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Interaction of Inert and Chemically Reactive Gaseous Jets with Hot Supersonic Flows

By

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Summary: An experimental investigation was carried out on the interaction of inert and chemically reactive gaseous jets with hot supersonic airstream in the Mach 1.81 supersonic combustion wind tunnel. Highly underexpanded nitrogen and hydrogen were injected from a converging slot nozzle oriented perpendicular to the airstream. In the experiments, temperature and oxygen concentration of the vitiated airstream, and injection pressure were varied, including conditions at which chemical reaction occurred. The wall static pressure distributions, temperature profiles and pitot pressure profiles were measured on the jet interaction flowfield with chemical reaction. At the same time, schlieren photographs were taken to determine the effect of the chemical reaction on the jet interaction flowfield. The results indicated the important role of the chemical reaction in the upstream separated region caused by the jet. Chemical reaction in the upstream separated region increased the separation distance significantly. Downstream of the jet, after a small induction zone, a turbulent flame was formed in the mixing region between the supersonic airstream and the injected hydrogen. However, the effect of the downstream turbulent flame on the jet interaction flowfield is found to be small in the range of present experimental conditions.

1. INTRODUCTION

The interaction between a transverse jet of inert or reactive gas and a supersonic airstream is of interest in many applications. Considerable investigations have been carried out from several points of view such as thrust vector control [*1*], [*2*], supersonic combustion [*3*]–[*6*] and external burning [*7*]–[*9*]. The resulting flowfield is complex, because mixing and momentum exchange between the jet and the supersonic airstream and, in some cases, chemical reaction and heat release occur involving shock and rarefaction waves.

One of the most interesting applications is external burning on vehicle surfaces, namely, the use of a reactive jet to provide a reaction force or moment for control of a future hypersonic vehicle flying in the atmosphere. This application is often called as reaction control jet. External burning typically involves a sonic or supersonic jet of very high pressure injected into a supersonic airstream and, at low altitudes, of high dynamic pressure and, therefore, of high stagnation temperature. Considerable work has been done on characterizing jet interaction under such conditions [*7*]–[*12*]. However, excepting several studies [*7*]–[*9*], experimental work has been concentrated mainly on the tests at low stagnation temperature, and where no combustion occurred.

The reason for this limitation on the available experimental results is, of course, the cost and difficulty of testing at high stagnation temperatures and in the presence of combustion. Because of the complexity of the jet interaction flowfield, the analytical investigations must contain several empirical assumptions and experimental results obtained in the cold flow experiments [13], [14]. Therefore, analytical approaches raise questions when they are applied to external burning and also when extrapolation is required.

This paper reports the experimental results on inert and chemically reactive jet interactions and effects of chemical reaction on the jet interaction flowfield produced in a supersonic airstream at higher stagnation temperatures than have hitherto been available. The high temperature airstream was produced by burning of city gas in air at lean mixture ratio and at high pressure. The hot burnt gas with oxygen (vitiated air) expanded through a two-dimensional Laval nozzle to the atmospheric pressure, and the Mach number of the vitiated airstream at the nozzle exit was 1.81. Nitrogen and hydrogen were injected perpendicularly into the supersonic vitiated airstream through a two-dimensional nozzle of a flat plate model. In these experiments, wall static pressure distributions, temperature and pitot pressure profiles were measured and schlieren photographs of the flowfield were taken. From these experimental results, the effects of the chemical reaction on the jet interaction were determined.

2. Experimental Apparatus

To perform realistic experiments on jet interaction with chemical reaction, quite large mass flow having high energy level is required. Among several methods available at present to produce the desired stream energy levels, the least restrained is thought to be combustion devices. Therefore, a supersonic combustion wind tunnel was newly designed and constructed which uses the city gas-air combustion gas as a substitute for the pure air as the test medium [15]. This wind tunnel consisted of the gas generator, the two-dimensional Mach 1.81 supersonic nozzle and the test section and is shown in Fig. 1. The burnt gas produced in the gas generator is accelerated by the Laval nozzle to Mach 1.81 to which, if necessary, controlled amount of oxygen can be added to maintain the oxygen concentration at some desired level. The inner liner of the gas generator is air cooled and forms the combustion chamber and the contraction of the supersonic nozzle. Nine small swirl burners are arranged in the combustion chamber which has square cross section of 160 mm $\times$ 160 mm and is 200 mm in length. City gas and air supplied to each burner are burnt at lean mixture ratio producing the vitiated air. From the end of the combustion chamber, the contraction starts, and all four sides of the inner liner are curved and continuous with those of the two-dimensional supersonic nozzle which accelerates the vitiated airstream to Mach 1.81 at atmospheric pressure. The two-dimensional supersonic nozzle is one-sized type and, therefore, the bottom wall is contoured whereas the top wall is straight. The side walls are parallel to the tunnel axis, spaced 45 mm apart, downstream of the contraction. All four walls of the nozzle are water cooled. The exit cross section of the nozzle is 45.00 mm $\times$ 34.42 mm. The vitiated airstream accelerated by the nozzle has the uniform Mach number and temperature distributions in the test section. The

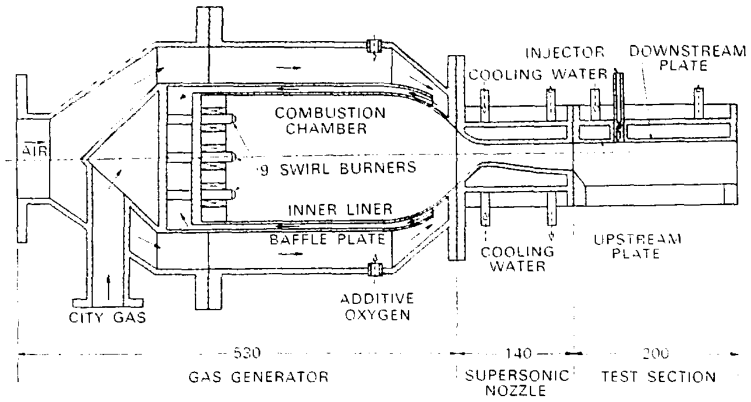


FIG. 1. Experimental Apparatus.

stagnation temperature of the vitiated airstream is variable from 1000 K to 1700 K by variation of the city gas-air equivalence ratio. The oxygen concentration is also variable from about 9% to 16% by adding oxygen to air before entering the combustion chamber. Reynolds number is calculated using the aerodynamic properties of the city gas-air combustion gas [*16*] and its value for the equivalence ratio of 0.5 is 9.286×10^6 per meter. Maximum flow rates of air, city gas, and oxygen were about 1600 Nm^3/h, 160 Nm^3/h and 110 Nm^3/h, respectively. Wind tunnel run duration varied from about 5 to 10 minutes depending on time spans required for measurements.

In the present study, nitrogen and hydrogen were supplied from respective storage bottles located outside the laboratory through a high capacity pressure regulator and injected through a two-dimensional sonic nozzle of the injector. The flat plate model was set up in the test section, forming the flat surface which is continuous with the top liner of the nozzle. This flat plate model is also shown in Fig. 1, and consists of three subassemblies, namely, upstream plate, injector, and downstream plate. It spans the 45-mm wide test section and its length is 200 mm. The upstream plate and the downstream plate are water cooled and thirty-one static pressure taps are flush mounted on the centerline of the model, twelve for the upstream plate and nineteen for the downstream plate. The injector has a slot nozzle which has a span of 35.0 mm and a width of 0.1 mm. Therefore, the aspect ratio is 350.

3. INSTRUMENTATION, DATA REDUCTION AND ACCURACY

With the exception of static pressures, all data were recorded continuously during each wind tunnel run. Static pressures were displayed on a forty-four tube manometer board and recorded photographically at times of interest. Event marker was used to mark the continuous records when data photographs and schlieren photographs were taken.

Pitot probe and temperature probe used in the present study are water cooled and cooling water is supplied to each probe at a pressure of 8.8×10^5 Pa. Their detailed structures are shown in Fig. 2. Tip diameter of pitot probe is 1.0 mm with lip thickness of 0.2 mm. Pitot pressure was read using a pressure transducer which was calibrated before the tunnel run. Temperature probe is a Pt-Pt 13% Rh thermocouple.

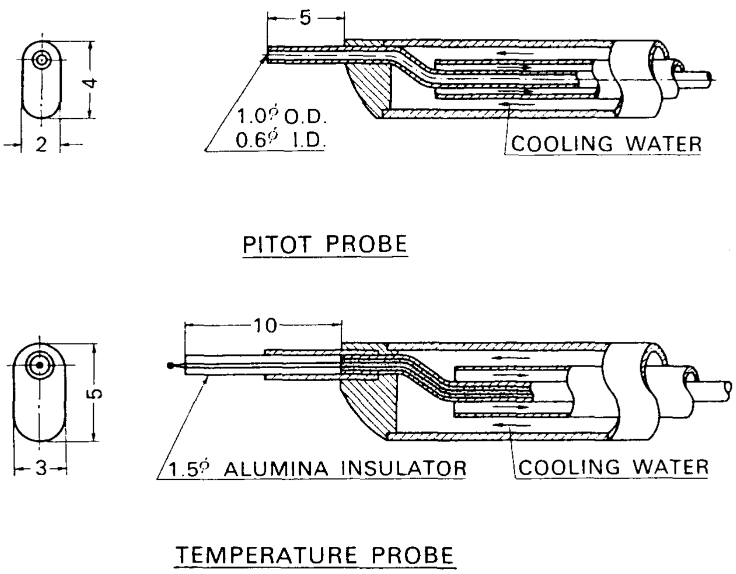


FIG. 2. Pitot Probe and Temperature Probe.

A 1.5 mm O. D. alumina insulator is installed in the front end of the probe to reduce the heat loss to the cooling water. Outer tube of each probe is flattened to an oval shape and bent at an angle of 90°. Longer dimension of the strut is oriented to the flow direction to decrease the aerodynamic loading and to increase the rigidity of the probe.

The measurement system constructed in the present study is shown schematically in Fig. 3. Pitot probe and temperature probe were mounted on an automatically operated traversing mechanism. The vertical location of the tips of the probes was measured using potentiometer installed in the traversing mechanism. Schlieren photographs were taken using a telephoto lens of which focal length was 2000 mm.

The flow rates of air, city gas, hydrogen and oxygen were calculated using calibrated

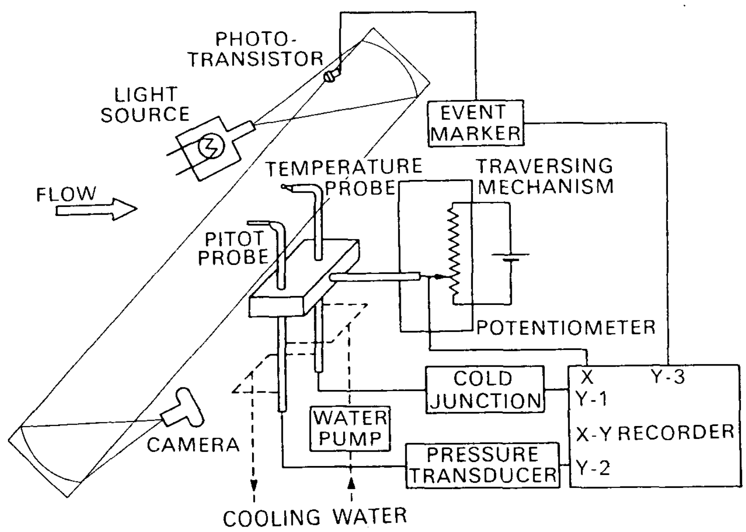


FIG. 3. Measurement System.

orifice plates installed in each feed line. The equivalence ratio of the city gas-air mixture in the gas generator was calculated from the respective flow rates. The flow rates and the equivalence ratio were reproducible within $\pm 0.1\%$.

The temperature and the pressure of the vitiated airstream were measured in the gas generator by a Pt-Pt 13% Rh thermocouple and a pressure transducer, respectively. The thermocouple tables were used to convert the thermocouple signals into temperature. And to convert the pressure transducer signals into absolute pressure, the pressure transducer calibration curves were used. The temperature and the pressure in the gas generator varied about $\pm 2\%$ from run to run.

The Mach number profiles of the supersonic vitiated airstream were proved to be uniform within $\pm 0.5\%$, and varied about $\pm 0.5\%$ from run to run. The temperature profiles of the airstream were proved to be uniform within $\pm 5\%$, and varied about $\pm 2\%$ from tun to run.

The injection pressure was regulated by an automatically operated control valve and was measured by a pressure transducer [*17*]. The injection pressure increased about 2% during injection, and varied $\pm 2\%$ from run to run.

Photographs of the manometer board and Bourdon gauges were developed, projected, and the pressures and mercury column heights were read and recorded. These recorded pressures were normalized by the instantaneous stagnation pressures in the gas generator to minimize errors due to small stagnation pressure variations in the vitiated airstream throughout the run.

The pitot pressure data measured by the pitot probes and the temperature data measured by the temperature probes at each survey point were keypunched and input into the data reduction computer program to yield values of Mach number and static temperature. These values were computed, assuming that the gas is perfect and using the equations for one-dimensional isentropic flow.

Probe position was measured with the potentiometer installed in the traversing mechanism and checked by evaluating schlieren photographs taken during each run with an accuracy of 0.1 mm.

4. Jet Interaction Flowfield with Nitrogen Injection

Data obtained from previous studies have made it possible to describe the jet interaction flowfield [*12*]. Some of the prominent features are shown in Fig. 4, which is a schematic diagram of a typical flowfield with the associated static pressure distribution of the wall. In this example, the jet is underexpanded, and the effective obstruction to the external supersonic flow that is produced by the jet is significantly larger than the undisturbed boundary layer thickness. At the beginning of the interaction, the static pressure on the wall rises to the separation pressure in about two boundary layer thicknesses and then rises more slowly to a first maximum or plateau value. The pressure rise in the plateau region corresponds to that which occurs when an inviscid flow is turned through the angle equal to the separation angle.

Instantaneous schlieren photographs were taken, in the present study, for hot airstream conditions to determine the differences in flow geometry among various nitrogen injection pressures. Schlieren photographs for two injection pressures are shown in

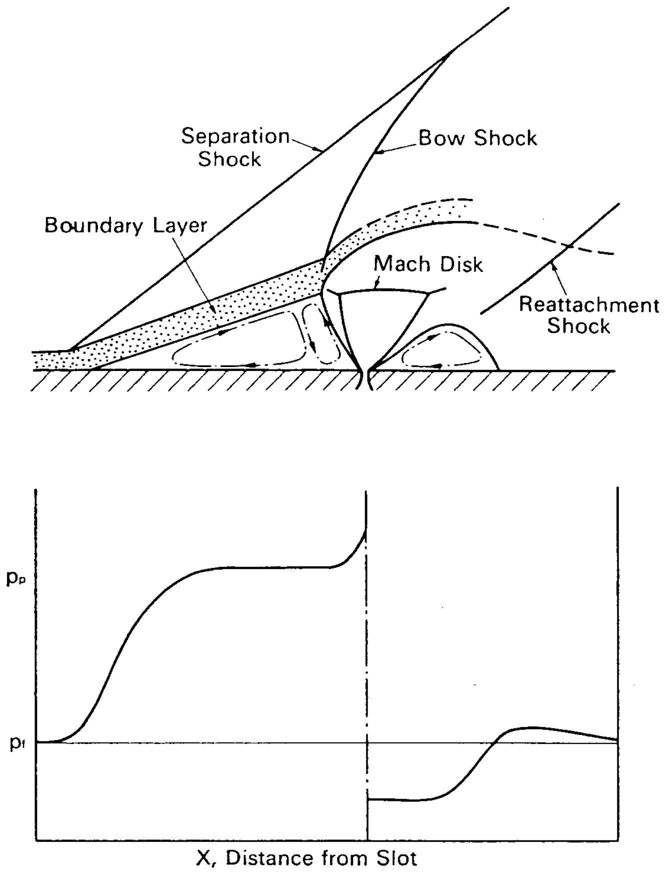
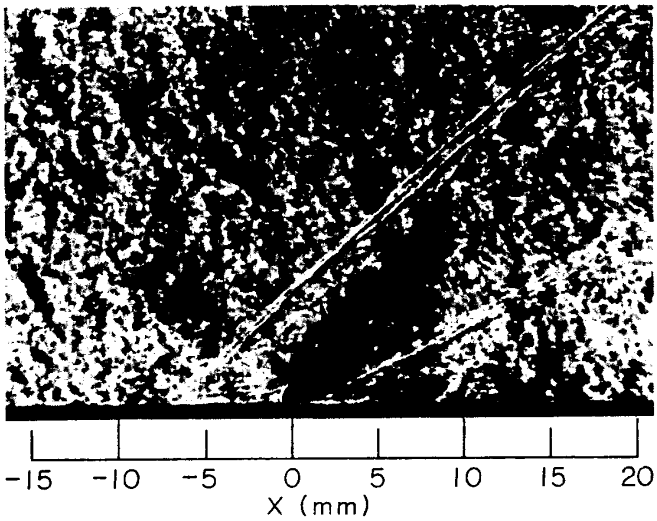


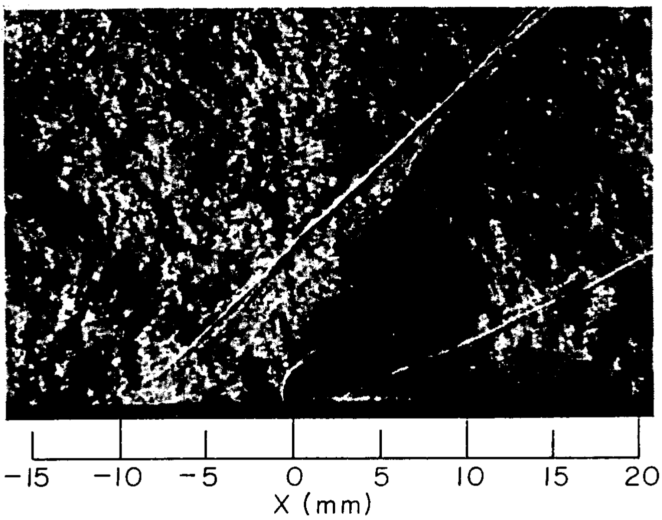
FIG. 4. Two-Dimensional Jet Interaction Flowfield.

Figs. 5 (a) and (b). For these examples, nitrogen enters the supersonic airstream through a slot nozzle, with a static pressure much higher than that of the undisturbed airstream. The flow is sonic at the injector exit and expands rapidly through a strong Prandtl-Meyer fan. The interaction of the two streams produces a strong bow shock on the upstream side of the injector, and the shock-induced pressure field turns the injectant until it moves approximately parallel to the wall. The injection pressure is so high that the jet height is larger than the undisturbed boundary layer thickness and the jet is exposed to the momentum of the supersonic airstream and is displaced. Therefore, the first Mach disk is inclined. The interaction between the bow shock and the boundary layer produces a region of the boundary layer separation upstream of the shock. For the case of the turbulent boundary layer, the separated region is short, and the oblique shock produced by separation is usually sufficiently strong to be observed. If the boundary layer is laminar, the separated region is much longer, and the angle between the separated flow and the wall is never more a few degrees [*18*]. Since typical features of the turbulent boundary layer were observed in the present study, the boundary layer of the airstream over the flat plate model was always turbulent within the range of conditions available without artificial boundary layer trips.

Some details of the flow near the jet are also shown in the photographs. As observed in the previous studies [*18*], [*19*], the streak indicating the injectant path was observed for nitrogen injection. Determination of the maximum distance between this streak



(a) $p_{oj}/p_f=18.6$.



(b) $p_{oj}/p_f=27.3$.

FIG. 5. Instantaneous Schlieren Photographs of Jet Interaction Flowfield with Nitrogen Injection.

and the wall gives a simple visual measure of the penetration of the injectant into the supersonic airstream.

Additional informations were obtained from wall static pressure measurements. The ratio of the wall static pressure to free stream pressure, p_d/p_f, is plotted for several injection pressures in Fig. 6 against x/d_s, where x represents coordinate parallel to the flat plate, measured from the sonic nozzle, and d_s sonic nozzle width. The wall static pressure distributions also show that the boundary layer at the location of the slot nozzle is fully turbulent. The strong dependence of the wall static pressure distributions on the injection pressure observed in this figure is very similar to that presented in Ref. 10. As would be expected, the wall pressure rose above the ambient value near the intersection of the shock system and the wall. Immediately upstream of the jet was a region where both injectant and airstream recirculated and the wall static pressure

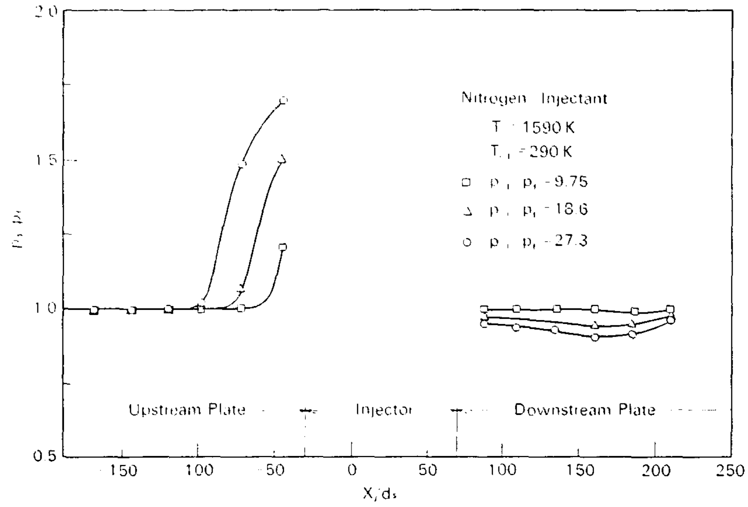


FIG. 6. Variation in Wall Static Pressure with Injection Pressure.

was found to be 1.70 atmospheric pressures. This value is found to be in good agreement with published data if we consider the similarity between boundary layer separation upstream of two-dimensional, transverse jets and forward facing steps [*20*]. Downstream of the jet was a region in which injectant flow separated from the wall and in which the pressure was far below the ambient value [*21*]. The pressure died out as the distance downstream from the jet increased.

The average distance to the intersection of the extrapolated separation shock with the plate agrees well with the distance to the start of the separation pressure rise. However, the separation shock location was definitely unsteady and was observed to move upstream and downstream of the average separation point. The nitrogen injection pressure was limited below 2.94×10^6 Pa due to the limitation of the supply system and the plateau pressure could not be observed distinctly. Therefore, the well-known "amplification" of simple jet thrust could not be obtained.

The separation angle formed by the wall and a line drawn from the separation point to the top of the jet is approximately 14° and this value agrees with that presented in Ref. 10.

5. JET INTERACTION FLOWFIELD WITH HYDROGEN INJECTION

To determine the effect of the injectant molecular weight on the jet interaction flowfield, hydrogen was used as the injectant, and injected under the same airstream conditions as those with nitrogen injection. For the case of hydrogen injection, a bulk flame was stabilized far downstream of the test section where the supersonic airstream mixed with the ambient quiescent air. To examine the effect of the injectant molecular weight in the hot supersonic airstream, it is necessary that the chemical reaction does not occur in the flowfield near the slot nozzle. Although the luminosity was not observed visually in this region, the possibility of the chemical heat release in this region could not be eliminated because of the non-luminosity of the flames of hydrogen with air. To investigate these problems, temperature distributions of the flowfield with the bulk flame formed far downstream were measured directly in detail and it was determined whether chemical heat release in the flowfield near the slot nozzle was significant or not.

Temperature measurements were made using Pt-Pt 13 % Rh bare wire thermocouples. Figure 7 shows the vertical temperature distributions at various streamwise locations. In this figure, y represents coordinate normal to the flat plate and T_{oa} stagnation temperature measured by the temperature probe. In this case, the airstream stagnation temperature was 1570 K, and the pressure ratio of the injectant was 26.0. In Fig. 7, in the region upstream of $x/d_s=127.7$, the temperature which is almost uniform

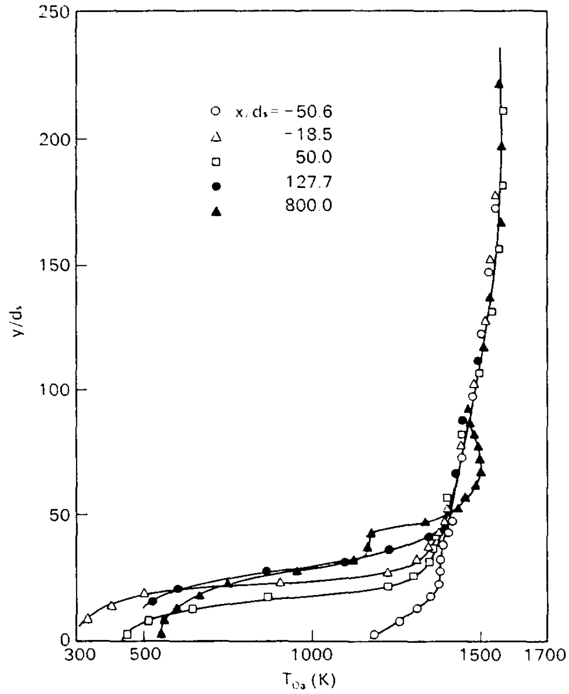


FIG. 7. Vertical Temperature Distributions with the Bulk Flame.

in the middle of the airstream decreases monotonously near the plate surface. In the upstream separated region, no chemical heat release is observed and, therefore, a part of the injected cold hydrogen only mixes with air and recirculates in this region. The thickness of the separated region increases rapidly and it is equal to the jet penetration height at the injection location, where the jet penetration height is maximum. The jet penetration height decreases gradually downstream of the injection location. In the downstream region near the injection location, no chemical heat release is observed. On the other hand, the temperature peak appears at $x/d_s=800.0$ where the bulk flame existed. The shocks induced by the fuel injection might cause the complicated shock and rarefaction waves in the downstream supersonic region where the supersonic vitiated airstream mixed with the ambient quiescent air. Behind these compression waves, the static temperature rises and the velocity of the airstream decreases. Therefore, the bulk flame may be stabilized in these regions.

From these experimental results, it can be concluded that the flowfield near the slot nozzle where the airstream is not disturbed by the mixing with the ambient quiescent air is not influenced by the chemical heat release even though the airstream stagnation

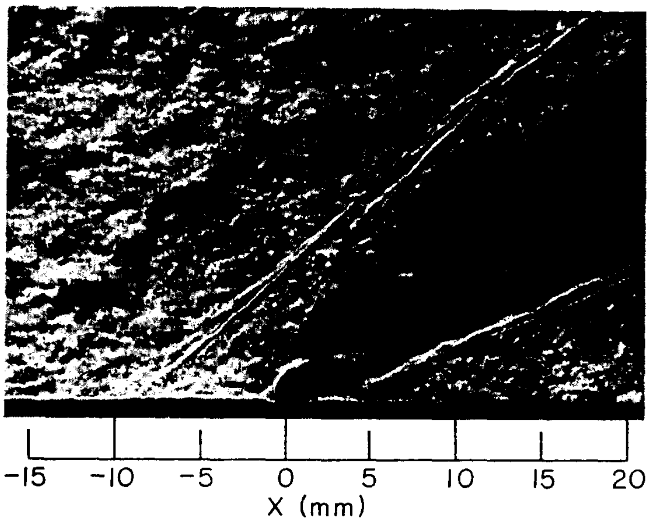


FIG. 8. Instantaneous Schlieren Photograph of the Flowfield with Hydrogen Injection, $T_o=1540$ K, $p_{oj}/p_f=26.4$.

temperature was as high as 1570 K. Therefore, this flowfield can be treated as that with no chemical reaction.

Figure 8 shows an example of the schlieren photographs taken for hydrogen at various injection pressures. This photograph was taken at the airstream stagnation temperature of 1540 K, and the pressure ratio of the injectant of 26.4. Comparing Figs. 5 (b) with 8, several differences are observed between hydrogen and nitrogen jets. Nitrogen jet expands more laterally than hydrogen jet and the upstream edge radius of the nitrogen jet is smaller than that of hydrogen. The jet normal shock heights of hydrogen and nitrogen jets injected at equal injection pressures appear almost identical. This observation agrees with shock height measurements in quiescent atmospheres [*22*]. However, the detailed examination of these schlieren photographs shows that the shock height of the hydrogen jet is slightly less than that of the nitrogen jet. This is probably due to a slightly smaller effective slot width for hydrogen due to a lower

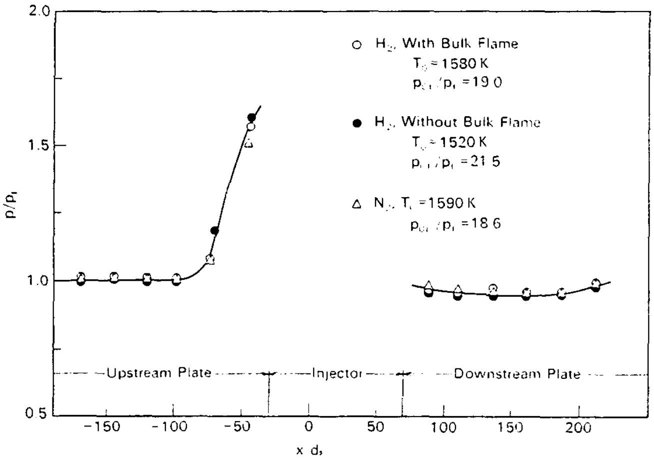


FIG. 9. Wall Static Pressure Distributions of Hydrogen and Nitrogen Jet Interaction Flowfield.

discharge coefficient. The streak which is observed for nitrogen jet and indicates the injectant path is not observed for hydrogen jet. However, no consistent differences in other respects, such as bow shock angle, separation distance and separation shock angle exist between hydrogen and nitrogen jets.

Figure 9 shows the wall static pressure distributions of hydrogen and nitrogen jet interaction flowfields at nearly equal injection pressures. From Fig. 9, it is obvious that the separation distance does not change with the injectant. This observation agrees with that obtained from schlieren photographs. This figure shows also a good agreement in the static pressure levels between hydrogen and nitrogen jets within the experimental error.

In these experimental results, significant differences in flow geometry and also in the wall static pressure distributions between hydrogen and nitrogen jets are not observed within the limited range of the present experimental variables. Therefore, the effect of the injectant molecular weight on the jet interaction flowfield is thought to be rather small.

6. Chemical Reaction in the Upstrean Separated Region

In the preceding phase of the investigation, it was proved that, if the oxygen concentration in the vitiated airstream was as low as 10%, the chemical reaction in the upstream separated region was not observed even at the extreme conditions available in the present study. The oxygen concentration in the vitiated airstream was considered to have a strong influence on the chemical reaction as the airstream temperature. Therefore, a series of experiments were carried out in which oxygen was added to the vitiated airstream, keeping the airstream stagnation temperature constant at about 1530 K. The amount of oxygen was increased until chemical reaction in the upstream separated region took place. Oxygen was added to air before entering the combustion chamber of the gas generator, the total flow rate of oxygen and air being constant at 1440 Nm^3/h. The city gas flow rate was held constant at maximum value of 160 Nm^3/h. The pressure ratio of the injectant was kept constant at 25.0 throughout this series of experiments.

With increasing the oxygen concentration, chemical reaction took place in the upstream separated region. For the small amount of oxygen added, however, chemical reation in the upstream separated region was unstable and the luminosity of this region was weak. When the amount of oxygen to be added was increased until the oxygen concentration became 13.5%, chemical reaction in the upstream separated region became stable and the luminosity increased. At the same time, after a small induction zone a weak turbulent flame which could not be photographed but could be observed visually appeared immediately downstream of the hydrogen jet. Figure 10 is the close-up of the luminous upstream separated region. This photograph was taken at the oxygen concentration of 13.5% which was about 4% higher than that used in the experiments of non-reactive jet interaction flowfield. Further increase in the oxygen concentration led again to the unstable ignition and weak luminosity in the upstream separated region. This is probably due to the small decrease of the airstream stagnation temperature with increasing the amount of the oxygen added.

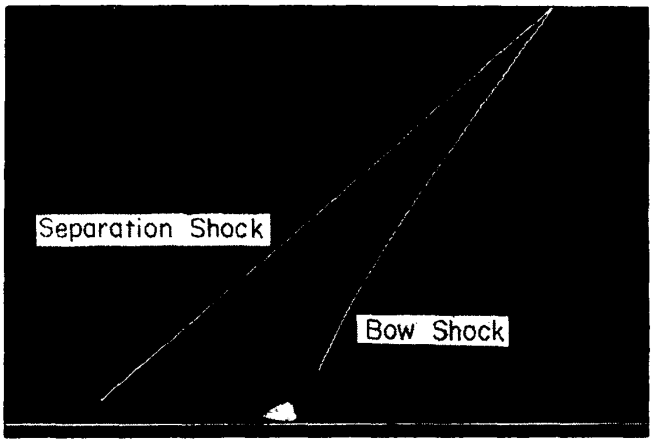


FIG. 10. Close-up of the Luminous Upstream Separated Region, $T_o = 1530$ K, $p_{oj}/p_f = 25.0$.

From this series of experiments, it is found that chemical reaction takes place in the upstream separated region and that after a small induction zone a weak turbulent flame appears and it spreads into the bulk flame far downstream of the jet. In this case, chemical reaction occurs in the upstream separated region with strong emission and the weak turbulent flame is stabilized near the slot nozzle. These regions are neither disturbed by the turbulent mixing with the ambient quiescent air nor influenced by the compression and rarefaction patterns which exist in the downstream region.

The reacting upstream separated region was bright blue, while the weak turbulent flame was faint blue-violet as is observed in the usual hydrogen air flame. The bright blue coloration in the upstream separated region is due to the carbon monoxide contained considerably in the vitiated airstream.

6.1 Effects of Chemical Reaction on Jet Interaction

Changes in the jet interaction flowfield due to chemical heat release in the upstream separated region and the downstream region were investigated by comparing the wall static pressure data and the schlieren photographs. Figure 11 shows an example of the instantaneous schlieren photographs of the jet interaction flowfield with chemical reaction. This photograph was taken at the airstream stagnation temperature of 1540 K and the oxygen concentration in the vitiated airstream of 13.7%. Hydrogen was injected at the pressure ratio of the injectant of 25.6. Comparing this figure with Figs. 5 (b) and 8 which show the non-reacting flowfield near the sonic nozzle, several differences between the non-reacting and the reacting cases are evident. In particular, it is found that the separation distance changes significantly due to chemical heat release in the upstream separated region. The increase in the separation distance is observed during all runs with chemical reaction. The chemical heat release in the upstream separated region does change neither separation shock angle, bow shock angle, nor Mach disk height (jet penetration height) in comparison with those of non-reacting jet of equal injection pressure. However, the reattachment shock which was produced downstream of the jet differs in shape substantially between these two cases.

When chemical reaction occurred in the upstream separated region, considerable

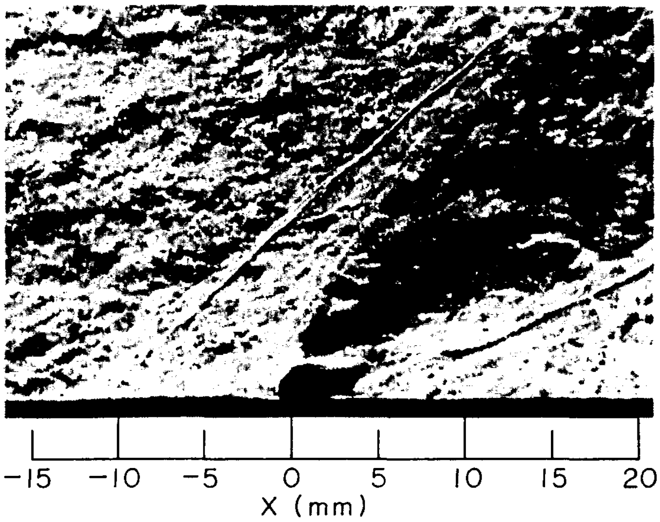


FIG. 11. Instantaneous Schlieren Photograph of the Jet Interaction Flowfield with Chemical Reaction, $T_o=1540$ K, $p_{oj}/p_f=25.6$.

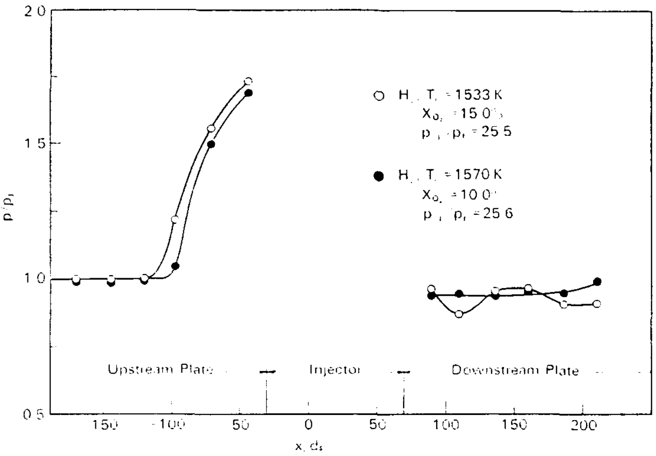


FIG. 12. Wall Static Pressure Distributions with and without Chemical Heat Release.

changes in the wall static pressure distributions were observed in the experiments. Figure 12 shows the wall static pressure distributions with and without chemical heat release at almost identical hydrogen injection pressures. Reacting data were taken at the airstream stagnation temperature of 1533 K and the oxygen concentration in the vitiated airstream of 15.0%. On the other hand, non-reacting data were obtained at the stagnation temperature of 1570 K and the oxygen concentration of 10.0%. Figure 12 shows that the separation distance increases significantly due to chemical heat release in the upstream separated region. This behavior was identical to that observed in the schlieren photographs. For the case of the pressure ratio of the injectant of 25.5, the twenty percent increase in the separation distance was observed. This increase improves the effectivity of the reaction control jet. The wall static pressure distributions downstream of the sonic nozzle also appear to be affected by the weak turbulent flame produced in the downstream region. However, the consistency in the differences could not be observed in the present study.

That the chemical reaction has some effects on the upstream separated region is not surprising, considering that the temperature in this region is high. The increase in the separation distance observed must be caused by the displacement of the external airstream due to chemical heat release. Considering the similarity between boundary layer separation upstream of two-dimensional, transverse jets and forward facing steps, data obtained using forward facing steps which has been accumulated can be useful to explain the experimental results obtained in the present study. In the case of the forward facing steps, wall pressure level is independent of the step heights when the step heights are larger than the boundary layer thickness [*20*]. The increase in the separation distance corresponds to the increase in the step height. Therefore, the increase in the separation distance does not lead to the changes in the wall pressure level. Moreover, the wall pressure was found to correlate with the separation Reynolds number [*6*]. Therefore, although the plateau pressure could not be observed distinctly in the present study, it can be deduced that the chemical heat release in the upstream separated region affects only the separation distance and that the pressure level is not affected by it.

6.2 Temperature Distributions

To determine the degree of chemical heat release in the jet interaction flowfield with chemical reaction, temperature distributions were measured at various streamwise locations. Figure 13 shows the vertical temperature distributions at five streamwise locations. The airstream stagnation temperature was 1540 K and the oxygen concentration in the vitiated airstream was adjusted to 13.5%. The pressure ratio of injectant

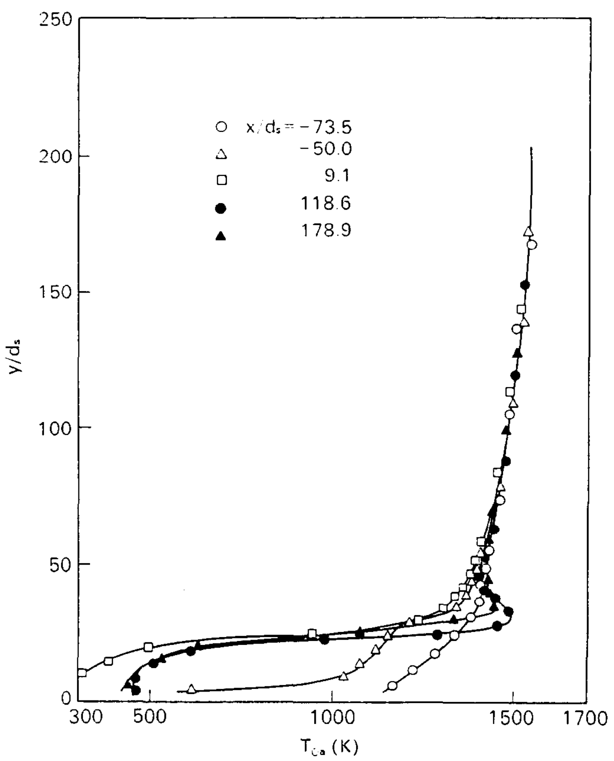


FIG. 13. Vertical Temperature Distributions of the Flowfield with Chemical Reaction.

was held constant throughout these experiments at 25.0. The temperature profiles at $x/d_s = -73.5$ displays that, with approaching the plate surface, the temperature decreases gradually in the undisturbed supersonic airstream at a small gradient and rapidly in the upstream separated region. On the other hand, at $x/d_s = -50.0$, a bulge of the temperature profile appears in the region where the temperature decreases rapidly toward the plate surface. This bulge of the temperature profiles is considered to result from chemical heat release in the upstream separated region. Since this bulge appears only in the downstream part of the separated region, the exothermic chemical reaction occurs in this restricted region. At $x/d_s = 9.1$, this bulge of the temperature profile disappears. From the visual observations, it has been proved that this region corresponds to the induction zone. Downstream of $x/d_s = 118.6$, a temperature peak which appears in the mixing layer between the vitiated airstream and the hydrogen flow is seen in each temperature profile. The peak value is about 1500 K and at most 130 K higher than the surroundings. By comparing these temperature profiles with the visual observations, it is evident that the peak locations correspond to those of the weak turbulent flame.

From direct temperature measurements, it is confirmed that the temperature in the upstream separated region is about 1100 K and that the chemical heat release occurs only in the downstream part of this region. These facts suggest that, although the chemical heat release is relatively small, it largely increases the extent of this region. These observations are in good agreement with those using the direct colour photographs. The temperature value is not so high as that observed in the usual hydrogen air flame. This may be attributed to the fact that in this region only rapid binary reactions may occur which are weakly exothermic and that strong exothermic reactions such as recombinations of radicals and free atoms via three-body collisions scarcely occur. The separated turbulent boundary layer containing these reactive species passes over the jet and mixes with hydrogen gradually. It is found from comparison of temperature distributions with schlieren photographs that the temperature peak appears downstream of some point where the reattachment shock crosses the mixing region of airstream and hydrogen. Behind the reattachment shock the static temperature and pressure increase and the velocity decreases, and the turbulent flame is produced in this region.

6.3 Pitot Pressure Distributions

To determine the influence of chemical reaction on the jet interaction flowfield, pitot pressure measurements were carried out at various streamwise locations. Since the pitot probe was maintained in a fixed direction parallel to the airstream, it had to be calibrated to provide corrections for the local flow angle. However, this correction was not made in the present study. In addtion, the pitot pressure measurements made in the vicinity of the shock wave involved intersecting shocks which were generated by the interaction between the shock waves occurring originally in the flowfield and that generated by the pitot probe, so that direct correction of such measurements was impossible. In these instances, data in the shock vicinity had to be interpreted by extrapolation of nearby measured data. Reproducibility of results was quite good as the temperature measurements. The degree of the probe interference was checked

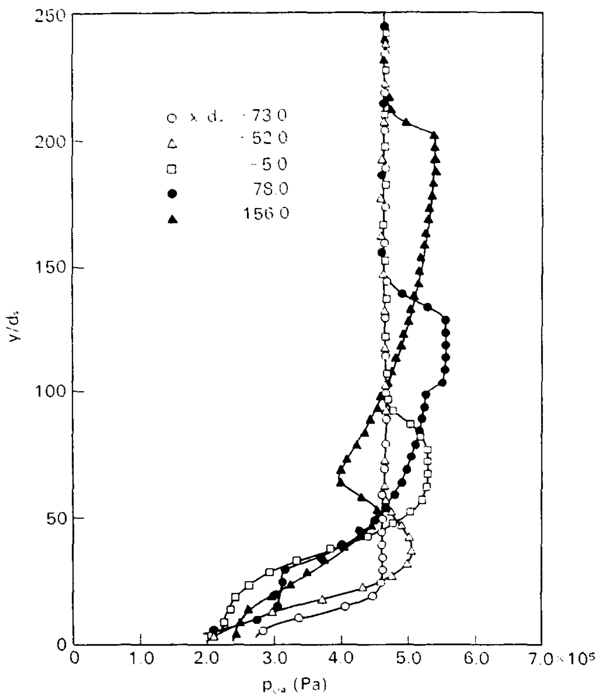


FIG. 14. Vertical Pitot Pressure Distributions of the Flowfield with Chemical Reaction.

by the wall static pressure distributions and the schlieren photographs.

Figure 14 shows the vertical pitot pressure distributions at five streamwise locations. The vitiated airstream and the injectant conditions were same as those used in the temperature measurements; the stagnation temperature and the oxygen concentration in the vitiated airstream were 1540 K and 13.5%, respectively, and the pressure ratio of the injectant was held constant at 25.0. In Fig. 14, the pitot pressure profile at $x/d_s = -73.0$ displays a fairly uniform pressure of 4.65×10^5 Pa in the inviscid supersonic flow region and a rapid decrease in the separated boundary layer near the plate surface. At $x/d_s = -52.0$ and -5.0, a small bulge appears in each pressure profile. By comparing these figures with schlieren photographs, it is proved that each pressure bulge exists in the region between the separation shock and the separated region. In this region, the supersonic flow is decelerated by the separation shock. Downstream of the hydrogen jet, the pitot pressure profiles are different from those of upstream region. With approaching the plate surface from the middle of the airstream, the pitot pressure suddenly increases and then gradually decreases. The point of sudden increase corresponds to the bow shock position. Immediately behind the bow shock, the supersonic flow is decelerated and the pitot pressure is higher than that of the undisturbed supersonic flow. In the region confined by the bow shock and the jet boundary, the supersonic flow which has passed through the bow shock changes its direction over the jet boundary near the injection location, expansion wave starts and the Mach number of the flow increases. Therefore, the pitot pressure decreases with approaching the jet boundary and the peak value gradually decreases with increasing the distance from the injection location. After the pitot probe has crossed the reattachment shock, the pitot pressure again increases because of the supersonic deceleration. Near the plate surface it decreases in the boundary layer because of the subsonic deceleration.

The pitot pressure profile at $x/d_s = -5.0$ shows that the pitot pressure level in the decelerated region between the separation shock and the separated region is higher than that at $x/d_s = -52.0$. If the separated region forms a wedge shape and the flowfield is strictly two-dimensional, the pitot pressure level in this decelerated region should be constant. On the other hand, the flow around a sharp nose body of revolution behind the attached shock is known to be decelerated isentropically to the body surface condition. Therefore, the pitot pressure increase observed in the present study may perhaps result from the three-dimensionality of the upstream separated region. Several causes are considered of three-dimensionality observed in the pitot pressure measurements. These can be separated into the effects which the probe has on the flowfield and the characteristics of the jet interaction flowfield of a finite-span jet which is essentially three-dimensional. For the case of the finite-span jet, the separation distance decreases as compared with that of the two-dimensional jet and strong lateral flows from the upstream separated region exist. The three-dimensional effects will certainly influence the centerline wall static pressure distributions when the ratio of the penetration height to the slot nozzle span is as small as 0.05 [*10*]. In the present study, this ratio roughly estimated using the schlieren photographs was found to be approximately 0.2. Therefore, the wall static pressure distributions may be affected by the three-dimensional effect. Penetration height of the jet is maximum at the center of the slot and minimum at the extremities of the slot and the separated region forms not the wedge shape but a part of a cone. The flow between the separation shock and the separated region is decelerated over the cone shaped separated region.

From pitot pressure measurements, it is confirmed that the influence of the chemical reaction in the supersonic airstream on the jet interaction flowfield is small in the range of experimental conditions.

7. CONCLUSIONS

The extensive experimental investigation was conducted on interaction of inert and chemically reactive gaseous jets with hot supersonic airstream. Experimental work has carried out in the Mach 1.81 supersonic combustion wind tunnel, which uses the city gas-air combustion gas as a test medium. Highly underexpanded hydrogen and nitrogen jets have been injected from a converging slot nozzle of a flat plate perpendicular to a uniform, Mach 1.81 vitiated airstream. In the experiments, temperature and oxygen concentration of the vitiated airstream, and injection pressure have been changed, including conditions at which the chemical reaction in the upstream separated region occurred. Conclusions based on this investigation of the inert and chemically reacting flows are summarized below.

(1) The structure of the two-dimensional, inert jet interaction flowfield inferred by a number of investigators was confirmed by schlieren photographs and wall static pressure distributions.

(2) The separation distance is increased about twenty percent by the chemcial reaction in the upstream separated region. This increase improves the effectivity of the reaction control jet. Downstream of the jet, after a small induction zone, the weak

turbulent flame is formed in the mixing region between the supersonic airstream and the injected hydrogen.

(3) Temperature in the upstream separated region is about 1100 K. This low value indicates that the reaction of hydrogen with air can not be completed in this region. The reacting separated region is the source of the reactive species such as radicals and free atoms which are required for the exothermic reactions in the main turbulent flame. The separated turbulent boundary layer containing these reactive species passes over the jet and mixes with hydrogen gradually and behind the reattachment shock the turbulent flame is produced.

(4) The effect of the chemical heat release in the supersonic airstream on the jet interaction flowfield is unexpectedly small in the range of present experimental conditions.

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