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Technical Notes

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Penetration of Gaseous Jets In Supersonic Flows

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Nomenclature

A–C, E–G,	=	coefficients appearing in the penetration correlation function
D	=	jet diameter, mm
L	=	test chamber width, mm
M	=	Mach number
$\bar{M}$	=	ratio of Mach numbers across a normal shock
M_a	=	air Mach number
$\mathcal{M}_A$	=	molecular mass of species A
P	=	jet penetration, mm
p	=	pressure, atm
$\bar{p}$	=	pressure ratio across a normal shock
q_r	=	$(\gamma p M^2)_{\rm jet}/(\gamma p M^2)_{\rm air}$ jet-to-air dynamic pressure ratio
Re	=	Reynolds number
x	=	downstream distance from injector center, mm
γ	=	specific heat ratio
δ	=	boundary-layer thickness, mm

Introduction

GASES injected transversely into a supersonic airstream penetrate to a height primarily determined by the dynamic pressure ratio, with additional parameters influencing the process, including the boundary-layer (BL) thickness at the injector location, molecular weight ratios, Reynolds numbers, etc. The injected plume generates a bow shock that interacts with the incoming air BL; a turbulent shear layer and a system of vortices spilling off the semicylindrical obstruction are formed. The jet is turned downstream and the vortices' rotation axes align nearly with the airstream, facilitating jet-air mixing. Near-field mixing is dominated by bulk mass transfer and the far-field mixing by the development of compressible shear layers.

When the BL thickness is small, typically less than the jet diameter, the gas penetrates through the BL and forms a strong, nearly normal, bow shock without significant BL separation; when the BL is thicker than the jet diameter, the jet penetrates straight. The Mach disc is almost parallel to the wall and the BL is separated by the bow shock interaction. These features are described in detail in the diagrams by Schetz and Billig [1].

Fuel penetration is an important precursor to mixing, therefore, various methods have been suggested to enhance mixing, including use of pylons and ramp injectors that deliver the majority of fuel into the freestream and away from the wall and BL [2–4]. These devices are intrusive to the flow, generate drag, and require cooling, thus wall injection continues to remain an attractive solution in many cases.

Empirically derived models of penetration in supersonic airflow with transverse fuel injection describe the penetration depth and spreading using a definition for the plume boundary based variously on injectant concentration, injectant mole fraction, or intensity of an image, depending on the particular study [5–8]. Thomas et al. [9] include a list of additional penetration studies of single and multiple injectors, including some quoted here.

Different ranges of experimental conditions were studied, and the derived penetration correlations incorporated different sets of independent variables, including the dynamic pressure ratio, downstream distance, boundary-layer thickness, and jet Mach number. There exists a substantial difference between current correlations; these differences are addressed in this work.

The purpose of this study is to supplement the existing database of jet penetration when the BL is thick and to attempt to reconcile differences between the existing penetration correlations. A strong dependence on the air Mach number was found, which is not emphasized by currently employed penetration correlations. A new penetration formulation is suggested that evidences this effect and that achieves complete agreement with experimental results collected over three decades in various facilities and under different conditions.

Experimental Facility

The experimental facility used in this study has been described in detail previously [2]. Briefly, this is a continuous-flow, direct-connect, supersonic-combustion wind tunnel that delivers 0.75 kg/s of air continuously at Mach numbers from 1.3 to 3.6 with stagnation temperature up to 1200 K and stagnation pressure to 1.4 MPa. The entrance to the test section was square with the side, $L = 25.4$ mm with a constant cross section along its 18 L length. Hydrogen, helium, or argon were injected transversely, at a location where the BL thickness was measured through 1, 1.5, and 3.2 mm orifices to vary the ratio of δ/D.

BL thickness was measured at several axial locations using a probe with a square-cut tip of 0.25 mm outside diameter and 0.13 mm bore diameter. The probe was inserted through the test section side wall and was traversed in 0.2 mm increments while measuring the stagnation pressure. Measurements were taken around the isolator outlet circumference for unheated air at 410 kPa stagnation pressure and nozzle exit Mach 1.6. The BL measurement was repeated for 550 kPa stagnation pressure, at both Mach 1.6 and Mach 2.5.

At each station, the BL thickness was taken as the point of 99% velocity or where the measured pitot pressure was 98% of the maximum value. The BL thickness at the jet injection location was approximated by linear interpolation between the two stations measured on either side of the port. For 550 kPa stagnation pressure and Mach 1.6 flow, the BL thickness at the injector port was 3.7 mm. At Mach 2.5, the BL thickness was 2.5 mm.

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Table 1 List and range of parameters included in the jet penetration analysis

Parameter	Range
Air Mach number	1.6 and 2.5
Injectant/air dynamic pressure ratio, q_r	0.5–3.0
BL/jet diameter relative thickness, δ/D	0.8–3.7
Injectant gas	He, H_2, Ar

Results and Analysis

Penetration Visualization

A lens-based schlieren system was used for penetration visualization; optical assessment of jet penetration has been demonstrated to give accurate and consistent depth compared with chemical sampling methods [8]. Jet penetration was defined here, as in the previous studies used for comparison, as the outer edge of the jet. The uncertainties associated with the optical accuracy of defining the outer jet are estimated to within 2% of the penetration height. To capture average penetration rather than instantaneous variations, each camera exposure was 20 ms.

Argon, hydrogen, and helium gas were transversely injected into the supersonic flow through circular orifices of 1.0, 1.5, and 3.2 mm diameter. Inspection of the schlieren images showed that the windward side of the gas plume is deflected at an angle downstream from the normal direction by subsonic air close to the wall, but that the lee side of the jet is not deflected.

Gases injected into a Mach 1.6 airstream did not penetrate far beyond the boundary layer if the jet diameter was less than half of the BL thickness. For Mach 1.6, the bow shock was weak when the BL was significantly thicker than the injector diameter. For Mach 2.5 flow, a distinct bow shock was visible and the interaction of the bow shock with the boundary layer was visible as well.

Penetration Measurement

Table 1 contains a list of the parameters changed during this study to evaluate their influence on the jet penetration.

The measured depth of argon, helium, and hydrogen penetration is presented in Fig. 1 as a function of a correlation of several independent variables considered to have an effect on gas penetration taken at Mach 1.6. Penetration was expressed as P/D. The independent variables were the jet-to-air dynamic pressure ratio, the downstream distance ratio at which penetration was measured, the BL thickness ratio, the jet-to-air Reynolds numbers ratio, and the jet-to-air molecular weight ratio.

The resulting penetration formula, based on the data of the present study, is

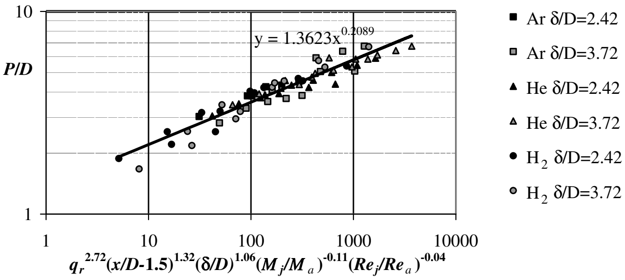

Fig. 1 Curve fit for injection into Mach 1.6 air at varied BL thicknesses.

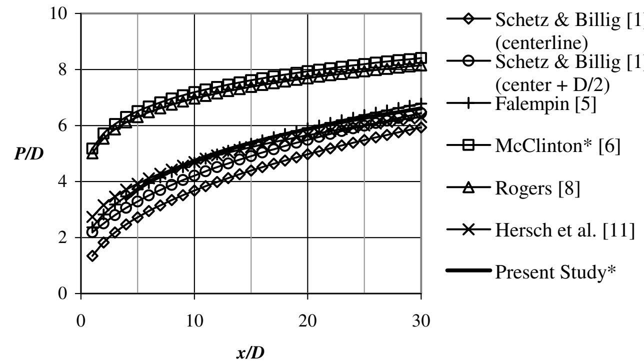

Fig. 2 Penetration correlations for various studies exhibit scatter; $q_r = 1.5$, $^*\delta/D = 2.4$ in these studies.

$$P/D = 1.362(q_r)^{0.568}(x/D - 1.5)^{.276}(\delta/D)^{.221} \times (Re_j/Re_a)^{-0.0084}(\mathcal{M}_j/\mathcal{M}_a)^{-0.025} \quad (1)$$

The ratio of jet-to-air dynamic pressure has the strongest effect on penetration of the variables examined, followed by the BL thickness effect. The Re number ratio has a negligible effect and was removed from the final correlation suggested here. The molecular weight effect is quite small, as indicated by Eq. (1).

It should be noted that additional parameters may be, and have been, included in previous correlations. Povinelli and Povinelli, [10], for example, included the air-to-jet Mach number ratio and found this effect was relatively weak. Most correlations use sonic jet injection and neglect this parameter.

Table 2 Penetration formula parameters resulting from various studies

	A	B	C	E	F	G	Mach no.
Schetz and Billig [1]	1	0.435	0	0.435	0	0	N/A
Falempin [5]	1.45	0.5	0.5	0.35	0	0	1.5
Hersch. et al. [11]	1.92	0.35	0.5	0.277	0	0	2
Rogers [8]	3.87	0.3	0	0.143	0	0	4
McClinton [6]	4.2	0.3	0	0.143	0.057	0	4
Present study	1.36	0.568	−1.5	0.276	0.221	−0.0251	1.6

Table 3 Penetration equation parameters as functions of the air Mach number

Coefficients for Eq. (2)	Function of air Mach number, M_a
$A=$	$1.049M_a - 0.192$
$B=$	$-0.08M_a + 0.615$
$C=$	$-2.34/M_a$
$E=$	$0.395M_a - 0.823$
$F=$	$-0.067M_a + 0.325$
$G=$	-0.025

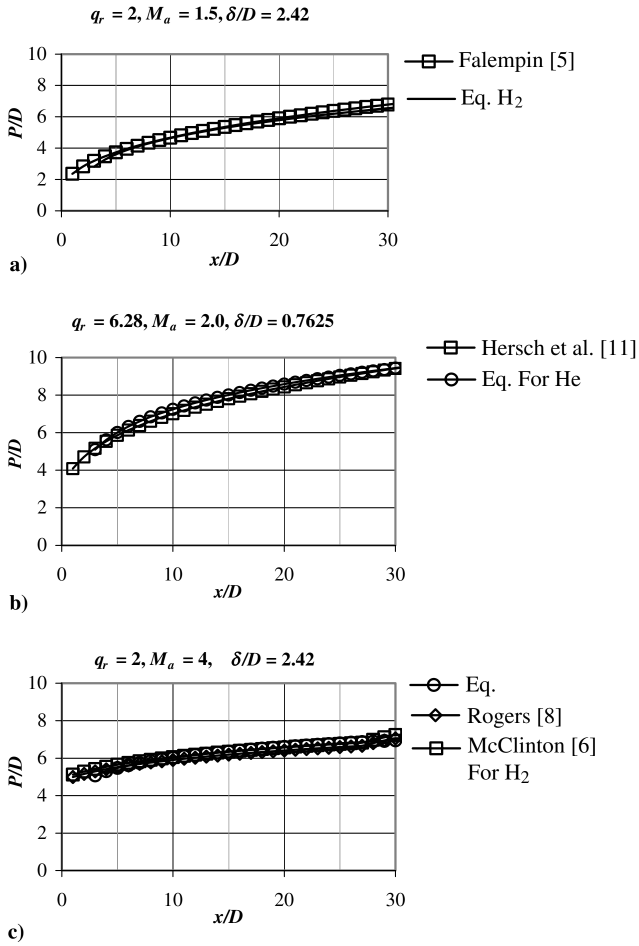

Fig. 3 Comparison of the Eq. (2) prediction with Mach dependent coefficients as in Table 2 with previous results.

Comparison to Previous Studies

Figure 2 shows a set of correlations predicting the jet outer edge penetration. Each of these tests was conducted at different experimental conditions, except for the Schetz and Billig [1] centerline prediction, which was analytically derived. In this analytical model, the injected fluid is accelerated downstream by momentum transfer while the air dissipates the jet's transverse momentum.

Equation (1), determined in this study, agrees well with the results of Falempin [5], Hersch et al. [11], and a modified Schetz and Billig [1] correlation for the outer diameter; there are, however, large differences between these results and the other studies.

The most significant difference in these studies is the air Mach number. For example, the correlation of Falempin [5], which gives results similar to the correlation derived in this study, was determined for air at Mach 1.5, which corresponds closely with the Mach 1.6 flow used in this study. Studies performed at Mach 2 conditions result in slightly deeper prediction of penetration, and studies at higher air Mach numbers (such as McClinton [6] and Rogers [8], both at Mach 4) indicated further penetration increases.

If the penetration equation used in these studies is presented in a generic form as

$$P/D = A(q_j/q_a)^B(x/D + C)^E(\delta/D)^F \times (\mathcal{M}_j/\mathcal{M}_a)^G \qquad (2)$$

the numerical values for the exponents are as listed in Table 2. The air Mach numbers at which each of the quoted correlations were derived are also included in the table. The list clearly indicates that experiments with similar Mach numbers produced comparable results. It is also remarkable that the constant A is, itself, quite close to the experiment's air Mach number.

The differences are caused by the strength of the shock associated with the detachment in front of the penetrating jet. The local conditions are changed and, locally, the *effective air dynamic pressure* is reduced by a stronger shock, leading to increased penetration. For example, if the simple assumption of a normal shock is made for an experiment at Mach 4, such as that of McClinton [6], the effective dynamic pressure ratio would be

$$q^{\mathrm{eff}}_{r_{M=4}} = q_r \frac{(\gamma p_s M^2)_{\mathrm{airnom}}}{(\gamma p_s M^2)_{\mathrm{air\ behind\ the\ shock}}} = q_r \bar{p}\bar{M}^2$$
$$= q_r \frac{1}{18.5}\frac{4^2}{0.43^2} = 4.6 q_r \qquad (3)$$

whereas for experiments at Mach 1.6, such as the present study, $q^{\mathrm{eff}}_{r_{M=1.6}} = 2 \cdot q_r$. If this effective dynamic pressure ratio is used rather than the dynamic pressure ratio based on the nominal Mach number, the correlation by McClinton [6] becomes much closer to the correlation determined at lower Mach numbers, such as in the present study and in [5,11]. Therefore, the effect of the air Mach number must be included in any penetration prediction correlation.

General Penetration Formula

If constants A through G in Table 2 are converted into functions of Mach number extracted from the set of data available in the literature, the expressions listed in Table 3 result. When applied to the data obtained in all studies quoted here, this correlation provides good compatibility as shown in Fig. 3. The inputs to the formula, including Mach number, BL thickness, and dynamic pressure ratio are taken directly from test data compiled in the previous studies.

To further evaluate the new penetration correlation, an independent verification with a new set of penetration data was obtained in the present study at $M_a = 2.5$. These data were not used to generate the penetration correlation. The results are presented in Fig. 4. Good agreement is evident, particularly in the midfield. Close to the injection location where the gradients are large or in the far field beyond 30 jet diameters, the differences between predictions based on Eq. (2) and test data are within one jet diameter.

Examination of Eq. (2) shows that penetration increases with increased dynamic pressure ratio, downstream distance, and BL thickness to jet diameter ratio, as expected; the penetration also increases with increased air Mach number, which would be expected based on consideration of the effective dynamic pressure ratio. Despite increased penetration from the wall when the Mach number is low supersonic and the BL is thick, the penetration out of the BL and into the freestream is decreased by a thick BL because the jet begins to bend downstream within the BL and emerges in the core stream at an angle. This leads to weaker oblique shocks, hence lower local effective dynamic pressure ratios. When the supersonic Mach number is high, much of the BL flow is also supersonic, resulting in a stronger detachment shock with consequent low dynamic pressure and increased penetration. As a result, the BL thickness has a lower effect on penetration as the air Mach number increases.

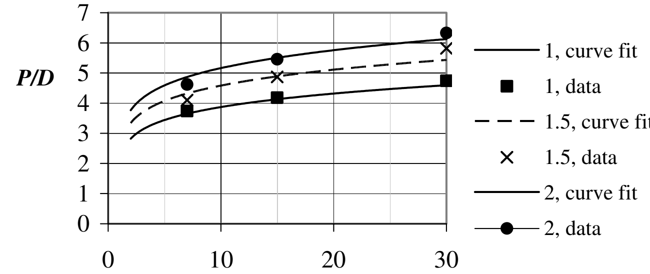

Fig. 4 Hydrogen penetration into a Mach 2.5 air at $q_r = 1$, 1.5, and 2.

Conclusion

This study has evaluated the penetration of gas jets into supersonic flows with boundary layers over various Mach numbers. Comparison with previous studies shows the following:

1) Transverse jet penetration is primarily dependent on q_r and, to a lesser degree, on the boundary-layer thickness and air Mach number.

2) The effect of molecular weight ratio on penetration is small and the effect of Reynolds number is negligible.

3) Increased air Mach number results in increased penetration due to greater effective dynamic pressure ratio at the injection location, a result of stronger bow shock generation.

4) The effect of the boundary-layer thickness on near-field jet penetration is significant at low supersonic Mach numbers but decreases with increased Mach number.

5) A new penetration correlation is proposed that incorporates air Mach number dependence and removes the discrepancies between several existing formulas. The air Mach number is used as an independent variable in the coefficients that determine the effects of selected parameters on jet penetration.

Acknowledgements

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