Experimental Study of Slot Injection into a Supersonic Stream

MICHAEL KENWORTHY* AND JOSEPH A. SCHETZ†
Virginia Polytechnic Institute and State University, Blacksburg, Va.

Theme

INJECTION of a gas through a wall slot parallel to a supersonic airstream is of interest for various potential applications, including thermal protection, fuel injection in ramjet engines, energizing of the inner portion of boundary layers in adverse pressure gradients, and skin-friction reduction on high-speed aircraft. The present study emphasizes the last of these and represents an effort to document a flowfield of this type, including direct skin-friction measurements, for a range of injectant mass flows.

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Figure 1 depicts the experimental setup. The slot injection apparatus was built directly into a two-dimensional, Mach 2.4 wind-tunnel nozzle. The streamline normally produced at the axis of a symmetric nozzle was replaced by a solid surface. Just beyond the last expansion wave in the nozzle, the surface stepped down to form the slot. This arrangement allowed ample room for an injectant plenum chamber in which the injectant (ambient-temperature air) was distributed spanwise in a header and straightened in section A. A very uniform two-dimensional flow from the slot resulted, as was confirmed by spanwise static pressure profiles.

The Mach 2.40 nozzle (test section) was 23 cm wide by 11 cm high. With a total pressure of 4.1×10^5 N/m^2 and ambient total temperature, the freestream unit Reynolds number was 4.3×10^6/m, and the thickness of the turbulent boundary layer at the injection station was roughly equal to the slot height. The primary observations included wall pressure (p_w) distributions, vertical profiles of pitot pressure, and cone-static pressures through the mixing region at four axial stations, direct measurements of skin friction with a floating, flushmounted self-nulling balance at axial stations 2, 3, and 4 (see Fig. 2), and schlieren photographs. A review of the literature in the full report shows that this is the first investigation of this type of problem in which all of these measurements have been obtained.

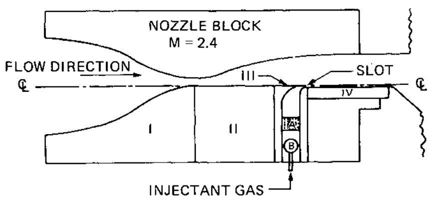

Fig. 1 Schematic of model: I) subsonic accelerating section, II) dummy section, III) plenum chamber and injection station, IIIA) flow straightener with plastic straws between screens, IIIB) header, IV) instrumented wall.

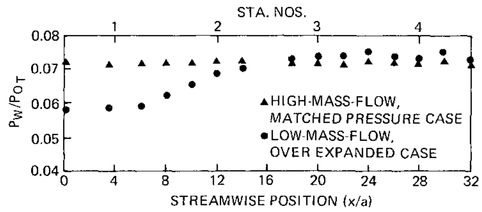

Fig. 2 Streamwise pressure distribution.

The slot height (a) was 0.64 cm, and the lip thickness was 0.013 cm. The main parameter varied was the injected mass flux $\rho_s u_s$, which was ratioed to the freestream mass flux $\rho_1 u_1$. A matched-static-pressure case, $\rho_s u_s/\rho_1 u_1 = 0.203$ (slot Mach number 0.66), and an overexpanded injection case, $\rho_s u_s/\rho_1 u_1 = 0.076$ (slot Mach number 0.31), were selected for detailed study. The streamwise wall-pressure distributions for these two cases are given in Fig. 2. (Here p_{o_t} is tunnel stagnation pressure, and x is axial distance from the slot; the points at $x/a = 0$ correspond to the slot exit conditions.) The matched static-pressure case shows an essentially constant wall pressure, whereas the low-mass-flow, overexpanded injection case shows a strong adverse pressure gradient between stations 1 and 2 due to a recompression region (see Fig. 3).

The cone-static and pitot pressure measurements were processed to give vertical distributions of static pressure, total pressure, and Mach number across the mixing region. Since the static pressure was approximately constant across this region at any given station (for the worst case, the maximum deviations from the mean were less than 10%), it was assumed that the boundary-layer form of the viscous flow equations could be employed for this flow problem. Deduced Mach number profiles for the two principal cases are presented in Fig. 4. Finally, with the plausible assumption of constant total temperature, these profiles can be converted into velocity profiles. The

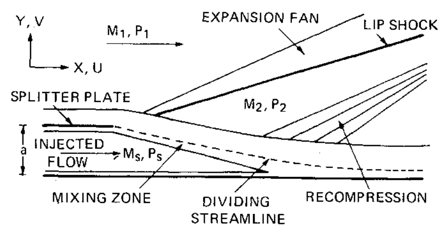

Fig. 3 Schematic of tangential injection flowfield.

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* Graduate Research Assistant.

† Professor and Chairman, Aerospace Engineering Department. Associate Fellow AIAA.

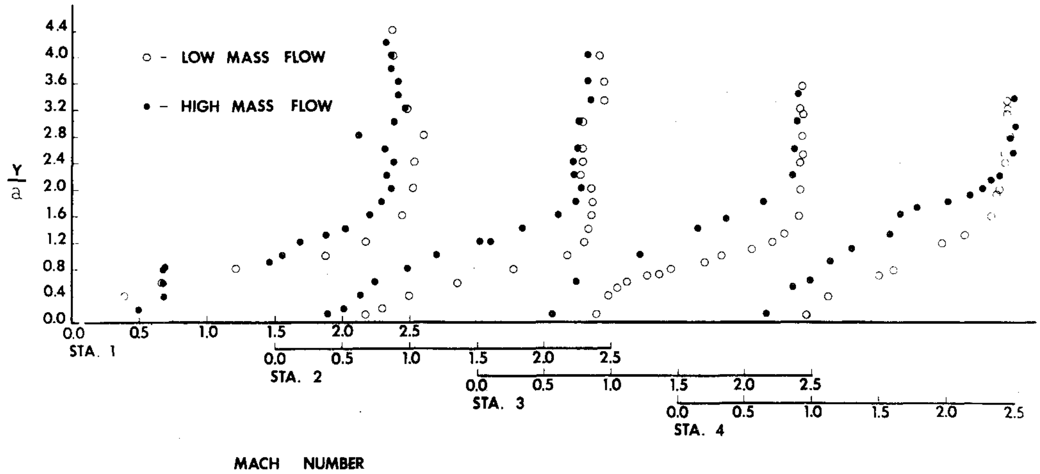

Fig. 4 Mach number profiles.

momentum integral equation can be employed with the profile data to roughly estimate wall shear as a consistency check on the directly measured values.

The wall shear (τ_w) results are shown in Fig. 5. For the matched-pressure case, the measured τ_w remained low to Station 3 and then increased slowly. However, for the overexpanded case, τ_w increased markedly at Station 3 due to the viscous work performed by the main stream in accelerating the low-speed injectant stream and the increasing pressure through the recompression zone. The positive τ_w measured at Station 2 for the latter case shows that there was no flow separation there despite the locally severe adverse pressure gradient. Figure 5 also shows the shear values inferred from the momentum integral procedure for the overexpanded case, which are even higher than the directly measured values. This observation adds credence to the perhaps unexpectedly high measured values at Stations 3 and 4.

To investigate further the shear effects at Station 4, a test series was run in which the mass flux ratio was varied from zero to underexpanded (slot Mach number sonic). The results are given in Fig. 6. The values of $\rho_s u_s/\rho_1 u_1$ for the two main test series are indicated on the abscissa. The fact that the matched-pressure case ($\rho_s u_s/\rho_1 u_1 \simeq 0.2$) gives the minimum wall shear is important for practical applications.

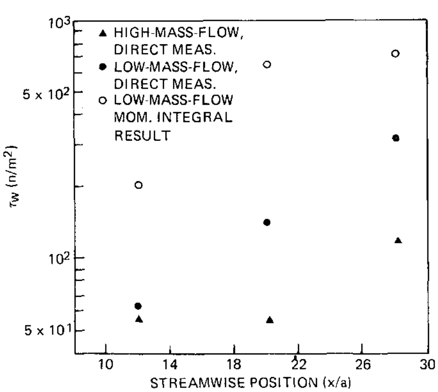

Fig. 5 Wall shear distribution.

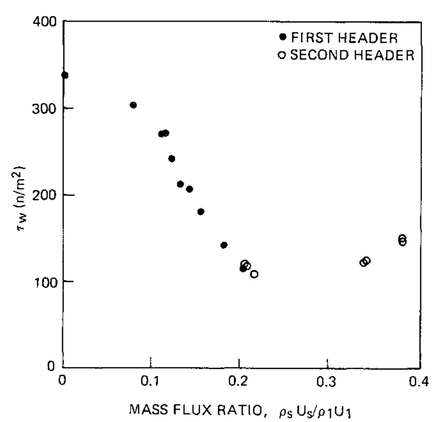

Fig. 6 Shear vs mass flux ratio at station four.