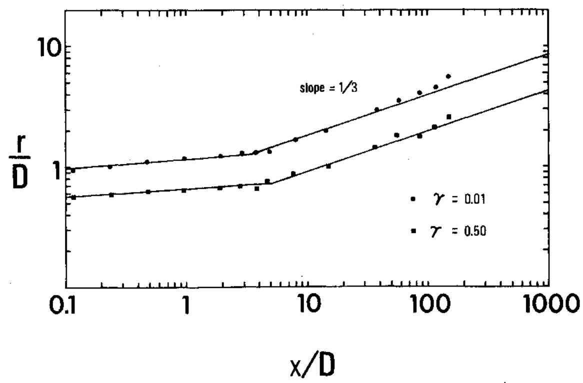

Fig. 5 Wake growth defined by the mean boundary location (γ = 0.5) and by the farthest spread of the turbulence (γ = 0.01).

reported by Hwang and Baldwin[4] in 1966. In the present work it was found that the probability of finding these laminar periods on the wake centerline increases with the downstream distance. Beyond the first 25 diameters, the corresponding decrease of the intermittency factor is proportional to $(x/D)^{-0.15}$, as seen in Fig. 4.

Figure 5 shows the growth of the wake in terms of the intermittency factor. After the first few diameters the wake radius may be seen to increase as $(x/D)^{1/3}$, as expected from similarity. Since the continuity equation requires the mean concentration per unit cross-sectional area of any scalar quantity contained within the wake C to vary inversely as the wake cross-sectional area, it might be expected that $C \sim (x/D)^{-2/3}$. However, this rate of decay does not allow for the intermittency observed in actual flows. When corrected for the intermittency on the centerline of the sphere wake, it is found that $C \sim (x/D)^{-0.82}$.

Assuming that this is a universal relation describing the decay of all scalars in the sphere wake, it was applied to the data of Gibson, Chen, and Lin,[5] who studied the decay of temperature and turbulence in the wake of a sphere in a water tunnel. The -0.82 power law was found to describe their results, both for the axial variation of the mean wake temperature and for the decay of the velocity and temperature fluctuations.

The mean defect velocity exhibits similarity for $x/D > 5$ and is well described by the familiar Gaussian profile. Figure 6 shows the turbulence intensity similarity profile. The curve has a peak near the point of maximum strain rate in the defect profile; that is, off the axis.

Also shown in Fig. 6 is the radial variation of the intermittency factor in terms of the Gaussian variable $r - \bar{r}/\sigma$, where $\bar{r}$ is the mean location of the wake boundary and σ is the standard deviation of the boundary fluctuations about $\bar{r}$. Although the distribution is not described by a single curve, even in the region of similarity, a Gaussian profile provides an adequate approximation, good to within a few percent.

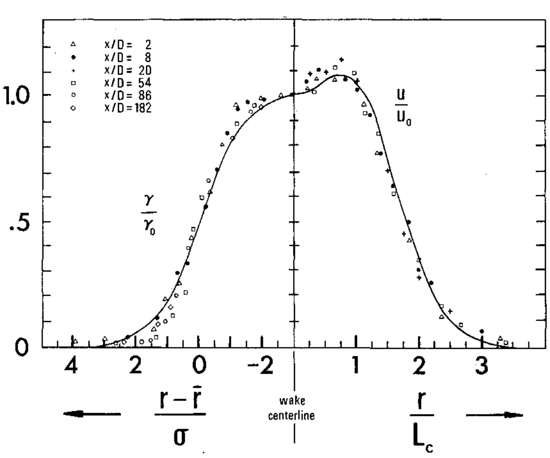

Fig. 6 Similarity profiles for the intermittency factor and turbulence intensity in the wake of a sphere.

References

[1] Riddhagni, P. R., "An Experimental Investigation of an Incompressible Turbulent Wake Behind a Sphere," MS thesis, 1968, Purdue Univ.

[2] Corrsin, S. and Kistler, A. L., "Free-stream Boundaries of Turbulent Flows," Rept. 1244, 1955, NACA.

[3] Uberoi, M. S. and Freymuth, P., "Turbulent Energy Balance and Spectra of the Axisymmetric Wake," *The Physics of Fluids*, Vol. 13, No. 9, 1970, pp. 2205–2210.

[4] Hwang, N. H. C. and Baldwin, L. V., "Decay of Turbulence in Axisymmetric Wakes," *Journal of Basic Engineering*, Vol. 88, 1966, pp. 261–268.

[5] Gibson, C. H., Chen, C. C., and Lin, S. C., "Measurements of Turbulent Velocity and Temperature Fluctuations in the Wake of a Sphere," AIAA Paper 67-20, New York, 1967.

Transition Regime Sphere Drag near the Free Molecule Limit

WINFRED M. PHILLIPS*
The Pennsylvania State University, University Park, Pa.

AND

A. R. KUHLTHAU†
The University of Virginia, Charlottesville, Va.

THERE is a great deal of interest in the problem of determining the drag on bodies in near-free-molecule flows as evidenced by a relatively extensive literature presenting both experimental data and numerical or analytical attempts to provide a solution. Also the Seventh International Symposium on Rarefied Gas Dynamics, held in Pisa during the summer of 1970, contained many contributions to the problem which should soon appear in print.

A subsidiary problem of special interest to many investigators in the field is that of the approach of the drag coefficient to the free molecule limit. This question is experimentally trying since the scatter in much of the reported data precludes any definite conclusion concerning the coincidence with this limit. Furthermore, the theoretical developments

Table 1 Sphere drag coefficient–nitrogen sample results

$M_\infty \sim$ 8–10		$T_w/T_0 \sim 1$	
C_D	$C_D/c_{D_{FM}}$	Re_2	Kn_∞
2.63	0.985	0.835	1.02
2.62	0.981	1.02	1.07
2.60	0.974	1.17	0.847
2.51	0.940	1.48	0.731
2.28	0.854	2.06	0.508
2.20	0.824	2.60	0.404
1.92	0.719	6.06	0.174
1.78	0.667	8.14	0.130
1.65	0.618	11.6	0.091
1.57	0.588	14.9	0.071
1.50	0.562	19.5	0.054

Received February 22, 1971. This research was sponsored by the U.S. Air Force Office of Scientific Research, Office of Aerospace Research Grant AF-AFOSR-1046-67 and in part by NSF-Grant GK5559.

* Assistant Professor of Aerospace Engineering. Member AIAA.

† Professor of Aerospace Engineering. Member AIAA.

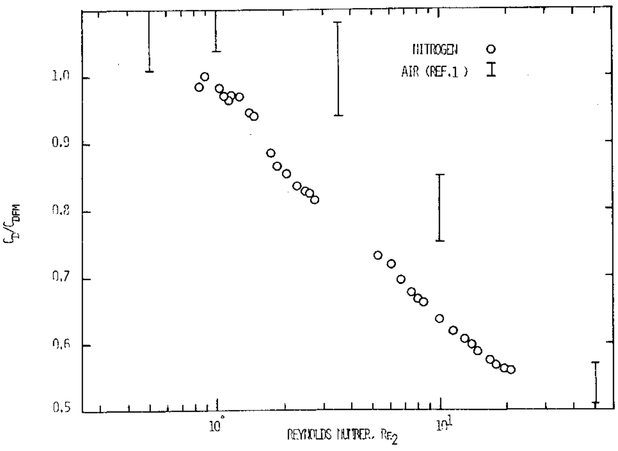

Fig. 1 Sphere drag in nitrogen and air.

have not yet reached the stage where they may speak with authority on this point. Kussoy et al. recently reported[1] some measurements with spheres using free-flight techniques which indicated an overshoot of the drag coefficient above the theoretical free molecule value. Other investigations, including the results obtained by the authors[2] using a magnetic suspension balance at the University of Virginia, imply an asymptotic approach from below with the free molecule value as the maximum limit. The objective of this Note is to present comparisons of some of the existing data and to report additional measurements relating to this problem.

All measurements at the University of Virginia were made in hypersonic flow from a freejet using a magnetic suspension system to obtain sting-free data which exhibit excellent reproducibility. Contrary to many low-density measurements obtained by other techniques, the magnetic suspension method has improved the drag force measurement to the point where the largest uncertainty is in the flow properties rather than the force determination.

Figure 1 is a representative plot of the observed drag coefficient related to the calculated value for free molecule flow in nitrogen for 0.6 mm–$\frac{1}{8}$th-in.-diam steel spheres. The independent parameter chosen is the Reynolds number behind a normal shock. Other parameters have been used with varying success in correlating data obtained under widely varying conditions,[3] and this choice is simply a matter of convenience. The data used is presented in tabular form in Table 1 and some of it has appeared previously.[2] In calculating the free molecule values, no attempt is made to infer surface or material effects and complete accommodation with diffuse reflection is assumed. This assumption appears valid in view of the improved observation of gas surface interaction which have become available during the past few years.[4] The recent results of Kussoy et al.[1] are also shown in Fig. 1 for comparison.

Focusing attention on the near-free-molecule limit, our data, which must be assumed as representative of a warm wall condition (i.e., $T_w/T_0 \simeq 1$), indicate no tendency to overshoot the free molecular limit, at least for Reynolds number of order unity. Unfortunately we are not able to operate at lower Reynolds numbers and so cannot obtain positive confirmation of this limit. However, recent results by Legge and Koppenwallner[5] support the absence of an overshoot for Re_2 of the order of 0.1. These results are again for warm wall conditions. The results of Kussoy et al., which are for cold wall conditions (i.e., $T_w/T_0 \ll 1$), seem to indicate an overshoot of the drag coefficient above the free molecular value, although the scatter in the data makes a definite interpretation difficult. Furthermore, it is noted that the normalization to the free molecular limit fails to collapse the data into agreement in the mid-transition range. However, a previous analysis[2] has shown that the warm wall data normalized to the free molecular value are in agreement with similarly reduced results of Kinslow and Potter[6] for cold wall conditions in the Reynolds number range from 1.0 to 10.

Table 2 Sphere drag coefficient–argon sample results

$M_\infty > 15$		$T_w/T_0 \sim 1$	
C_D	Kn_∞	C_D	Kn_∞
2.73	0.76	2.11	0.189
2.69	0.68	1.53	0.039
2.50	0.379	1.47	0.026
2.27	0.251	1.41	0.017
2.14	0.209	1.38	0.014

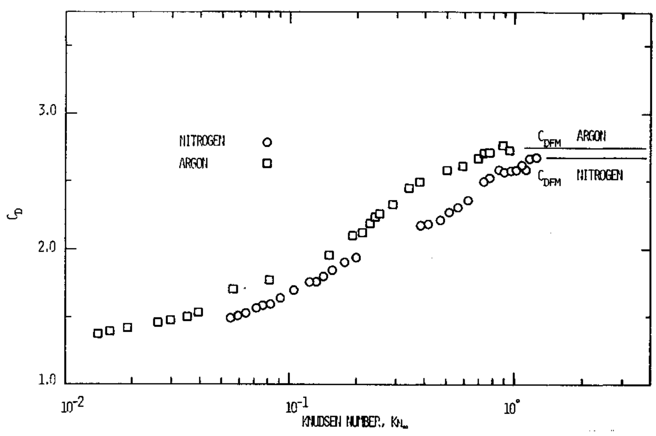

Fig. 2 A comparison of sphere drag in nitrogen and argon.

In Fig. 2 we present additional results similarly obtained for argon together with those for nitrogen. Here the observed drag coefficient is plotted as a function of the freestream Knudsen number. The values of the data points for argon are given in Table 2. Here again a smooth approach from below to the free molecular limit is noted at an abscissa value of approximately unity. While the argon data rises more quickly to its free molecular limit, there is no suggestion of any overshoot.

In conclusion, therefore, it would seem that there is no evidence to support a free molecular overshoot for warm wall sphere drag data. There is certainly room for conjecture when considering cold wall conditions. The problem is complicated not only by the need for more accurate measurements but also by the need to be concerned with such effects as adsorption due to the cold wall or some reduction in the value of the molecular reflection parameter which may be expected to take place at higher incident energies.

References

[1] Kussoy, M. I., Stewart, D. A., and Horstman, C. C., "Sphere Drag in Near Free-Molecule Hypersonic Flow," *AIAA Journal*, Vol. 8, No. 11, Nov. 1970, p. 2104.

[2] Phillips, W. M. and Kuhlthau, A. R., "Drag Measurements on Magnetically Supported Spheres in Low Density High Speed Flow," *Rarefied Gas Dynamics*, Vol. 1, Academic Press, New York, 1969, p. 711.

[3] Potter, J. L. and Miller, J. T., "Sphere Drag and Dynamic Simulation in Near-Free-Molecular Flow," *Rarefied Gas Dynamics*, Vol. 1, Academic Press, New York, 1969, p. 723.

[4] Fisher, S. S., Hagena, O. F., and Wilmoth, R. C. W., "Flux and Speed Distributions of Molecular Beams after Scattering by Metal Surfaces," *The Journal of Chemical Physics*, Vol. 49, 1968, p. 1562.

[5] Legge, H. and Koppenwallner, G., "Sphere Drag Measurements in a Free Jet and a Hypersonic Low Density Tunnel," *Rarefied Gas Dynamics*, Academic Press, New York, to be published, 1971.

[6] Kinslow, M. and Potter, J. L., "The Drag of Spheres in Rarefied Hypervelocity Flow," AEDC-TDR-62-205, Dec. 1962, Arnold Engineering Development Center, Tullahoma, Tenn.