# Hypersonic Low-Density Cone Drag

A. G. Keel Jr.,* L. G. Kraige,† R. D. Passmore,† and R. N. Zapata‡
*University of Virginia, Charlottesville, Va.*

## Theme

THE objective of this experimental study has been to obtain precise cone drag data in the transition regime of low-density hypersonic flow. Data of sufficient quality to 1) establish the variation of $C_D$ over this regime, 2) allow meaningful comparison with theory, and 3) allow single parameter studies to be conducted has been sought.

In conjunction with a capability of high resolution, the first and perhaps foremost requirement of such data is reproducibility since common systematic uncertainties are usually more tolerable when variations (especially normalized) are of primary interest or when relative comparisons (to determine a single parameter's influence) are to be made.

## Contents

Steady-state drag data for nine-degree semivertex angle cones at zero angle of attack have been obtained. The effect of varying the degree of nose bluntness was investigated. The experimental conditions and the range of flow parameters involved are shown in Table 1. An electromagnetic suspension system with three independent force axes is used for model support and force measurement. The flowfield is generated by means of a freejet expansion whose axial properties are computed using the semi-empirical relation for the isentropic Mach number developed by Ashkenas and Sherman.[1] Excessive viscous effects and condensation in the jet core are avoided with the present choice of test conditions (see Table 1). A simple procedure first used by Phillips[2] is employed to determine a range of supply pressures ($P_0$) such that the model drag is unaffected by the test chamber background pressure. An empirical technique[3] developed to assess the influence of axial flow gradients on the drag data is used to determine the value of $C_D$ corresponding to a uniform freestream characterized by the freestream conditions (in the freejet) at the model nose. The lack of flowfield calibration and the necessity of accounting for the flowfield gradients empirically contribute uncertainty to the absolute values of quoted drag coefficients (see Table 1).

**Table 1 Summary of experimental conditions**[a]

| Model characteristics—$\theta_c = 9°$ | | | |
|---|---|---|---|
| Model No.[b] | Length $L$, mm | Diameter $D$, mm | Bluntness ratio $\psi = 2r_n/D$ |
| 9 | 4.99 | 1.68 | 0.04 |
| 8 | 2.26 | 1.01 | 0.30 |
| 3 | 4.52 | 2.26 | 0.45 |
| 6 | 4.55 | 3.23 | 0.55 |
| Test conditions—nitrogen | | | |
| $M = 7.6$ | $\alpha = 0°$ | $T_w = 295°K$ | $T_w/T_0 = 1$ |
| $2.8 \leq Re_{W,L} \leq 103$ | | $0.069 \leq Kn(D) \leq 2.6$ | |
| $P_0 d_{0\max} = 400$ torr-mm | | $Re_{d_{0\min}} \equiv \rho^* U^* d_0/\mu^* = 600$ | |

[a] Common systematic uncertainty: in measurement of $C_D$ ±1–1.5%; in flow determination +5%.
[b] Estimated uncertainty in flow gradient assessment: model 8 ±1–2%; model 9 ±2–3%; model 3 ±3–4%; model 6 ±4–5%.

The range and quality of the data are best illustrated by the results obtained with the smallest model investigated, model 8 of Table 1. In Fig. 1 the results corresponding to 12 independent runs utilizing a total of five different source orifices ($d_0$) are presented as a plot of $C_D$ vs $Kn(D) \equiv \lambda_0\rho_0/\rho_\infty D$, where $\lambda_0$ is source mean-free-path, $\rho_0$ is source density. For the case of hard-sphere molecules $Kn(D)$ reduces to the freestream Knudsen number. More germane is the fact that $S_w/Kn(D)$, where $S_w \equiv U_\infty/(2RT_w)^{1/2}$, is simply related to an inverse Knudsen number of re-emitted molecules colliding with the incident stream. For the present conditions ($T_w = T_0$) the parameter $Kn(D)$ is related to

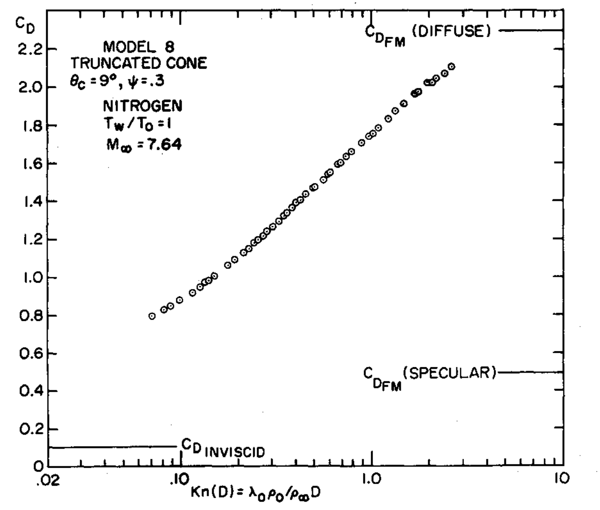


**Fig. 1 Transition regime drag results for blunt cone.**

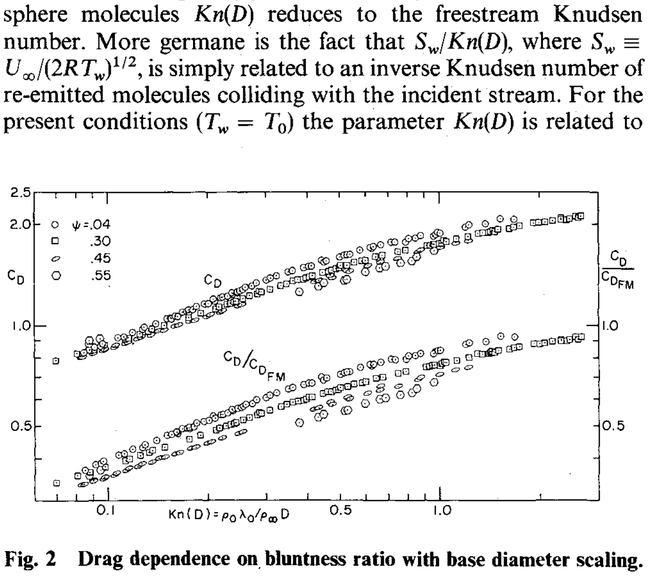


**Fig. 2 Drag dependence on bluntness ratio with base diameter scaling.**

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* Senior Scientist; now at Naval Ordnance Laboratory, Silver Spring, Md. Member AIAA.

† Graduate Research Assistant, Department of Aerospace Engineering and Engineering Physics.

‡ Associate Professor, Department of Aerospace Engineering and Engineering Physics. Member AIAA.

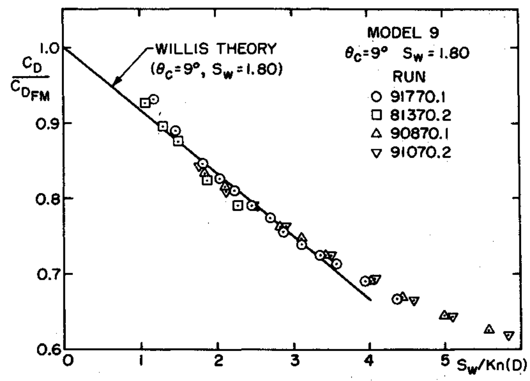


**Fig. 3 Comparison of sharp cone results with Willis' theory.**

the frequently employed "wall" Reynolds number $Re_{W,D} \equiv \rho_\infty U_\infty D/\mu_W$ through the expression $S_W/Kn(D) = [1/(\pi)^{1/2}]Re_{W,D}$. The data of Fig. 1 indicate a smooth, continuous behavior of the drag coefficient over the entire transition regime. The dependence on an essentially density-based parameter appears to be linear in the semilog plot over most of the regime with a definite tendency (at the extremes of the regime) to flare in the direction of the limiting asymptotes.

The influence of bluntness on $C_D$ is summarized in Fig. 2. In Fig. 2, plots of $C_D$ vs $Kn(D)$ and $C_D/C_{D_{FM}}$ vs $Kn(D)$ are shown. In the transition regime the systematic dependence of $C_D$ on bluntness is opposite to that predicted by free molecular calculations. Thus the spread of the traces is accentuated by the normalization of the data with respect to $C_{D_{FM}}$.

The curves begin to converge at the merged flow (higher density) end of transition. An indication of this dependence on bluntness was found by Geiger[4] for a blunt ($\psi = 0.3$) and a sharp cone of the same length. Other experimenters[5,6] have observed convergence of traces of $C_D$ for blunt and sharp cones as the merged flow regime is approached from the continuum end. The present results represent the first systematic substantiation of the bluntness influence over the transition regime.

A comparison between the upper transition regime portion of the present sharp cone results and the near-free molecule theoretical predictions of Willis[7] is shown in Fig. 3. In evaluating Willis' expansion parameter $\alpha_{bc}$ the incident/reflected collision frequency (per unit number density of reflected molecules) is assumed to be a constant for a given incident stream velocity ($U_\infty$) regardless of the velocity of reflected molecules, i.e., temperature of the model wall ($T_w$) for the assumed case of complete accommodation to the surface. For the cold-wall limit ($T_w \equiv 0$) an expression for this frequency can be formally deduced by treating the two classes of molecules (incident and reflected) as constant velocity gases. With the pseudo-Maxwell molecule assumption, this expression for a cold-wall can be used for the hot-wall case. Using a viscosity-defined collision cross section, this approach yields the following relation for Willis' expansion parameter

$$\alpha_{bc} = [\rho_\infty U_\infty L/(2\pi)^{1/2} \cos\theta_c](T_{rel}/T_w)^{1/2}/[\mu(T_{rel})] \qquad (1)$$

where $T_{rel}$ is a "measure" of the average relative velocity of incident and reflected molecules in the cold-wall case, viz. $U_\infty$. The relationship is taken as

$$T_{rel} \equiv (\pi/16R)v_{rel}^2 = (\pi/16R)U_\infty^2 \qquad (2)$$

in this case.§ The proposed method for evaluating a representative incident/reflected collision frequency yields good agreement between the experimental results and the theoretical predictions of Willis.

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§ From a practical standpoint, $T_{rel} = T_0$ could easily be justified, yielding $\alpha_{bc} = [1/(2)^{3/2} \sin\theta_c]S_w/Kn(D)$.