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Tangential Injection from Overlaid Slots into a Supersonic Stream

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The results of an experimental study of tangential supersonic slot injection into a supersonic airstream with tangential subsonic injection through an additional slot above the main slot is presented. Such a flow is of interest for at least two propulsion-related applications. First, one can simulate a near-separation boundary-layer profile by subsonic injection through the upper slot, which is then to be re-energized by supersonic injection through the lower slot. Second, this flow is also of interest for application to fuel/oxidizer/pilot injection from multiple overlaid slots. The experiments were performed in an intermittent, vacuum wind tunnel at a freestream Mach number of 2.85. The supersonic injectant had a Mach number of 2.00, and the subsonic injection was at Mach numbers of 0.26 and 0.72. The results are presented in the form of spark schlieren photographs, interferograms, and wall-static pressure measurements. Density profiles at several axial locations determined from the interferograms are presented, as well as streamwise and spanwise static pressure distributions. The major conclusions drawn from the tandem injection results, are first, that a near-separation boundary-layer profile can be simulated in this way. Next, tandemly injected subsonic and supersonic flow can be divided into separate components that closely resemble the respective individual injections into an undisturbed freestream. Also, the effects of the subsonic injection were completely mixed out at a downstream location of six slot heights. Therefore, adverse-pressure-gradient-inducing devices should be positioned at least six slot heights downstream of the supersonic injection station if the effects of supersonic injection into a near-separation boundary layer for the purpose of re-energizing it are to be studied.

Nomenclature

a = slot height
M = Mach number
p = pressure
S = test section span
T = temperature
u = x component of velocity
v = y component of velocity
x = streamwise coordinate
y = normal coordinate
z = spanwise coordinate
ρ = density

Subscripts
b = conditions in the subsonic injection slot flow
j = conditions in the supersonic injection slot flow
t = total or stagnation conditions
1 = conditions in the undisturbed freestream

Introduction

THE tangential injection of a fluid into a moving stream by means of a wall slot has been suggested as a solution to several aerodynamic problems. For example, it is sometimes used to provide thermal protection for aerodynamic surfaces. Slot injection in this case would supply a protective layer of fluid next to the exposed aerodynamic surface. Interest has also been expressed in combining thermal protection with a gaseous-fuel-injection system for supersonic combustion engines. Therefore, much attention has been focused on injection into a supersonic or hypersonic external flow.

There has also been consideration of the possibility of re-energizing a freestream boundary layer on the verge of separation by a jet of subsonic or supersonic fluid, so that it may then continue downstream a considerable distance into a further pressure gradient without separating. It is this concept that mainly stimulated the work that is presented in this article. Results of experiments conducted by Schetz et al.,[1] at freestream conditions identical to those in this study, have shown that subsonic injection into a supersonic freestream could substantially reduce the capability of the boundary layer to negotiate an adverse pressure gradient. The effects on the boundary layer were measured by forcing the flow over surface wedges downstream of the injection station and noting that the boundary layer separated more easily with upstream subsonic injection than it did without injection. Based on these results, a tandem slot injection device was built. The notion is that one can simulate a near-separation boundary-layer profile by subsonic injection through an upper slot, which is then to be re-energized by supersonic injection through a lower slot. An illustration of the flowfield produced by tandem injection into a supersonic stream is shown in Fig. 1. This general flowfield is also of interest for fuel-injection schemes employing overlaid so-called stacked injectors. One could have fuel out of one slot and an oxidizer or pilot jet out of the other slot.

The experimental work was conducted in an intermittent vacuum wind tunnel at a freestream Mach number of 2.85, and the principal results are presented in the form of 0.4-μs spark schlieren photographs, wall-pressure distributions, and the results of interferometric studies. The density profiles generated from interferograms are presented for several downstream axial locations.

Many experimental studies of the various aspects of slot injection into supersonic flow have been performed.[2–13] However, none of these considered the effects of two slots, one over the other.

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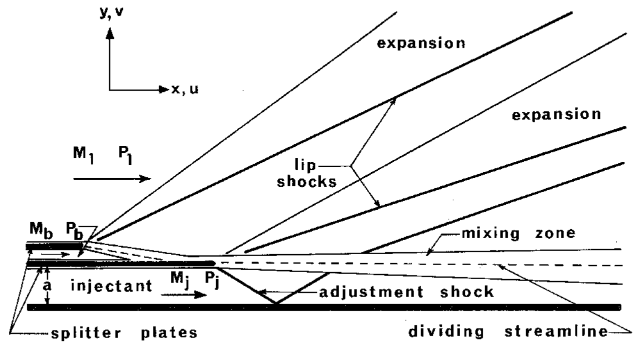

Fig. 1 Flowfield for tandem slot injection into a supersonic freestream.

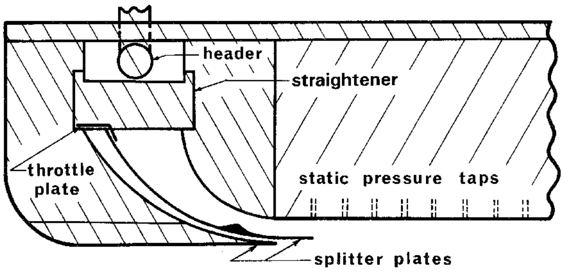

Fig. 2 Sketch of tandem slot injection model.

Experimental Apparatus and Procedure

The experiments were conducted in a 15.2 × 15.2 cm supersonic wind tunnel of an intermittent vacuum type. The conditions of the surrounding air at the tunnel intake were assumed to be atmospheric and constant throughout each tunnel operation, making the total pressure and temperature 1 atm and 300 K, respectively. For these experiments, the tunnel was fitted with a nozzle block that provided a freestream Mach number of 2.85, giving a Reynolds number per meter of 8.2×10^6.

The injection model used was a modification of one used previously for both subsonic and supersonic slot injection studies.[1,7] The modifications included the insertion of a dividing plate into the basic subsonic model configuration, and the dividing surface was constructed to provide different internal contours for the inner and outer passages. One was designed to provide subsonic flow, whereas the inner was fabricated to provide supersonic injection at Mach 2.0, as shown in Fig. 2. The viscous flowfield produced by the subsonic injectant and the freestream boundary layer together can then be considered as the initial outer boundary-layer profile for the supersonic injectant. Throttling of the subsonic passage flow was necessary to prevent this flow from becoming sonic at the injector exit. The complete model assembly formed the upper part of the tunnel half-nozzle and part of the tunnel upper wall with the splitter plate positioned along the plane of symmetry of the test section. The distance between the tunnel nozzle throat and the subsonic injection point was 14 cm. The supersonic injection station was 2.5 cm farther downstream. The test section rhombus began 1.2 cm before the subsonic injection point, thus ensuring that both injection stations and all downstream pressure taps were enclosed within the uniform flow region.

The splitter plates were made of brass, with their trailing edges machined as thin as practical to eliminate any undesirable effects caused by a trailing-edge wake. The outer splitter plate trailing edge was 0.13 mm thick, whereas the tip of the inner trailing edge was feathered to a sharp edge approximately 0.08 mm thick. The supersonic injection slot height measured 9.5 mm, and the subsonic injection slot was 2.4 mm high.

Visualization of the flow by spark (4×10^{-7} s) schlieren and Mach–Zehnder interferometric methods provided a major part of the experimental results. The interferometer employed a mercury arc lamp with an interference filter centered at 4367 Å and a camera with Polaroid type 57 film at a shutter speed of 1 ms. The interferometer photographs were used to determine density profiles at various downstream locations. The uncertainty in the density profiles is approximately 10%.

Tandem injection tests were conducted at two different mass flow rates. The supersonic injection was at Mach 2.0 for both tests, whereas the freestream Mach number was 2.85. The subsonic injection was at Mach 0.26 and 0.72.

Results

Tangential injection into a moving freestream may be performed in three modes: 1) subsonic, 2) sonic, and 3) supersonic. Investigations of all three types of injection were conducted by Schetz et al.[1] and Gilreath[7] at the same flow conditions as those of this report. The two types of injection that are pertinent here: 1) subsonic and 2) supersonic, are now described briefly.

A photograph and schematic representation of low-subsonic injection into a supersonic freestream are presented in Fig. 3. At low injection rates, the flowfield is seen to closely resemble the flow over a rearward-facing step. The large corner expansion and following lip shock are easily identified. At higher injection rates, the initial amount of expansion is reduced along with a correspondingly higher initial static pressure and a less severe recompression. The adjustment between the two streams that determines the initial injectant static pressure depends primarily on the mixing rate. The mass flow rate per unit area of the freestream is greater than that of the injectant flow, therefore, any mixing will cause the dividing streamline to deflect toward the lower wall. Independent choices of pressure and Mach number (or pressure and mass flow rate) cannot be made for subsonic injection, since the Mach number corresponding to a given initial pressure is determined by the interaction with the external flow.

Three different conditions of flow are possible when the injectant flow is supersonic: 1) overexpanded, 2) fully expanded, and 3) underexpanded. These conditions correspond to the static pressure at injection being less than, equal to, or greater than the static pressure of the freestream, respectively. A schematic and spark schlieren of a slightly overexpanded case are shown in Fig. 4. Observations have shown that the initial adjustment between the injected flow and the freestream occurs as a shock wave in the injectant with an expansion preceding a lip shock in the freestream. The reflection of the adjustment shock at the wall is followed by an interaction with

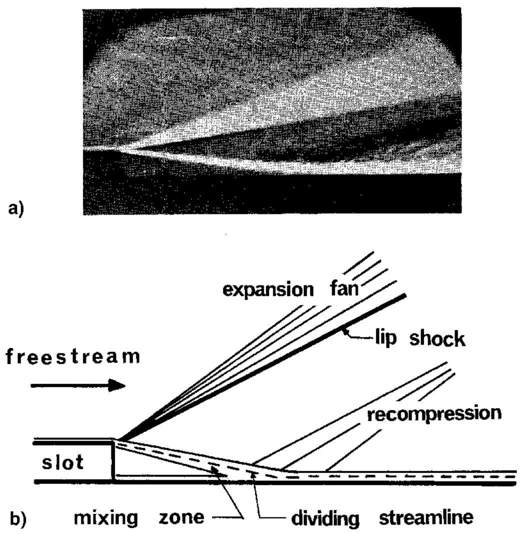

Fig. 3 Single-slot subsonic injection: a) spark schlieren, $M_1 = 2.85$, $M_j = 0.290$ (Ref. 1) and b) sketch of the flowfield.

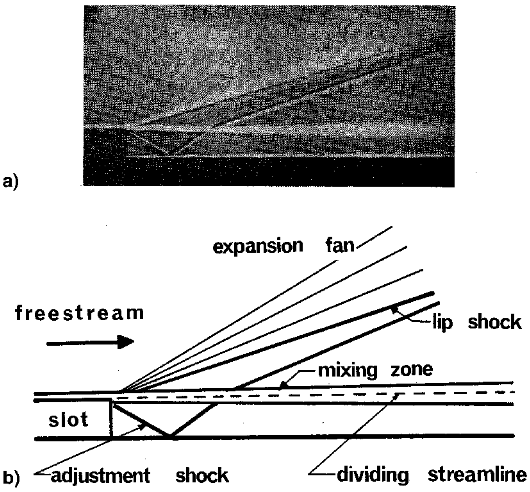

Fig. 4 Single-slot supersonic injection: a) spark schlieren, M_1 = 2.85, M_j = 2.00 (Ref. 1) and b) sketch of the flowfield.

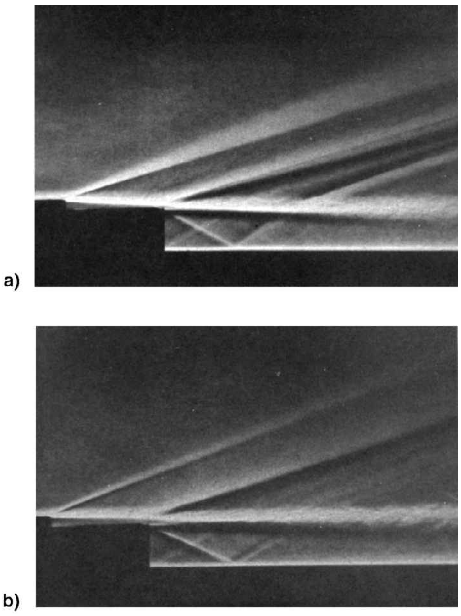

Fig. 5 Tandem slot injection (M_1 = 2.85): a) M_j = 2.00, M_b = 0.257 and b) M_j = 2.00, M_b = 0.715.

the mixing layer where part of the incident wave is transmitted and part is reflected.

Experiments reported in Ref. 1 with subsonic injection had shown that subsonic injection into a supersonic freestream resulted in weakening the ability of the flow to negotiate an adverse pressure gradient induced by a downstream wedge, contrary to the case of the freestream boundary layer flowing over the wedges without upstream injection. Those results led to the formulation of the tandem injection studies reported here. It was felt that a near-separation boundary layer could be simulated at the supersonic injection station by an upstream subsonic injection.

Spark schlieren photographs in Fig. 5 and the corresponding wall pressure distributions in Fig. 6 are presented for two injectant mass flow rates. The flowfield near the subsonic injection region closely resembles the subsonic injectant flow shown in Fig. 3. The expansion region emanating from the trailing edge of the outer splitter plate and the recompression zone are readily identifiable in Figs. 5a and 5b. The greater deflection of the dividing streamline indicated by the shear layer is also very noticeable for the case of the lower subsonic Mach number, and thus mass flow rate, in Fig. 5a. The smaller expansion zone in Fig. 5b is explained by the higher Mach number and mass flow rate that corresponds to a higher initial injectant pressure for this case.

The supersonic portion of the tandem injection (the lower jet) has the same general flow characteristics as the single-slot supersonic injection case shown in Fig. 4. A slight expansion with a terminating lip shock is noticed just after the lower splitter plate trailing edge. The adjustment shock can easily be identified as it impinges upon the lower wall and thickens the boundary layer in that area. After the shock reflects from the lower wall and traverses the mixing region, it does not show clearly in the photographs. This suggests that either the shock has been weakened or that the region above the shear layer has a low Mach number. For the single-slot injection case, most of the shock traverses the shear layer, while part is reflected back toward the lower wall. In Ref. 1, the results of pressure measurements indicate that these reflections propagate downstream; however, they cannot be seen in the schlieren photographs. The sequence of shock reflections between the wall and the shear layer also exists for tandem injection. These reflections are not seen in the spark schlieren photographs, but are verified by the wall-pressure measurements that show regions of compression and expansion downstream of the shock impingement location. These regions can also be identified in the interferograms and resulting density profiles shown in Figs. 7–9.

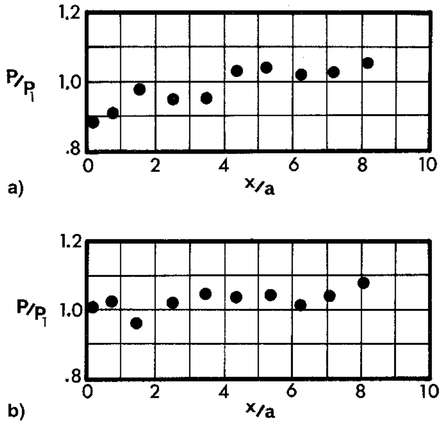

Fig. 6 Streamwise wall static pressure distributions (M_1 = 2.85): a) M_j = 2.00, M_b = 0.257 and b) M_j = 2.00, M_b = 0.715.

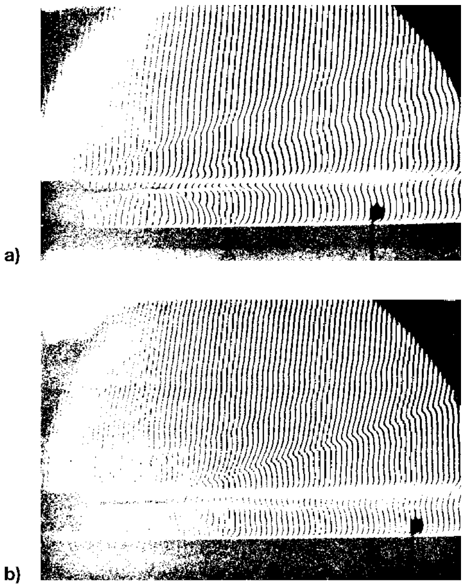

Fig. 7 Interferograms for tandem slot injection (M_1 = 2.85): a) M_j = 2.00, M_b = 0.257 and b) M_j = 2.00, M_b = 0.715.

Comparison with single-slot supersonic injection also brings out a difference in the relative thicknesses of the shear layers. As expected, the shear layer produced by tandem injection is much thicker.

Referring now to the streamwise pressure distributions shown in Fig. 6, it is seen that similar overall characteristics are exhibited for both high and low mass flow rates. The supersonic injectant is overexpanded in the case of the lower mass flow rates, and slightly underexpanded in the higher mass

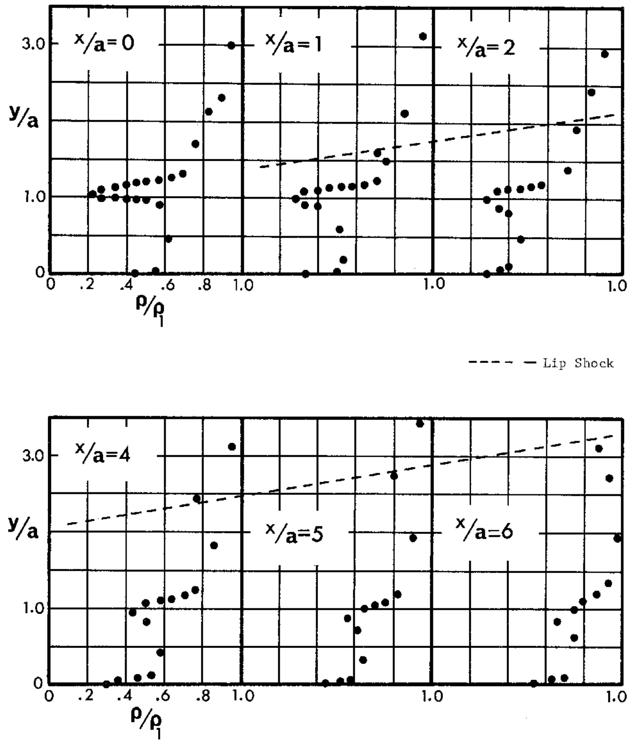

Fig. 8 Density profiles at several downstream locations (M_1 = 2.00, M_b = 0.257).

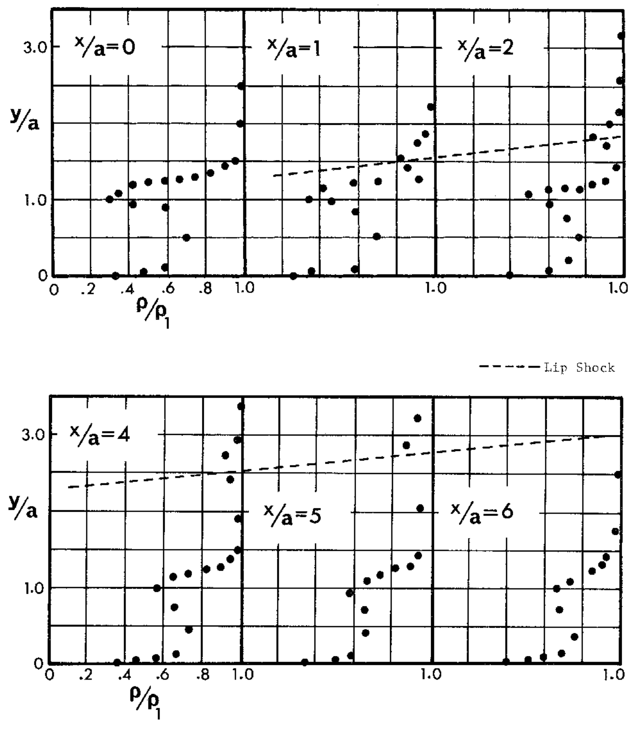

Fig. 9 Density profiles at several downstream locations (M_1 = 2.00, M_b = 0.715).

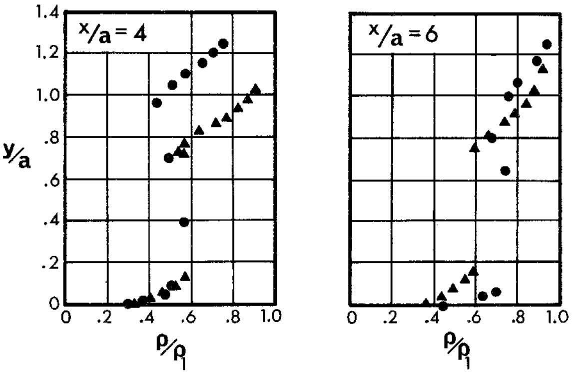

Fig. 10 Comparison of density profiles with those for single-slot supersonic injection. ●, M_j = 2.00, M_b = 0.257 and , M_j = 2.00, M_b = 0 (Ref. 1).

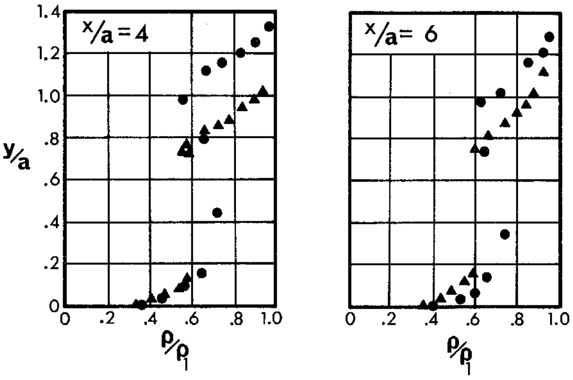

Fig. 11 Comparison of density profiles with those for single-slot supersonic injection. ●, M_j = 2.00, M_b = 0.715 and , M_j = 2.00, M_b = 0 (Ref. 1).

flow rate condition. The static pressure distribution tends to rise slightly from the point of injection to the vicinity of the adjustment shock impingement where there is a small disturbance. Afterwards, the pressure distribution rises slowly again, since the flow has now entered a recompression region. Then, a slight expansion region is noticed, followed by a sharper recompression area about seven slot heights downstream.

Density profiles at several downstream locations generated from the interferograms are presented in Figs. 8 and 9. These profiles are compared in Figs. 10 and 11 with the profiles obtained earlier for single-slot supersonic injection in Ref. 1. From these comparisons, it can be seen that the effects of the subsonic injection are mixed out as the flow moves downstream. This result is also brought out by noting in Figs. 10 and 11 that all three density profiles nearly coincide at a downstream distance of six slot heights. In fact, most of the differences at this location are the result of the differences in total injected mass flow rates for the different cases. At this location, the variation in the density profiles caused by the expansion fan and lip shock off the lower splitter plate have also decayed (see Figs. 8 and 9). In Fig. 12, the streamwise variation of the minimum density ratio in the shear layer formed by the subsonic jet is presented. Here, it is seen that the minimum densities are nearly the same at a downstream distance of five slot heights.

Since there are no axial pressure gradients of any consequence throughout the flowfield, it can be assumed that the total enthalpy varies linearly with axial velocity, i.e., a Crocco integral is approximately valid. In such cases, a qualitative representation of the velocity field may be obtained from a quantitative density distribution such as obtained here from interferograms. Thus, the rate of density increase between the subsonic and supersonic streams has been assumed here to give an indication of the amount of mixing between the two

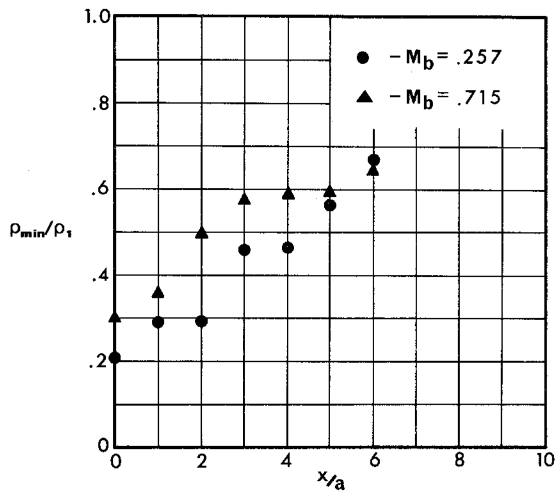

Fig. 12 Streamwise distribution of minimum density ratio in subsonic jet.

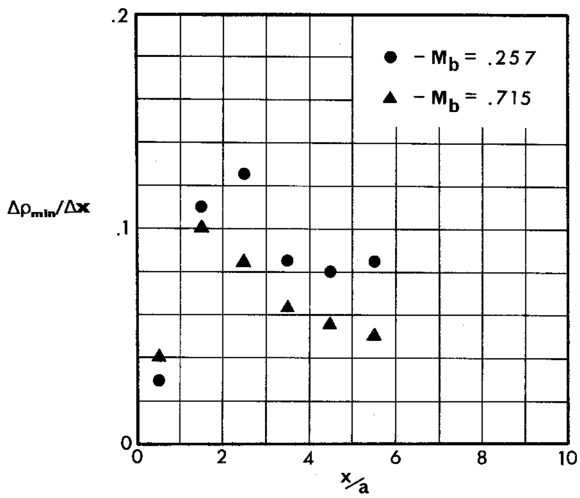

Fig. 13 Average rate of change of minimum density ratio in subsonic jet.

streams. This is shown in Fig. 13, where the average rate of change of the minimum density in the subsonic jet is presented as a function of downstream position. As expected, the stream with the higher Mach number, and thus, mass flow rate, has a lower rate of change in the density minimum for the location farther downstream. The injectant with a higher mass flow rate has a higher streamwise velocity (closer to the freestream velocity), which results in less shear and less diffusive action between the two streams. Judging from the spark schlieren photographs, fully turbulent mixing begins about three slot heights downstream of the point of injection. These results are of importance in areas of study such as fuel injection into a supersonic stream, where high mixing rates are desired to distribute an injected fuel throughout the freestream.

From the results of the density measurements, it was concluded that to determine the net effects of the pressure rise capability of the boundary layer formed after the supersonic injection, adverse-pressure-gradient-inducing devices such as wedges should be positioned at least six slot heights downstream of the injection station. This is because the effects of subsonic injection from the upper slot were found to be completely dissipated by that location.

Conclusions

After examining the test results, several conclusions can be reached. First, tandemly injected subsonic and supersonic flow can be studied as separate components, which closely resemble the respective individual injection of subsonic and supersonic flows into an undisturbed supersonic freestream.

Second, the effects of the subsonic secondary injection were almost completely mixed out at a downstream distance of six slot heights. This observation is based on the density profiles generated from interferograms of the flow and on a comparison of these profiles with those produced by injection at the same flow conditions into an undisturbed freestream. Estimations of the rate of density change have shown that the injectant with the lower Mach number and, thus, lower mass flow rate and velocity, mixed more freely with the freestream.

Third, subsonic injection at these flow conditions is a useful method for simulating a near-separation boundary layer; subsonic injection conditions may be varied to suit the test conditions. If a study is to be made at the same flow conditions on the effects that supersonic injection has on a freestream with a near-separation boundary layer, a pressure-gradient-inducing device should be placed at least six slot heights downstream from the injection station.

Finally, these results provide some preliminary information on the behavior of overlaid fuel or fuel/oxidizer injection systems.

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