better the upstream propagation of the precombustion shock and its wall pressure distribution.

These comparisons show that the new model provides better descriptions of the wall pressure distributions and the over-all shock pressure rises for the available test data. Further testing is needed to determine whether more complex expressions for s_d will be needed if the combustor inlet conditions are significantly changed.

References

[1] Dugger, G. L., "Comparison of Hypersonic Ramjet Engines with Subsonic and Supersonic Combustion," Fourth AGARD Colloquium, Milan, Italy; also *Combustion and Propulsion-High Mach Number Air Breathing Engines*, edited by Jaumotte, Rothrock, and Le Febvre, Pergamon Press, New York, 1960.

[2] Ferri, A., "Review of Scramjet Technology," *Journal of Aircraft*, Vol. 5, No. 1, Jan. 1968, pp.3–10.

[3] Billig, F. S. and Dugger, G. L., "The Interaction of Shock Waves and Heat Addition in the Design of Supersonic Combustors," *Twelfth Symposium (International) on Combustion*, The Combustion Inst., Pittsburgh, Pa. 1969, pp. 1125–1139.

[4] Billig, F. S., Dugger, G. L., and Waltrup, P. J., "Inlet-Combustor Interface Problems in Scramjet Engines," *The First International Symposium on Air Breathing Propulsion*, Marseille, France, June 1972.

[5] Waltrup, P. J. and Billig, F. S., "The Structure of Shock Waves in Cylindrical Ducts," *AIAA Journal*, Vol. 11, No. 10, Oct. 1973, pp. 1404–1408.

Correlation of Hypersonic Zero-Lift Drag Data

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Nomenclature

$(C_{D,l^2})_{min}$ = minimum or zero-lift drag coefficient, based on length squared
C'_∞ = Chapman-Rubesin viscosity coefficient, $[(T_\infty/T')\mu'/\mu_\infty]$
l = model length
M = Mach number
n = power law exponent
P = pressure
$Re_{\infty,l}$ = freestream Reynolds number based on model length
T = temperature
$\bar{V}'_\infty$ = viscous correlation parameter, $M_\infty(C'_\infty/Re_{\infty,l})^{1/2}$
x = longitudinal coordinate with origin at body nose
y = lateral coordinate with origin at body centerline
μ = viscosity
γ = ratio of specific heats

Subscripts
∞ = freestream conditions
T = stagnation conditions

Superscripts
$(\ )'$ = based on reference temperature conditions (Ref. 5)

Introduction

HYPERSONIC wind-tunnel testing in support of basic research or application programs such as the Shuttle during the past few years has focused attention on the need for properly correlating force data taken under varying test conditions. This Note demonstrates the applicability of one correlation parameter for drag coefficients. The present investigation, part of a more comprehensive study, demonstrates correlation of zero-lift drag coefficients of several simple shapes measured at $M = 10.03$ in air and at $M = 20$ in helium with the theoretical inviscid values.

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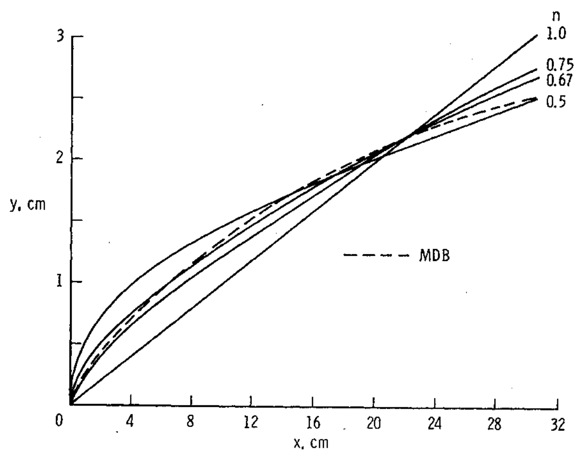

Fig. 1 Comparison of test model planforms.

Tests and Analysis

The shapes tested were a series of power-law bodies $[y = y_{max}(x/l)^n]$ and a theoretical minimum drag body (MDB). All bodies had circular cross sections and were constrained to the same length and volume. A comparison of the contours of the bodies is shown in Fig. 1 with the vertical scale expanded to emphasize the differences. These bodies are described in more detail in Ref. 1 and 2.

The inviscid values of $(C_{D,l^2})_{min}$ were obtained by the method of characteristics using a 45° conical nose to initiate the calculations. Zero-lift drag coefficient is based on model length squared since both planform area and base area vary from model to model due to the length-volume constraint.

The experimental data were obtained in the 22-in. Helium Tunnel and the 15-in. Hypersonic Flow Tunnel at the Langley Research Center. Except for the minimum drag shape in the 22-in. Helium Tunnel, all of the data have been previously published.[1,2] The test conditions for all of the tests are presented in Table 1.

An attempt to correlate the zero-lift drag data obtained in these facilities with inviscid values using the parameter $M_\infty(Re_{\infty,l})^{-1/2}$ (Fig. 2) was unsuccessful, although this parameter has been used with success in the past[3] to correlate hypersonic data from air tunnels at similar temperatures. The parameter did correlate the $M = 20$ data and the inviscid results linearly, while the $M = 10.03$ data are considerably above the correlation curves. Apparently, general correlation requires that the wide variations in test temperatures and possible variations due to differences in the ratios of specific heat be considered.

Table 1 Test conditions

Test	M_∞	$Re_{\infty,l}$	P_T, N/m²	T_T, °K	Facility
Present investigation and Ref. 2	18.1	1.65×10^6	2.2×10^6	306.5	22-in. Helium Tunnel
	19.0	2.50×10^6	3.6×10^6	305.4	
	20.3	4.40×10^6	7.0×10^6	307.6	
	21.6	8.00×10^6	13.9×10^6	303.2	
Ref. 1	10.0	1.4×10^6	6.9×10^6	1000.0	15-in. Hypersonic Flow Tunnel

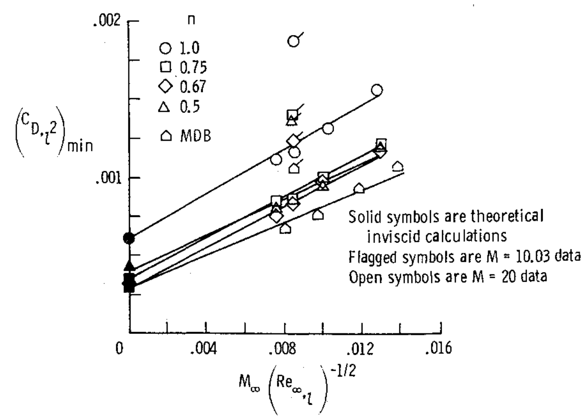

Fig. 2 Minimum drag coefficient variation as a function of $M_\infty(Re_{\infty,l})^{-1/2}$.

A better correlation parameter for the present data is the "hypersonic viscous parameter," $\bar{V}'_\infty = M_\infty(C'_\infty/Re_{\infty,l})^{1/2}$, which was shown by Whitfield and Griffith[4] to be useful in correlating hypersonic zero-lift drag data on cones with theory. Values of $\bar{V}'_\infty$ for the data were calculated from test conditions using the equations from Ref. 5 to determine the C'_∞. These equations are formulated such that for helium the variation of viscosity with temperature follows a power law, while for air a modified form of Sutherland's Law is followed. Monaghan's relationship was used to determine reference temperature. The correlation with $\bar{V}'_\infty$ of the zero-lift drag coefficient, based on body length squared, is shown in Fig. 3. The correlation is excellent, considering that it not only involves inviscid and viscous conditions, varying Mach number, and ratio of specific heats, but it also retains linearity.

Conclusions

Results presented support use of the hypersonic viscous parameter, $\bar{V}'_\infty$, advocated by Whitfield and Griffith in the correlation of hypersonic zero-lift drag results obtained from a wide spectrum of state conditions varying from the theoretical inviscid conditions to viscous flow. The excellent correlation obtained for zero-lift drag data of a series of power-law bodies and a theoretical minimum drag body offers promise that this parameter may also be useful in extrapolating ground facility data to flight conditions. Additional wind-tunnel tests at different conditions and free-flight data are needed to verify this conclusion.

References

[1] Spencer, B., Jr. and Fox, C. H., Jr., "Hypersonic Aerodynamic Performance of Minimum-Wave-Drag Bodies," TR-R-250, 1966, NASA.

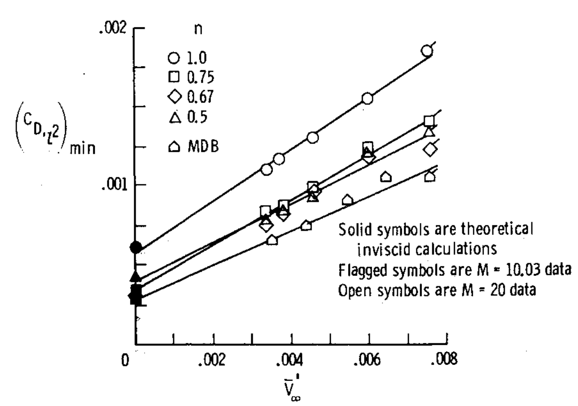

Fig. 3 Minimum drag coefficient variation as a function of the hypersonic viscous parameter.

[2] Love, E. S., Woods, W. C., Rainey, R. W., and Ashby, G. C., Jr., "Some Topics in Hypersonic Body Shaping," AIAA Paper 69-181, New York, 1969.

[3] Mueller, J. N. and Winebarger, R. M., "Viscous Effects on Hypersonic L/D of Three Classes of Manned Spacecraft," *Journal of Spacecraft and Rockets*, Vol. 4, No. 10, Oct. 1967, pp. 1394–1395.

[4] Whitfield, J. D. and Griffith, B. J., "Hypersonic Viscous Drag Effects on Blunt Slender Cones," *AIAA Journal*, Vol. 2, No. 10, Oct. 1964, pp. 1714–1722.

[5] Bertram, M. H., "Hypersonic Laminar Viscous Interaction Effects on the Aerodynamics of Two-Dimensional Wedge and Triangular Planform Wings," TN-D-3523, 1966, NASA.

Correlation of Ion and Beam Current Densities in Kaufman Thrusters

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IN the absence of significant direct impingement erosion, electrostatic thruster accelerator grid lifetime will be determined by the charge exchange erosion that occurs where the ion beam current density peaks. In order to maximize the thrust from an engine with a specified grid lifetime, the ion beam current density profile should therefore be as flat as possible. Knauer[1] has suggested this can be achieved by establishing a radial plasma uniformity within the thruster discharge chamber, and his tests with the radial field thruster provide an example of uniform plasma properties within the chamber and a flat ion beam profile occurring together. The following study shows that in particular the ion density profile within the chamber determines the beam current density profile and that a uniform ion density profile at the screen grid end of the discharge chamber should lead to a flat beam current density profile.

A 15 cm, SERT II thruster described in Ref. 2 was equipped alternately with flat grids (0.23 cm separation) and dished grids (0.089 cm separation) and was operated over the range of beam current and high voltage conditions indicated in Table 1. In addition the cathode pole piece was modified so the critical magnetic field line and hence the ion density profile at the screen grid could be altered. The mean ion beam current density profile at the accelerator grid was determined by sweeping a Faraday probe through the beam at the four axial locations indicated in Fig. 1 and extrapolating the resulting data at several radial positions. back to the plane tangent to the center of the accel grid. Similarly, Langmuir probe data were obtained at locations shown on Fig. 1 which are 11 mm and 23 mm from the plane of contact of the screen grid and thruster body (Tests 1–5) or the 11 mm, 17 mm and 23 mm locations (Tests 6–9). These data were then used to extrapolate to the ion densities at this plane of contact. The current and ion density profiles at the accel and screen grids were normalized using, respectively, the maximum current and ion densities corresponding to the profile in question.

A typical comparison between the resulting profiles is presented as Fig. 2 (Test 3 of Table 1). A linear regression analysis[3] was conducted using the ion density data points shown as solid symbols on the typical plot and the values of beam current density at the same radial location (picked from the dotted line). The resulting correlation coefficients for each set of data, as well as the correlation coefficient for the pooled data (0.945) are given in Table 1. Since the data were

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