Further Experiments Concerning Secondary Injection of Gases into a Supersonic Flow

FRANK W. SPAID* AND EDWARD E. ZUKOSKI†
California Institute of Technology, Pasadena, Calif.

Nomenclature

c = discharge coefficient
C_p^* = pressure coefficient corresponding to stagnation conditions behind a normal shock in the undisturbed flow
d = hole diameter
h = scale parameter
M = Mach number
P = static pressure
P_0 = stagnation pressure
Re_L = Reynolds number based on distance between leading edge of the plate and injector centerline
x, y, z = coordinate axes
γ = specific heat ratio
δ = boundary-layer thickness

Subscripts

j = injectant stream
∞ = primary stream

AN earlier paper presented by the authors[1] described a study of the flowfield associated with the sonic injection of a gas through a wall and normal to a supersonic primary flow that is uniform and rectilinear outside a wall boundary layer. The results of a series of wind-tunnel experiments were presented, and a scale parameter was proposed, based upon a simple, inviscid model of the flowfield. New informa-

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* Graduate Student; now Engineer/Scientist Specialist, Missile and Space Systems Division, Douglas Aircraft Co. Inc., Santa Monica, Calif. Member AIAA.

† Professor of Jet Propulsion. Associate Fellow AIAA.

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tion, resulting from an additional set of wind-tunnel experiments, is presented in this note, which extends the range of the data published previously and which enables a more precise determination of the limits of applicability of the scale parameter. These experiments were conducted in the 20-in. supersonic wind tunnel at the Jet Propulsion Laboratory (JPL). The analysis of Ref. 1 and all of the experimental data pertaining to injection through circular holes are given in Ref. 2.

The right-handed Cartesian coordinate system, which is used for describing the flowfield, is as follows: the x axis lies in the plane of the wall, passes through the center of the circular injection port, and is parallel to the primary flow. The origin is the point of intersection of an extrapolation of the bow shock wave caused by injection with the x axis, and the direction of the primary flow is taken as positive. The wall is the x-y plane, and the z axis is normal to it.

The proposed scale parameter, a characteristic length scale for the flowfield, was calculated from a momentum balance in the x direction. The equation for this scale parameter h is as follows:

$$\frac{h}{d(c)^{1/2}} = \left[\left(\frac{1}{M_\infty}\right)\left(\frac{P_{0j}}{P_\infty}\frac{\gamma_j}{\gamma_\infty}\frac{2}{C_p^*}\right)^{1/2} \times \left\{\frac{2}{\gamma_j-1}\left(\frac{2}{\gamma_j+1}\right)^{(\gamma_j+1)/(\gamma_j-1)}\left[1-\left(\frac{P_\infty}{P_{0j}}\right)^{(\gamma_j-1)/\gamma_j}\right]\right\}^{1/4}\right] \qquad (1)$$

Figure 1 is a plot of normalized static pressure P/P_∞ vs the dimensionless distance along the x axis, x/h. Data are presented for a variation of h of a factor of about 4, for gaseous nitrogen, and for helium injectants. The primary-stream Mach number was 3.50, and the boundary layer in the vicinity of the injection port was turbulent. In Ref. 1, only laminar boundary-layer data were presented at this Mach number. It can be seen that the scaling is reasonably good, but that some discrepancies exist.

The region where the nitrogen injection data of Fig. 1 show the poorest agreement is $3 \leq x/h \leq 5$. This region has been called the reattachment region, because it is believed to be the region in which the injectant jet attaches to the wall. In Ref. 1, the authors suggested that the pressure variation in this region was a function of the injectant-to-freestream pressure ratio P_{0j}/P_∞. This assertion was tested by comparing pressure distributions of flows for which the total pressure of the injectant was held fixed and for which h was changed by changing the diameter of the injector. The results (see Fig. 2) clearly show that the pressure overshoot changes rapidly with hole size, and therefore that this suggestion is incorrect.

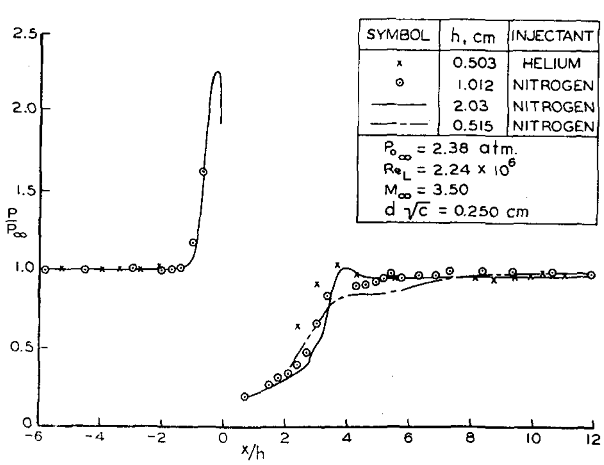

Fig. 1 Influence of scale height on flat-plate static-pressure distributions in plane of injector: turbulent boundary layer.

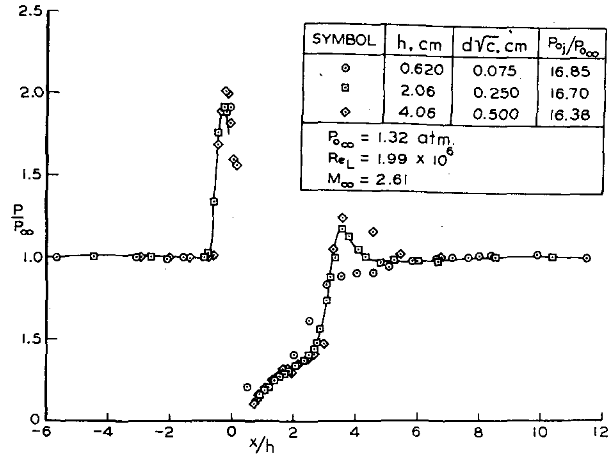

Fig. 2 Flat-plate static-pressure distributions in plane of injector with constant injection pressure ratio: turbulent boundary layer.

A second hypothesis was proposed in which the ratio of h to the boundary-layer thickness δ was the important parameter. Because the boundary-layer thickness was not changed, this suggestion was tested by varying the injector diameter and injection pressure ratio in such a manner that h was held fixed. Three comparisons were made with $M_\infty = 2.61$, $h/\delta = 5.8$; $M_\infty = 2.61$, $h/\delta = 1.5$; and $M_\infty = 3.5$, $h/\delta = 5.8$; and in each, the injector diameter was changed by a factor of 2. The results, an example of which is presented in Fig. 3, are in excellent agreement, despite the two-to-one change in injector diameter. This suggests that the ratio h/δ is important in fixing the phenomena responsible for the pressure overshoot at the reattachment point. Data are also presented in Ref. 2 which indicate that the scaling procedure begins to fail when the ratio of h to the injector diameter h/d approaches unity.

The data of Fig. 1 also exhibit a discrepancy between data for nitrogen and helium injection in the region downstream of the injection port. Additional data for a direct com-

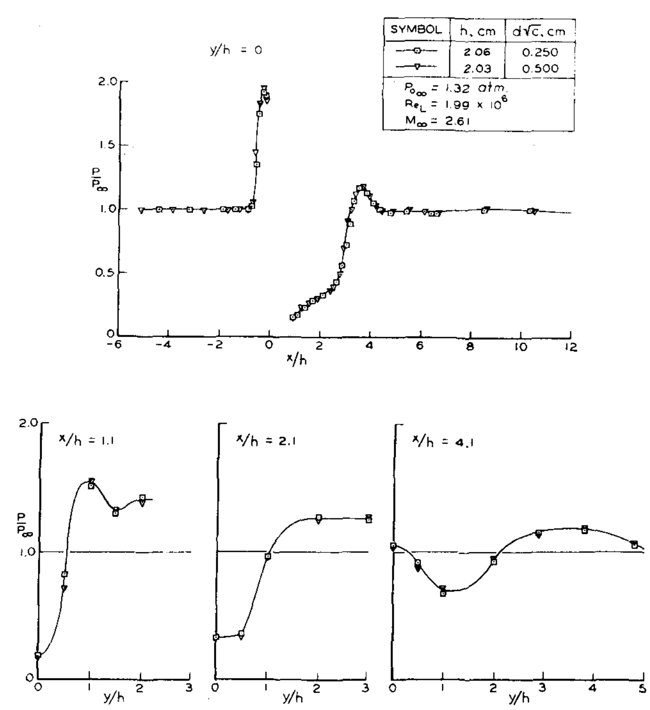

Fig. 3 Flat-plate static-pressure distributions in several planes with constant scale height but with different injection port diameters: turbulent boundary layer.

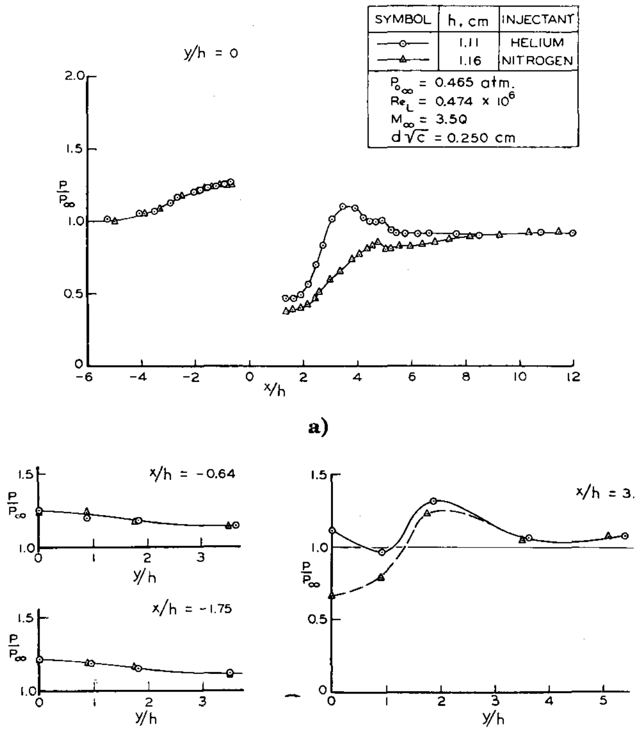

Fig. 4 Influence of injectant properties on flat-plate static-pressure distributions in several planes: laminar boundary layer.

parison between nitrogen and helium injection at a Mach number of 3.50 and with a laminar boundary layer near the injection port are presented in Fig. 4. The value of h is approximately the same for the two cases that are shown here. Figure 4a gives the pressure distributions along the x axis, and Fig. 4b shows the pressure distributions along lines parallel to the y axis at values of x/h of -0.64, -1.75, and 3.4. The distributions upstream of the injector, at -0.64 and -1.75, are identical. However, there is a systematic difference in the downstream distributions; this difference is illustrated by the example shown here, at $x/h = 3.4$. This difference is most important at the x axis, and it decreases with increasing y/h. Note that, for this off-axis cut, the difference between the two pressure distributions at the x axis was approximately maximum. In this experiment, h/δ is constant and $h/d(c)^{1/2}$ is much greater than 1; consequently, the differences shown by the curves of Fig. 4 are most probably due to changes in injectant composition.

Data presented in Ref. 2 comparing nitrogen and helium injection at a Mach number of 2.61 exhibit characteristics similar to those shown in Fig. 4, except that the lower Mach number data show a much less pronounced difference between the nitrogen and helium injection. These data indicate that the shock system and boundary-layer separation caused by injection of helium and nitrogen are the same when equal values of h are used and that the effective obstacles created by injection are the same. However, the markedly higher pressures observed in the reattachment region for injection with helium indicate that this zone is strongly affected by the composition of the injectant.

The data presented here support the validity of the scaling procedure proposed in Ref. 1. These results indicate that h/δ should be matched for accurate scaling of the attachment region of the jet, and that the precise value of the pressure ratio P_{0j}/P_∞ is relatively unimportant if h/δ is matched. This result applies if P_{0j}/P_∞ is sufficiently large such that h/d is not near unity. Experiments with nitrogen and helium injection indicate that the effective obstacles created by nitrogen and helium injection are the same if h is matched, but that differences in the pressure distributions occur in the region near the x axis and immediately downstream of the injector.

References

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[2] Spaid, F. W., Zukoski, E. E., and Rosen, R., "A study of secondary injection of gases into a supersonic flow," Jet Propulsion Lab. TR 32-834 (March 1, 1966).