Injection Slot Location for Boundary-Layer Control in Shock-Induced Separation

P. R. Viswanath*
NASA Ames Research Center, Moffett Field, California
L. Sankaran†
Hindustan Aeronautics Limited, Bangalore, India
P. M. Sagdeo‡
Georgia Institute of Technology, Atlanta, Georgia
and
R. Narasimha§ and A. Prabhu¶
Indian Institute of Science, Bangalore, India

An experimental investigation of the effect of tangential air injection in controlling shock-induced turbulent boundary-layer separation is presented, in particular when the injection slot is located inside of what would otherwise have been the recirculating zone in a separated flow. The experiments were carried out at a freestream Mach number of 2.5 in the separated flow induced by a compression corner with a 20 deg angle. The observations made were wall static pressures, pitot profiles, and schlieren visualizations of the flow. The results show that the present location for injection is more effective in suppressing boundary-layer separation than the more conventional one, where the slot is located upstream of where separation would occur in the absence of injection.

Nomenclature

b	= slot width
h	= slot or step height
l_i	= distance between slot (or step) and ramp corner (injection distance)
l_u	= a suitable length characterizing upstream influence
M	= local Mach number
M_∞	= freestream Mach number
p	= local static pressure
p_∞	= freestream static pressure
P_i	= injection (or blowing) stagnation pressure
P_0	= freestream stagnation pressure
R	= Reynolds number in freestream per meter
x	= streamwise distance with origin at ramp location
y	= distance normal to the surface
δ	= boundary-layer thickness
Δ_b	= bubble length (defined in Fig. 9)
Δ_r	= reattachment length (defined in Fig. 10)
Δ^*	= displacement thickness
δ^{**}	= momentum thickness
θ	= ramp (or compression corner) angle

Introduction

THE idea of using air injection or blowing for boundary-layer control is not new and has been studied in some detail at low speeds.[1,2] At supersonic speeds, where applications cover aircraft intakes and control surfaces, some exploratory studies have been reported[3-7] in both two-dimensional and axisymmetric flows on the use of blowing to prevent shock-induced boundary-layer separation; these studies have revealed that blowing is generally effective in controlling separation. Some workers[4,5] have even attempted to give simple correlations for the effectiveness of injection, but these are based on limited data and their general validity is not established yet. Earlier studies[3,8,9] have also revealed that, among various factors that determine the effectiveness of injection, the location of the injection slot relative to the shock is rather critical. It is this general problem of slot location which is studied in some detail in the present work. Only the two-dimensional case is considered here.

At the outset it is convenient to distinguish between two types of injection depending on the location of the injection slot:

1) U-type: injection is upstream of where the separation point would have been in the absence of injection (i.e., the conventional location adopted for boundary-layer control).

2) D-type: injection is downstream of the same point, but within the recirculating (or "dead air") zone.

Based on detailed experiments at a freestream Mach number of 1.8 with what we call U-type injection, Peake[3] made an important distinction between wall flow reversal and wake (or outer flow) reversal, and found that there was an optimum slot location at which both wall and wake flow reversals were avoided. For his experimental conditions, this optimum was at $l_i \simeq 6\delta$, where l_i is the distance of the slot from the shock location in inviscid flow and δ is the local boundary-layer thickness.

The recent experiments of Krishnamurthy[8] and Manjunath[9] with U-type supersonic injection to control separation at a compression corner revealed some interesting and unexpected features. The first is what may be called "separation reversal"; with increase in injection total pressure P_i, the extent of separation first decreases and then *increases* (as inferred from wall static pressure distributions) after a certain value of P_i, which seems to depend on l_i and on the compression corner angle (all other conditions remaining the same). This puts a serious limitation on the range of P_i

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*NRC Research Associate (presently with Joint Institute for Aeronautics and Acoustics, Stanford University, Stanford, Calif.). Member AIAA.
†Engineer.
‡Graduate Student, Department of Aerospace Engineering.
§Professor, Department of Aerospace Engineering.
¶Associate Professor, Department of Aerospace Engineering.

that can be usefully employed to suppress separation. The second feature is that the upstream influence or the extent of separation in the absence of injection was much larger than what would be expected from earlier observations with similar flow conditions and ramp angle. It was suspected that this abnormal upstream influence could be due to the effects on the oncoming boundary layer of the injection slot geometry, which acts as a backward-facing step in the absence of injection. [In order to ensure tangential injection, the nozzle is generally so shaped that it has a small overhang on the surface at the nozzle exit and is parallel to it (see the injection nozzle in Fig. 1)].

Further experiments by Sagdeo[10] confirmed the slot effect on upstream influence. Using schlieren photography, it was shown that D-type injection could be effective and might reduce (if not eliminate) both of the adverse effects associated with U-type injection mentioned above.

At this stage, it is appropriate to mention the studies of Chinneck et al.,[11] who used both U- and D-type injection (as we refer to them here) to improve control effectiveness in the presence of normal shock-induced boundary-layer separation at transonic speeds. Based on measurements of wall static pressures, they concluded that D-type injection is more effective, but no information on wake (or outer) flow behavior was provided. In their study, there was simultaneous variation of several parameters, including the strength and location of the shock; further, no quantitative estimates of the relative merits of the U- and D-types with regard to the suppression of boundary-layer separation at given flow conditions were offered. Perhaps for these reasons, further work on D-type injection does not seem to have been reported.

Interestingly, D-type injection has been studied only in cases where it was obtained naturally rather than by design, e.g., when large-scale separation is present, as in interactions involving normal shock waves. This appears to be true also in a recent study by Wong,[7] who used discrete slot injection to control shock-induced boundary-layer separation in supersonic inlets.

The present experiments[12] were conducted mainly to assess quantitatively the effectiveness of D-type tangential injection in a clean and simple flow situation such as shock-induced turbulent boundary-layer separation. The results obtained show very clearly the benefits of blowing inside the separated region, in comparison with the conventional method. Further basic studies and applications seem warranted.

Experiments

The experiments were conducted in the 175×125 mm supersonic wind tunnel at the Indian Institute of Science at a freestream Mach number of 2.5. A schematic view of the test section with the injection rig is shown in Fig. 1. The rig and the front aluminum block form the floor of the tunnel, which is run with a special one-sided nozzle. The separation of the turbulent boundary layer is induced by a compression corner (or ramp) with an angle of 20 deg.

Experimental Configuration

Detailed information on the construction of the injection rig used is available in Ref. 13; here we present only some of the salient features. The rig consists of two parts: the injection nozzle and a box section (Fig. 1) into which air for injection is first admitted. The box section is made of 12.5 mm thick mild steel plates, and a 6.2 mm thick smooth brass plate is fixed on the top. This plate consists of 130 static pressure holes of 0.4 mm diameter positioned very close to the centerline at intervals of 3.2 mm in the streamwise direction. Some static pressure holes across the span at a few streamwise stations are also provided for checking the two-dimensionality. Air for injection is taken from a reservoir at 690 kPa (100 psia) through an intermediate settling chamber (0.5 m diameter and 0.90 m long) and then is led into the box section. The blowing stagnation pressure is controlled by means of a throttle valve located just ahead of the intermediate settling chamber. From the box section, which is 0.43 m long (Fig. 1), the air issues through the nozzle exit parallel to the brass plate.

The nozzle block is made of stainless steel with a lip thickness of 0.5 mm to minimize distortion. The inside of the nozzle is contoured so that the air coming out of the box section will turn back (along the main flow direction) gradually and smoothly. The slot width b is 1.08 mm, which results in a jet exit Mach number of about 1.9. The variation in the slot width across the span is less than 4%. In order to ensure tangential injection, the nozzle is shaped to have a small overhang on the brass plate (Fig. 1). The slot forms an equivalent step of height 1.58 mm in the absence of injection. The nozzle block also has 10 static pressure holes of 0.4 mm diameter located along the centerline; however, no static hole can be accommodated within the first 25 mm upstream of the nozzle exit plane because of the thin injection lip.

In some preliminary runs with the ramp located close to the slot, schlieren photographs showed that the boundary layer separated in the vicinity of the lip. In order to get the complete static pressure distribution, at least in the absence of injection, the flow past the injection slot was simulated experimentally (as in Ref. 10) by replacing the slot with an equivalent step of height h equal to 1.58 mm. A step model was used for this purpose (see sketch in Fig. 2); it was made of

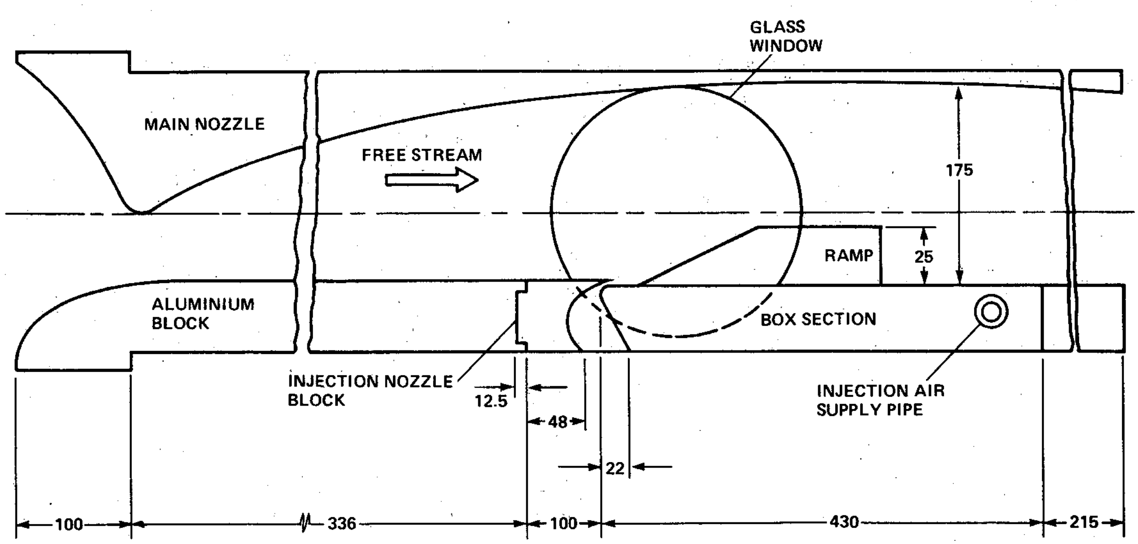

Fig. 1 Schematic arrangement of test section with injection rig.

a brass plate with a step formed at the slot location and had 40 static pressure tappings located on and near the centerline.

The ramp model used is shown in Fig. 3; it is made of a wooden block to which is fitted a brass plate 76×76×3.2 mm provided with 20 static pressure tappings located very close to the centerline. The ramp angle chosen is 20 deg, to provide enough length for the pressure to rise to the asymptotic inviscid value downstream of the shock without causing choking of the tunnel. The ramp can be fixed on the brass plate of the injection rig (or on the step model) at any desired distance from the slot (or the step).

Experimental Conditions

Table 1 lists the test conditions under which the experiments were carried out. The boundary layer on the floor of the tunnel was tripped using a 2.5 cm wide emery sheet just upstream of the throat of the nozzle. The velocity profile 2.5 cm upstream of the slot agreed very well with a power law typical of a fully developed turbulent boundary layer. The boundary-layer thickness parameters are given in Table 1.

Various techniques such as surface flow visualization[14] and measurement of spanwise variation of flow parameters are in use to assess the two-dimensionality of a flow; end plates are often used[14] to minimize three-dimensional effects. The use of end plates for the present model was considered but not adopted; they prevent the taking of schlieren pictures, which were considered very important in the present study. Moreover, the boundary layers on the end plates, likely to be laminar, separate at a relatively low pressure rise across the shocks, which could itself lead to some three-dimensional effects. In the present experiments, the following two observations indicate good two-dimensionality: 1) reasonably good agreement of the measured total pressure rise with the value given by oblique shock relations (see Figs. 4-6), and 2) small variation ($<10\%$) of the static pressure across the span over the central 5 cm in the separated region. Because all of the pressure measurements were made on or near the centerline and because the tunnel span is about 15 times the typical boundary-layer thickness, it is believed that the flow was two-dimensional to a satisfactory accuracy.

Measurements

Measurements made included mainly static pressure distributions in the region affected by separation and pitot profiles in the boundary layer at various stations. The schlieren technique was used for flow visualization. The static pressures were measured using a multitube mercury manometer, accurate to 1-2 mm.

Two values of injection distance l_i—namely, 0.77δ and 1.54δ—were tried; both locations correspond to D-type injection. The injection total pressure P_i was varied up to 365 kPa (53 psia) in both cases.

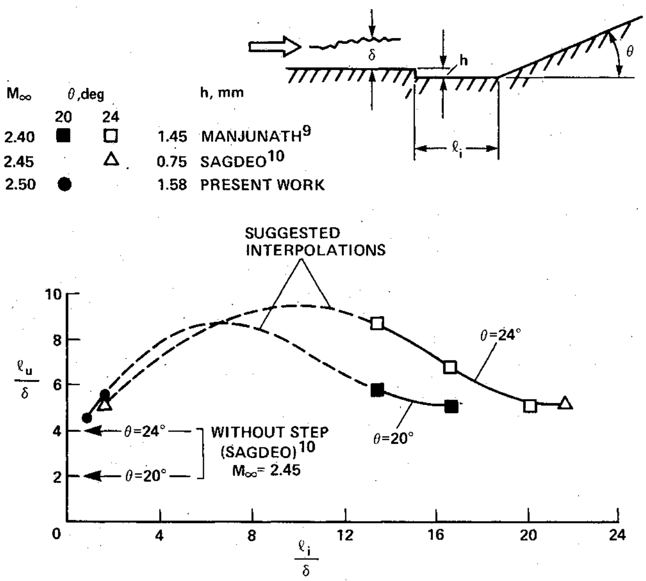

Fig. 2 Upstream influence in the presence of slot or step.

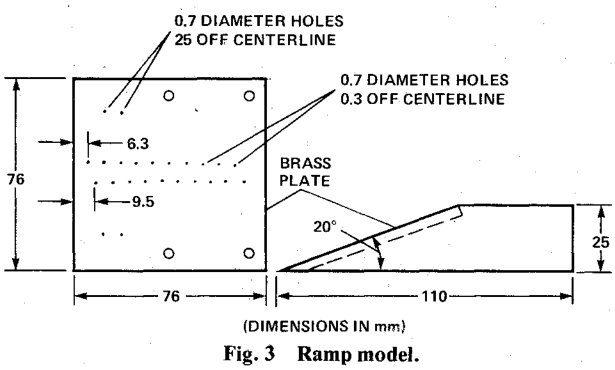

Fig. 3 Ramp model.

Table 1 Test conditions

Freestream Mach number	2.5
Total temperature (average)	298 K
Tunnel stagnation pressure	300 kPa (44.3 psia)
Freestream unit Reynolds number	43×10^6/m (1.1×10^6/in.)
Freestream Reynolds number based on momentum thickness	1.98×10^4
Undisturbed turbulent boundary-layer properties:	
Total thickness δ	8.1 mm
Displacement thickness δ^*	1.6 mm
Momentum thickness δ^{**}	0.45 mm
Shape factor δ^*/δ^{**}	3.5

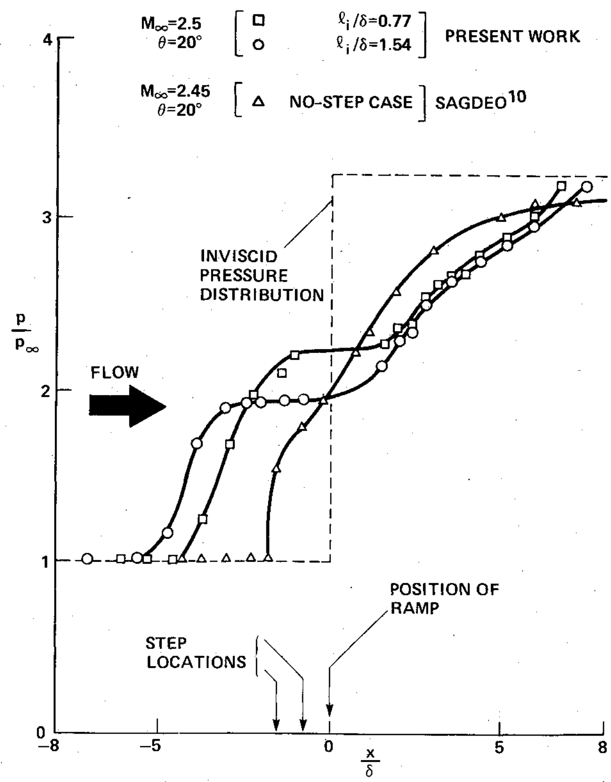

Fig. 4 Static pressure distributions without injection (step model: $h = 1.58$ mm).

Results and Discussion

Without Injection

Data obtained from the step model mentioned earlier with a step height of 1.58 mm are shown in Fig. 4. Also shown is the pressure distribution for the 20 deg ramp, in the absence of the step, at practically the same freestream conditions as in the present case. It is quite clear that the extent of upstream influence and the length of the separated region are both much larger with the step than without, even when the step is located quite close to the ramp.

More explicitly, we may use as a measure of the upstream influence the length l_u, defined as the distance from the ramp corner to the point upstream where the pressure rise is 10% of the freestream pressure p_∞. Figure 2 shows values of l_u/δ plotted against l_i/δ for the present as well as earlier measurements on 20 and 24 deg ramps.[8-10] The dotted lines are "suggested interpolations" where data are not available. [For each ramp angle (Fig. 2), the step height h is a parameter; however, in drawing the suggested interpolation, the influence of h on l_u over a small range of h has been assumed weak.] It is interesting to note that, for both ramp angles, the upstream influence first increases with l_i and then eventually decreases for larger distances. It is seen that l_u/δ does not reach the no-step value even for $l_i = 20\delta$, suggesting that the disturbance created in the boundary layer by the step has not decayed completely. It is believed that the longer upstream influence with the step (or slot) reflects the effect on the boundary layer of the separation-reattachment processes associated with the step, in particular through the changes in the wall shear stress.

With Injection

The pressure distributions with injection at $l_i = 0.77\delta$ and 1.54δ, as well as those on the step model without injection (Fig. 4), are shown in Figs. 5 and 6, respectively. Two schlieren photographs corresponding to no injection and injection at a pressure of 227 kPa are shown in Fig. 7. (The two waves seen upstream of the separation shock are Mach waves generated at the junction of the aluminum block and the injection nozzle block.) With the increase in injection pressure P_i, the maximum slope of the pressure distributions increases monotonically, the rate of increase being particularly high for low values of P_i. There is also a corresponding upstream shift in the position of the maximum slope point, indicating a reduction in the size of the separation bubble.

Boundary-layer pitot profiles with injection have been measured[15] at four stations in the flow, two upstream and two downstream of the compression corner for the case $l_i = 1.54\delta$;

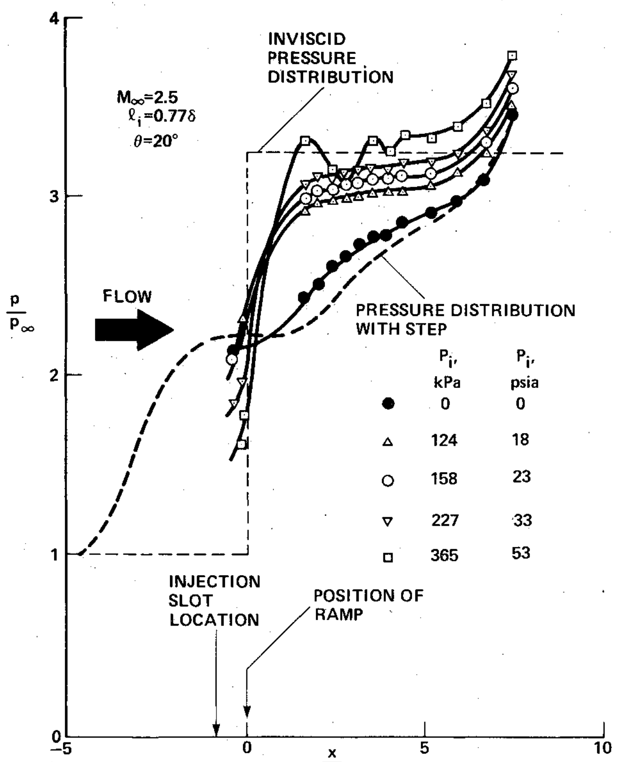

Fig. 5 Static pressure distributions with injection at $l_i = 0.77\delta$.

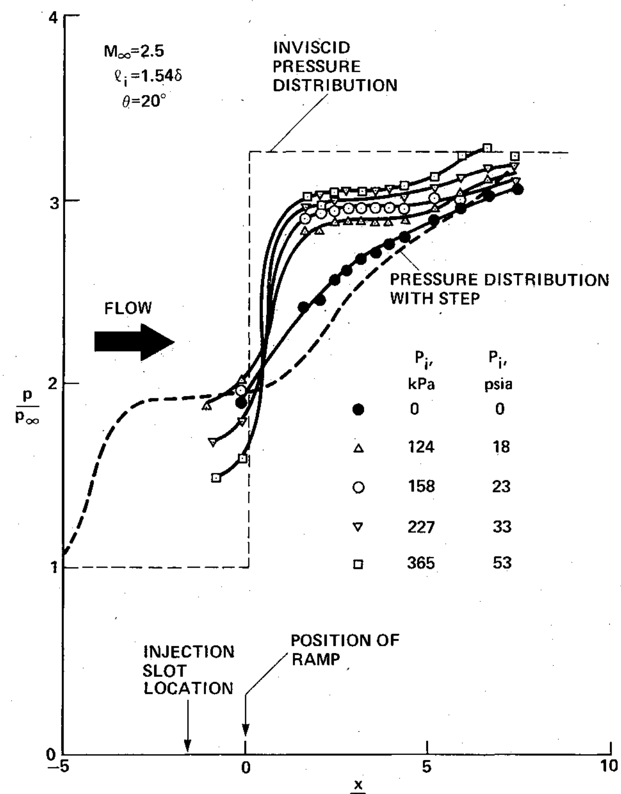

Fig. 6 Static pressure distributions with injection at $l_i = 1.54\delta$.

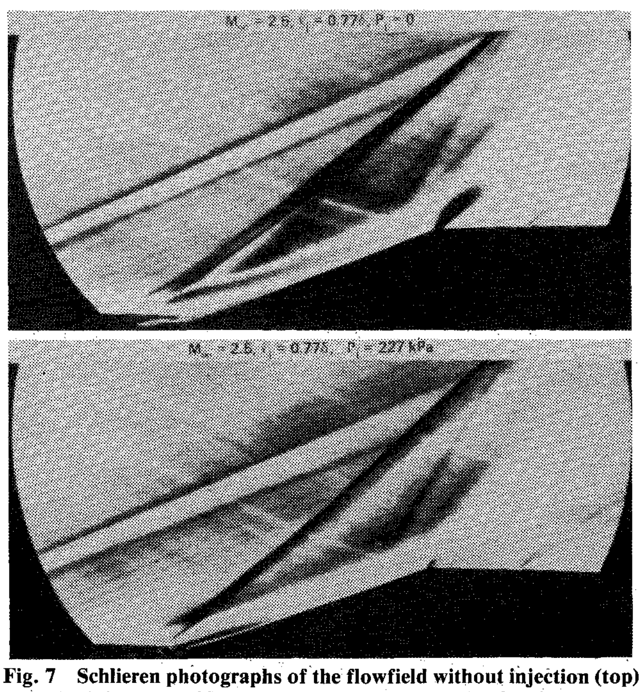

Fig. 7 Schlieren photographs of the flowfield without injection (top) and with injection at 227 kPa (bottom). $M_\infty = 2.5$, $l_i = 0.77\delta$.

the location of these stations and the calculated Mach number profiles are shown in Fig. 8. The profiles downstream of the slot are all nonmonotonic; comparison with schlieren photographs showed that the bumps in the profiles were due to the shock waves emanating from the region of compressive flow. It will be seen that in all of these profiles the local Mach number is always positive, conclusively showing the absence of wake flow reversal. Therefore, we conclude that, with injection as used here, boundary-layer separation has been completely suppressed.

The results obtained do not reveal significant differences in the effects of injection between the two values of l_i (a further discussion of this point is presented later), although the lower value of l_i ($=0.77\delta$) may be preferable in applications because of the relatively smaller upstream influence without injection. The separation reversal phenomenon described earlier was not observed in the range of P_i covered in the present experiments.

Mechanism of Suppression of Separation

We have seen that D-type injection is quite effective in controlling boundary-layer separation; this has been shown by wall static pressure measurements, Mach number profiles, and schlieren photography. As may be evident in the present study, it is the dead-air region that is energized by the wall jet rather than the boundary layer upstream of separation, as in the conventional configuration. Although a demonstration of the mechanism by which separation is suppressed warrants a detailed study involving extensive probing of the flowfield, it is suggested here that an important factor is the interaction of the jet injected at high total pressure with the (otherwise reversed-flow) boundary layer, leading to an eventual destruction of the reattachment point. Entrainment by the jet of the recirculating flow may also play a role.

Effectiveness of Injection and Comparison with Earlier Results

Having seen the favorable effects of injection, it would be further useful from the practical viewpoint to determine the precise manner in which the separation bubble collapses with increasing injection pressure, and also to assess the merits of D-type injection in comparison with the conventional U-type. To do this, it would be desirable to obtain a measure of the bubble length (Δ_b) from the measured pressure distributions, for example, by drawing tangents (at maximum slope) to the separation, plateau, and reattachment pressure rise regions (see sketch in Fig. 9). However, due to lack of information about the pressure distribution near separation, particularly with blowing, this method could not be adopted. However, we will use a measure of Δ_b, again derived from the pressure distributions, as will be shown subsequently.

Two alternative measures that may help in examining the effectiveness of injection are 1) a suitably defined "reattachment length" and 2) the pressure recovery in the reattachment region.

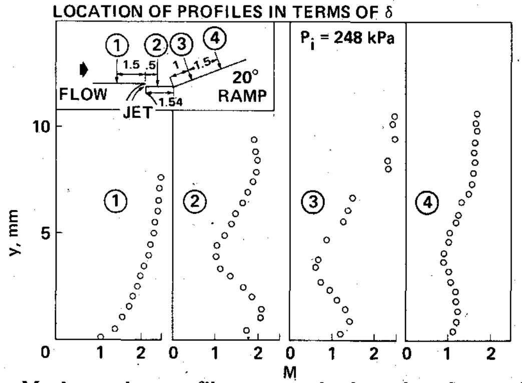

Fig. 8 Mach number profiles across the boundary layer with injection ($l_i = 1.54\delta$).

We will consider each of these in some detail in the following paragraphs. The present results are compared with those of Krishnamurthy[8] and Manjunath[9] who used U-type injection. Their experiments were performed under practically the same conditions as the present study—except that the slot width was 0.125 mm smaller, which resulted in a jet Mach number of 1.8. These small variations resulted in reductions in the mass and momentum injected in their studies[8,9] compared to the present work (respectively by 5 and 8%). Results from the studies of Peake[3] and Lakshmikantha et al.[5] (with impinging shock waves) have not been included for comparison in view of certain interference effects suspected to be present in their studies: the expansion fan from the shock generator they used interfered with the interaction zone, appreciably reducing the total pressure rise across the shocks. Again, Grin's results[4] have not been included due to inadequate information in his paper on experimental conditions.

Reattachment Length

The reattachment length is defined here as

$$\Delta_r = \frac{p_* - p_0}{(\mathrm{d}p/\mathrm{d}x)_{\max}}$$

where p_* is 95% of the far downstream pressure p_d (p_d can be estimated from oblique shock relations for known M_∞ and ramp angle), p_0 is the measured static pressure at the ramp location (i.e., at $x=0$), and $(\mathrm{d}p/\mathrm{d}x)_{\max}$ is the maximum slope in the pressure rise region (Fig. 10). The reattachment length Δ_r can be estimated quite accurately from the measured pressure distributions. Interestingly, Δ_b and Δ_r are related (Fig. 9), and Δ_b is virtually zero when Δ_r is less than δ. Figure 10 shows Δ_r/δ as a function of injection pressure ratio P_i/P_0 where P_0 is the tunnel stagnation pressure. Present results show that the values of Δ_r are practically the same (within the uncertainty of estimation of Δ_r, shown by a vertical bar in Fig. 10) for both values of l_i and are hence not shown separately. It may be seen that the reattachment length

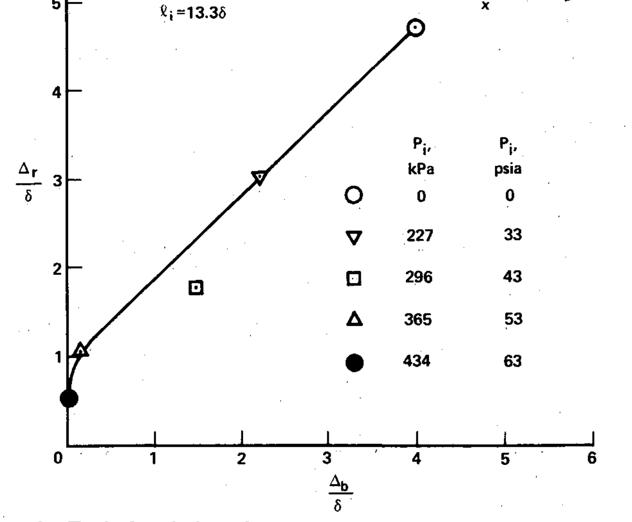

Fig. 9 Typical variation of Δ_b and Δ_r with injection (data from Ref. 9).

shrinks more rapidly with increase in injection pressure than in U-type injection. For $P_i/P_0 \lesssim 1.0$, Δ_r/δ with D-type injection is less than half that for U-type injection. The rapid decrease of Δ_r with injection suggests a correspondingly rapid collapse of the bubble.

Pressure Recovery in the Reattachment Region

Here we consider, at a given reference location on the ramp, the pressure rise with injection as a fraction of the pressure rise to the inviscid value p_d. We define a pressure coefficient

$$C_{pr} = \frac{p_{\mathrm{ref}(i)} - p_{\mathrm{ref}(0)}}{p_d - p_{\mathrm{ref}(0)}}$$

where $p_{\mathrm{ref}(i)}$ and $p_{\mathrm{ref}(0)}$ denote static pressures at a reference point with and without injection, respectively. Figure 11 shows C_{pr} vs P_i/P_0 with l_i as a parameter for two reference locations at distances δ and 2.5δ from the ramp corner. It is seen that in the present experiments the pressure recovery is rapid at relatively low values of P_i/P_0. The pressure recovery plot, unlike the plot of Δ_r (Fig. 10), reveals distinctly the superiority of injection at $l_i = 0.77\delta$ over that at $l_i = 1.54\delta$.

The two measures discussed above indicate that D-type injection is distinctly superior to U-type; the upstream influence is lower in the absence of injection and so is the momentum loss in the jet due to wall skin friction (since l_i is small). These conclusions of the present work, through explicit comparisons with U-type injection, give further support to the observations of Chinneck et al.[11] on the superiority of D-type injection.

It is not clear what the injection effectiveness would be for the intermediate range of values of l_i, say $4\delta \lesssim l_i \lesssim 10\delta$, as *reliable* data in this range are not available. However, if the "suggested interpolations" shown in Fig. 2 are qualitatively correct, we may expect that the effectiveness of injection for the intermediate range of l_i is going to be somewhat worse than at larger values of l_i $(10\delta \lesssim l_i \lesssim 15\delta)$. More data in the intermediate range are required before any definite statement can be made.

The elimination of wake reversal could be an important requirement in certain applications (e.g., intakes). Although in the present experiments both wall and wake flow reversal have been suppressed by injection, it may be noted that even the suppression of wall-flow reversal alone would itself be useful in many circumstances, such as in separated flows with heat transfer.

From an application point of view, it would be useful to get an idea of the injectant requirements to suppress separation. In the present experiments, the mass and momentum of the injectant have values of 18 and 14% of the mass and momentum, respectively, in the oncoming boundary layer; these estimates correspond to a value of Δ_r/δ equal to 0.75 (see Fig. 9). However, it may be noted that these are not necessarily the optimum requirements.

The problem discussed here certainly presents complexity in flow modeling and in calculation methods. There has been hardly any attempt to calculate these interacting turbulent flows with tangential fluid injection at high speeds. From an engineering viewpoint, a viscous-inviscid interactive type of calculation, with the viscous flow represented by an integral method, may be adequate. Even with U-type injection, there is insufficient mean flow data at high speeds covering a range of flow and geometrical parameters to enable construction of a reliable integral method. Experience gained in calculating low-speed wall jet flowfields in adverse pressure gradients (e.g., see Refs. 16-19) could be utilized as a first step in predicting these viscous flows at high speeds. With D-type injection, the complexity may be even greater, and further understanding of the physical mechanisms at play is essential before any modeling or calculation method can be formulated.

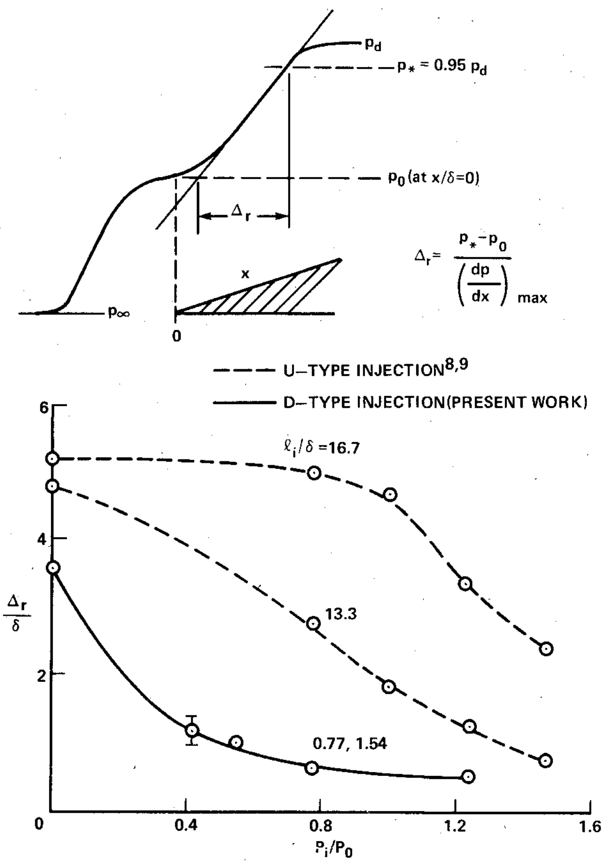

Fig. 10 Variation of reattachment length with injection.

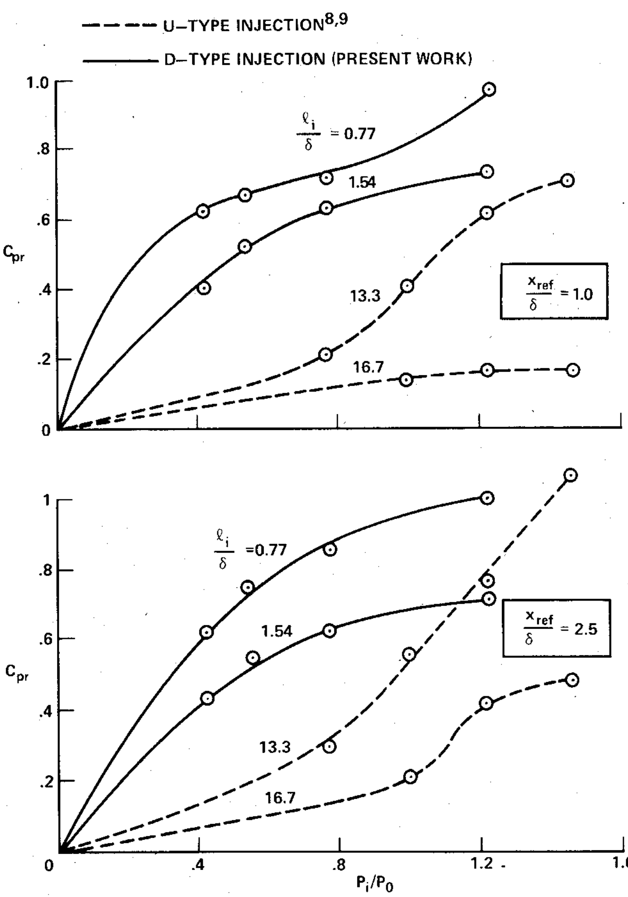

Fig. 11 Pressure recovery in the reattachment region with injection.

Conclusions

Injection slot location is an important parameter in the control of boundary-layer separation. To the authors' knowledge, a comparative study of the effectiveness of U- and D-type injection (respectively, upstream and downstream of where separation would have occurred in the absence of injection) in suppressing boundary-layer separation has been reported here for the first time. To effect a certain reduction in the extent of separation, much lower blowing pressures are required with D-type compared with U-type injection. The mechanism of suppression of separation in the D-type presumably lies in removing the reattachment point by energizing the dead-air region rather than the boundary-layer upstream of separation. However, more detailed studies are necessary to explain the observations and to understand the physical mechanisms involved. Further work on D-type injection is necessary to assess its effectiveness in other separating flows and in practical applications.

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