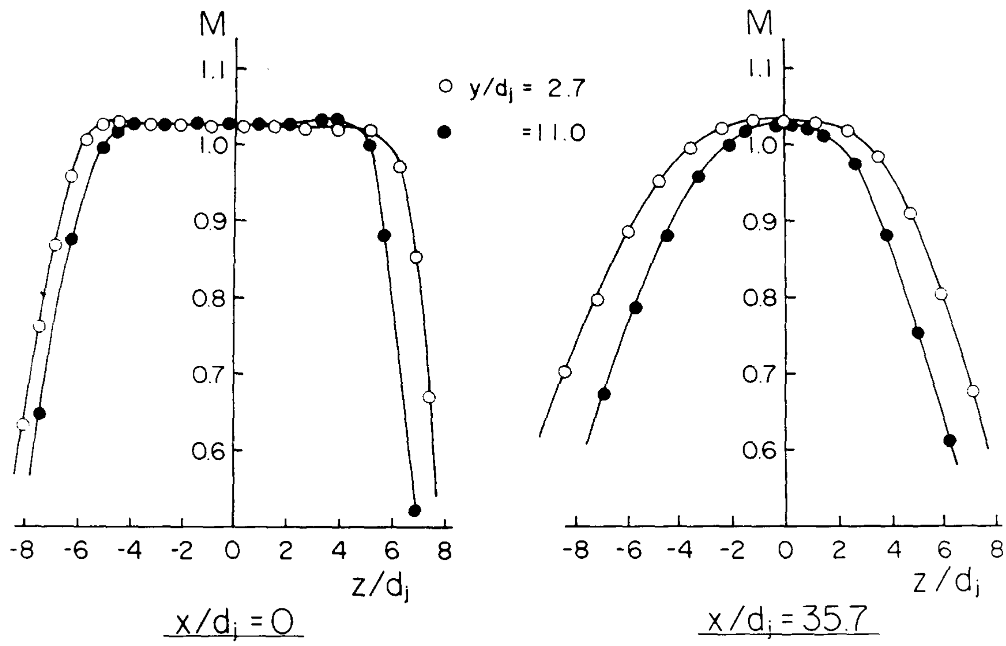
Thus the supersonic flow field in which Mach number and total temperature profiles are thought to be uniform (x/d_j<35.7) was used for the supersonic combustion study.

5-2. *Combustion of Gaseous Fuels Injected Transversely into a Supersonic Vitiated Airstream*

In the present study, through the sonic nozzle of the flat palte model, three kinds of gaseous fuels were injected transversely into the supersonic vitiated airstream at various jet total pressures. The Mach number of the vitiated airstream was about 1.10 with the total temperature of about 1700°K and the static temperature of about 1470°K. City gas, methane and ethylene were used as gaseous fuels, and the jet total pressures of injected fuels were 1.95, 4.20 and 6.00 kg/cm^2 abs. for city gas, and 11.0, 16.0 and 21.0 kg/cm^2 abs. for methane and ethylene. For all fuels used in the present study, stable combustion was achieved with spontaneous ignition even at these relatively low airstream temperatures. The direct colour photographs of the flames generated in this way were taken not only from the flank but also from above. Several representative photographs of the flame are shown in Figure 7. It



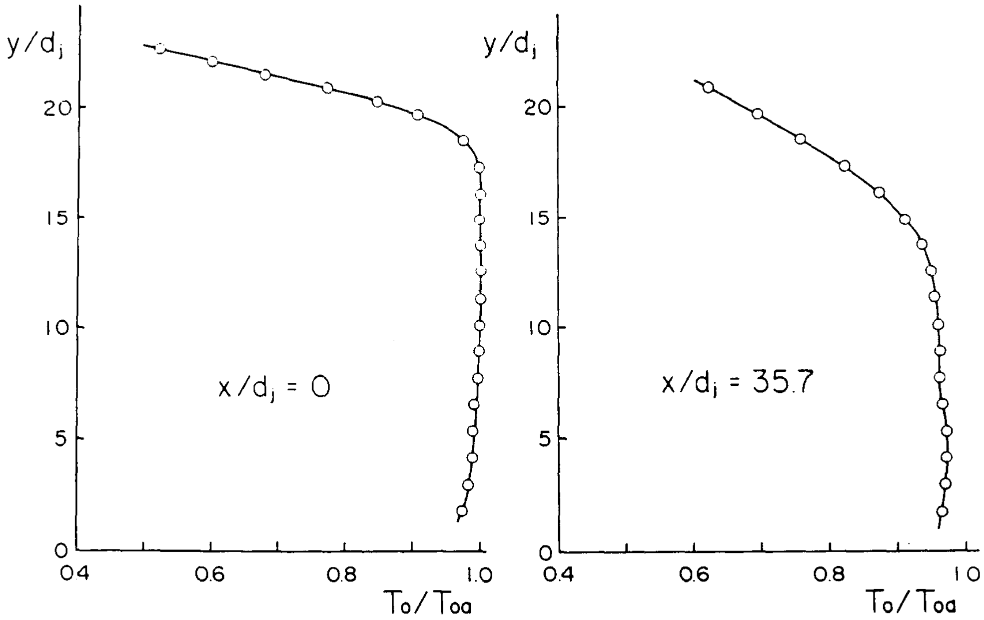
(a) Vertical Mach number profiles.



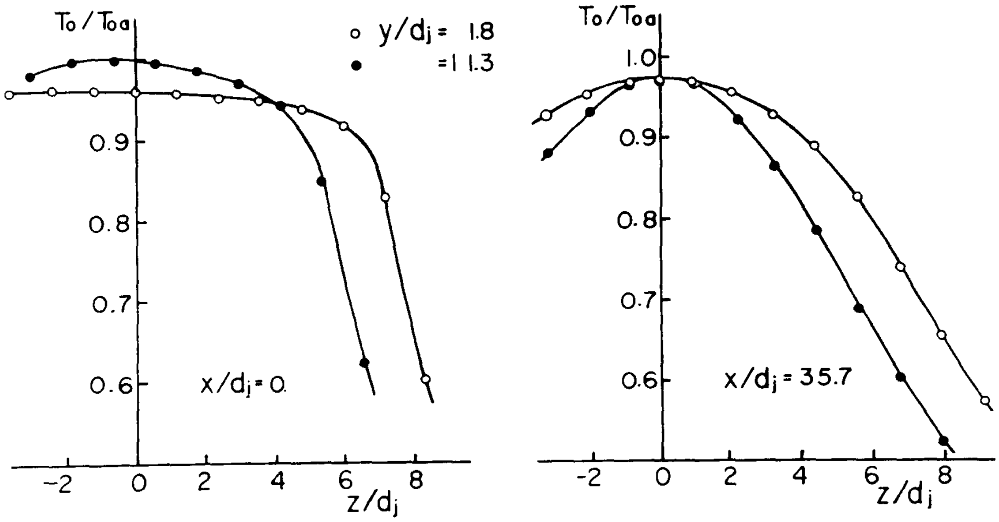
(b) Horizontal Mach number profiles.

FIG. 6. Structure of vitiated airstream.

is found in these photographs that the city gas flame and the ethylene flame are very luminous, while the luminosity of the methane flame is comparatively weak, and that the flame shapes of methane and ethylene are similar and flame shape depends mainly on the injection pressure. The fuel issuing from an underexpanded nozzle into a supersonic airstream produces a complex three dimensional flow system, which rapidly turns in a downstream direction, and after travelling less than



(c) Vertical total temperature profiles.



(d) Horizontal total temperature profiles.

FIG. 6. Concluded.

10 jet diameters, the flame front is nearly parallel to the main stream. In the neighbourhood of the fuel injection nozzle, the initial region of luminosity has a sharp front, followed by rapid fading, while at downstream location the luminous flame zone becomes wide. A typical flame shape is shown schematically in Figure 5.

The jet penetration has been discussed considerably by several investigators [*15*]–[*18*], and various definitions of penetration were suggested. In reference [*17*] the term "penetration" was referred to the edge of the mixing region in the vertical

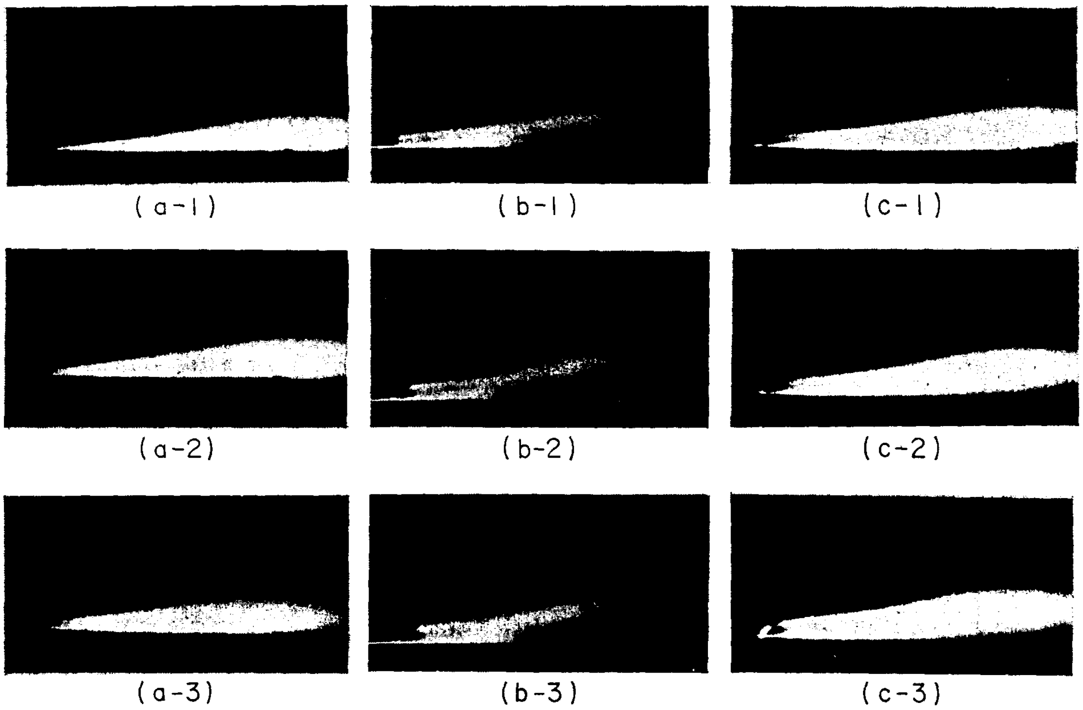


FIG. 7. Direct photographs of flames.

(a)	City gas flame.	(b)	Methane flame.	(c)	Ethylene flame.
(a-1)	$P_{oj}/P_{oa}=1.95$	(b-1)	$P_{oj}/P_{oa}=11$	(c-1)	$P_{oj}/P_{oa}=11$
(a-2)	$=4.20$	(b-2)	$=16$	(c-2)	$=16$
(a-3)	$=6.00$	(b-3)	$=21$	(c-3)	$\doteq 21$

center line plane and the following correlating equation for the experimental data was given for the nonreacting jet penetration:

$$\frac{y}{d_j}=\left(\frac{P_{oj}}{P_{oa}}\right)^{0.507} M_j^{0.114} \frac{x/d_j+0.5}{1+0.24x/d_j} \qquad (1)$$

where x is downstream distance from nozzle center line, y penetration measured normal to the plate surface, d_j throat diameter, P_{oj} jet total pressure, P_{oa} air total pressure and M_j injection Mach number.

In the present study, the edge of the luminous flame zone extended in y-direction in proportion to the 0.37 power of the total pressure ratio at all x/d_j stations. Therefore, this flame boundary is assumed to be represented by the following equation, analogous to Equation (1):

$$\frac{y}{d_j}=\left(\frac{P_{oj}}{P_{oa}}\right)^{0.37} M_j^{0.114} \frac{x/d_j+0.5}{1+0.24x/d_j} \qquad (2)$$

In Figure 8, for the case of methane injection at P_{oj}/P_{oa} of 16, Equation (2) and the flame boundary obtained in the present study are plotted. From this figure, it is confirmed that Equation (2) which is analogous to Equation (1) for the nonreacting jet penetration, predicts the flame boundary considerably well, suggesting that the flow field is influenced only a little by the heat release of the fuel. The

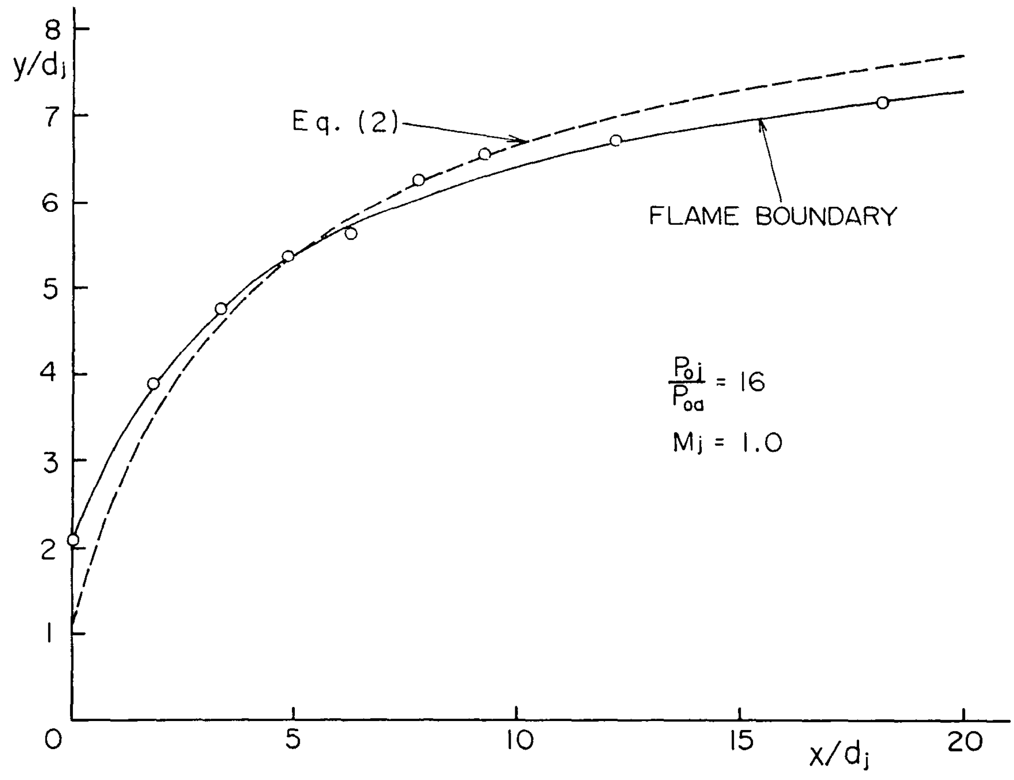


FIG. 8. Comparison of correlation Eq. (2) with flame boundary for representative values of injection pressure.

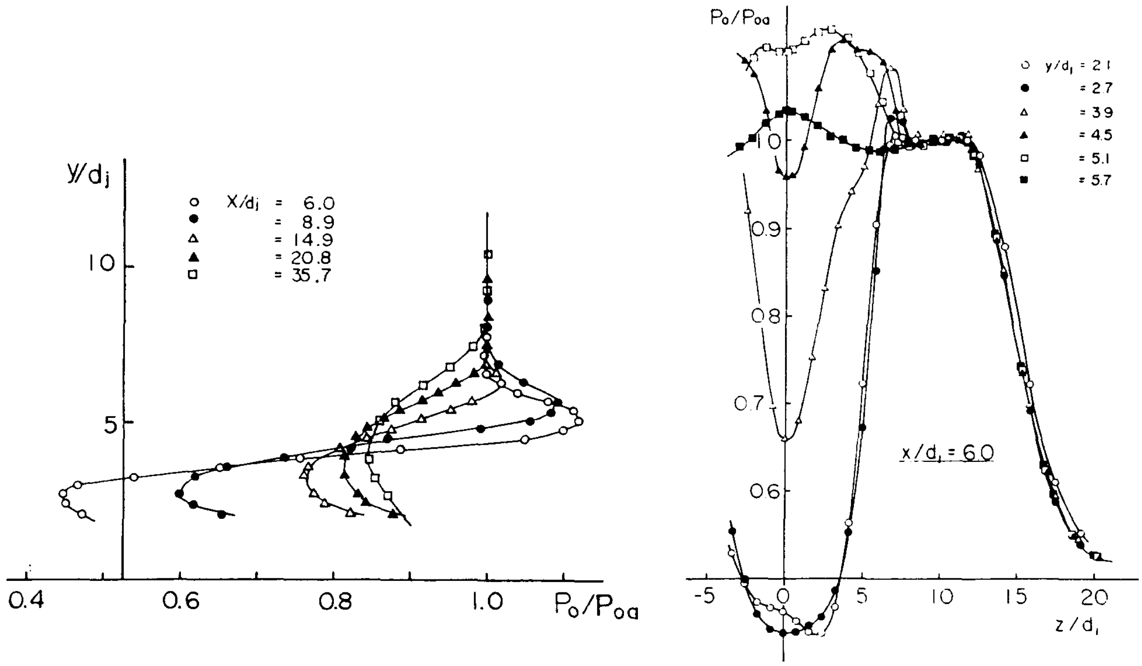
difference in pressure exponent between Equations (1) and (2) is probably due to the different injected gases and boundary-layer thicknesses.

5-3. Total Pressure Measurement

Measurements of the total pressure and the temperature in the combustion flow field were made only for the methane injection at $P_{oj}/P_{oa}=16$. The profiles of the total pressure P_0 for vertical and horizontal directions were obtained by means of the quartz proble (Probe II). The results are shown in Figure 9–a for vertical survey and in Figure 9–b for horizontal survey. As the reference pressure, the main stream total pressure was taken in these figures. In this way, run-to-run variations in total pressures due to slight changes in main stream conditions were reduced. P_o/P_{oa} of 0.526 corresponds to the condition that the measured total pressure is equal to the surrounding atmospheric pressure, that is, the velocity component in the main stream direction is equal to zero.

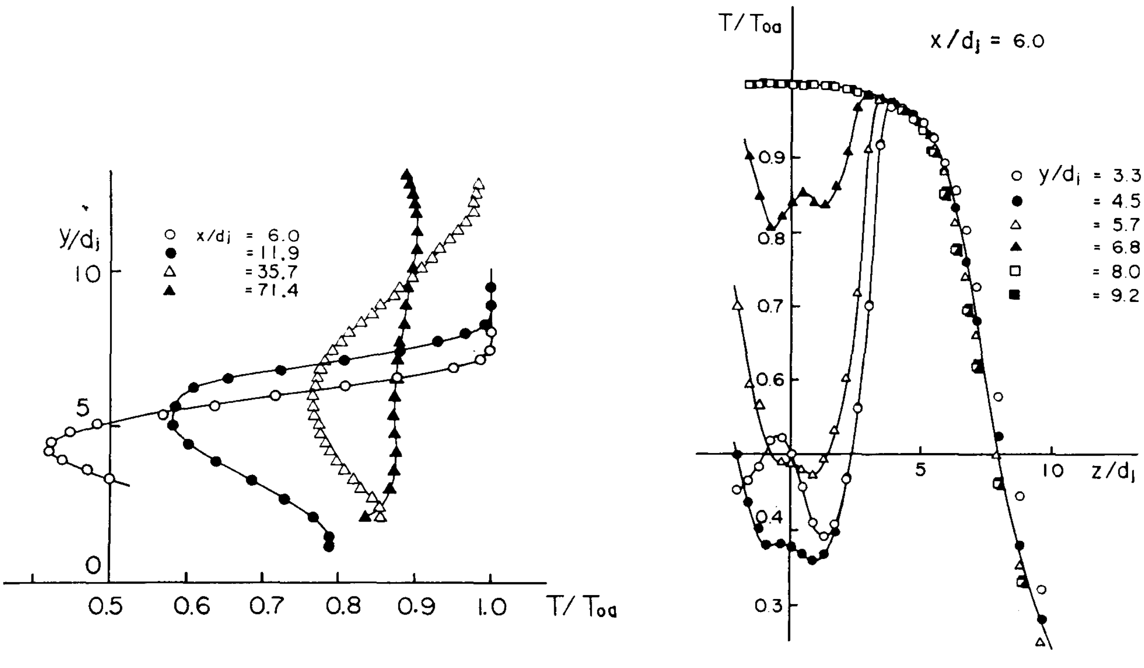
In these figures, it was confirmed that, near the plate surface, there is the region where the total pressure was below the surrounding atmospheric pressure at an x/d_j smaller than 6.0, recovering above the atmospheric pressure at an x/d_j of 8.9. These experimental results indicate that there was a relatively large recirculation region caused by the boundary-layer separation immediately downstream of the underexpanded fuel jet.

The pressure peak shown in these figures results from the high total pressure of



(a) Vertical survey. (b) Horizontal survey.

FIG. 9. Nondimensional total pressure profiles. $P_{oj}/P_{oa}=16$.



(a) Vertical survey. (b) Horizontal survey.

FIG. 10. Nondimensional temperature profiles. $P_{oj}/P_{oa}=16$.

the underexpanded fuel jet. It decreases rapidly at downstream location due to mixing of fuel jet and main stream, and at an x/d_j of 20.8 the peak becomes unnoticeable. It is found that, as a result of the action of the deflecting flow and the recirculation zone, the particles of the jet all branch out more and more from the plane of symmetry and the cross section of the jet takes the form of "horseshoe". As shown in Figure 5 schematically, the legs of this "horseshoe" move apart at downstream location, giving rise to the possibility of additional circulatory motion in the jet.

5-4. *Temperature Measurement*

The temperature measurements for vertical and horizontal directions were made using Pt/Pt-Rh 13% exposed-junction thermocouples, and the observed temperature profiles are shown in Figure 10–a for vertical survey and in Figure 10–b for horizontal survey, respectively. In these measurements neither the radiation correction nor the recovery correction were made. The main stream temperature for each particular run was used as the reference temperature and the values of the measured temperature was normalized by this reference temperature.

The fuel jet temperature is below the main stream temperature, and in these figures it is found that this lower temperature region of the fuel jet spreads out toward downstream, indicating that the jet mixes with the higher temperature main stream rapidly at downstream location. Although a rather sharp peak of the temperature profile is observed generally in the combustion region with diffusion flame, no sharp peak is found in the present study. This is probably because of the fact that the total enthalpy increase due to the supersonic combustion is very small compared with the high total enthalpy of the main stream. It was confirmed that at an x/d_j equal to or greater than 71.4 the temperature of the flow field as a whole is higher than that in the case of no fuel injection. In this region, the main stream becomes subsonic resulting from the mixing of the supersonic main stream and the surrounding still air, and the temperature decreases and the oxygen concentration increases. This suggests that, in the present experimental setup, the majority of the fuel (methane) injected into the main stream burns in the subsonic region.

6. CONCLUSIONS

In the present study, the highly underexpanded fuel jet was injected perpendicular to the supersonic vitiated airstream supplied by a specially designed compact gas generator, and the flame shape was studied by the visual and photographic observations. The total pressure and the temperature profiles of the combustion flow field were measured in detail in order to examine the aerodynamical and thermal structure of the flame. The present study has brought about the following conclusions:

(1) The stable supersonic combustion was maintained in the vitiated airstream even in the total temperature range of 1650°K to 1700°K.

(2) By comparing the edge of the luminous flame zone with the penetration data, it was confirmed that the edge of the luminous flame zone could be correlated well by the nonreacting jet penetration at the Mach number of the present study.

(3) Total pressure measurements show that there was the relatively large recirculation region immediately downstream of the fuel jet, and that the jet cross section was the shape of "horseshoe".

(4) Temperature measurements show no sharp peak in the temperature profiles in the combustion flow field, while in the downstream subsonic region the temperature as a whole was higher than that in the case of no fuel injection.

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Department of Jet Propulsion,
Institute of Space and Aeronautical Science,
University of Tokyo, Tokyo,
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