Research Report SC-RR-64-1796, 1965, Sandia Corp., Albuquerque, N. Mex.

[14] Pasiuk, L., "Measurements of the Static Pressure Distributions and Shock Shape on an Oblate Spheroid at Mach Numbers of 3 and 6," NOLTR 66-138, July 1966, Naval Ordnance Lab., Silver Spring, Md.

[15] Van Dyke, M. D., "Hypersonic Flow Behind a Paraboloidal Shock Wave," *Journal de Mécanique*, Vol. 4, No. 4, Dec. 1965, pp. 477–493.

Measurements in the Turbulent Wake of a Sphere

P. R. Riddhagni,* P. M. Bevilaqua,† and P. S. Lykoudis‡
Purdue University, West Lafayette, Ind.

Introduction

THIS work stems from current interest in the axial decay of scalars in turbulent wakes. An axisymmetric wake was generated in a low speed, closed circuit wind tunnel using a one inch sphere suspended at the inlet of the test section with four piano wires. The test Reynolds number was 78,000.

A TSI anemometer of constant temperature type with a tungsten sensor 150 μin. in diameter was used. The intermittency circuit was similar to the one described by Corrsin and Kistler[2] and was constructed by Riddhagni. The wake was probed at 15 stations spanning 200 diam downstream of the sphere into the tunnel diffuser. Measurements made in the diffuser were later repeated in another tunnel with a longer test section. The same results were obtained.

Wake Similarity

Below the critical Reynolds Number, the boundary layer remains laminar across the front face of the sphere, separating as it enters the adverse pressure gradient on the rear face. The separated boundary layer and the flow that has been accelerated around the sphere combine to form a strong shear layer in the first diameter downstream. The mean velocity overshoots its freestream value, U_∞, within the first diameter, Fig. 1, and the turbulence intensity reaches its peak value at the end of this region.

In the next few diameters the wake becomes dynamically similar; that is, all profiles become independent of axial position when normalized with characteristic length and velocity scales, L_c and U_c. In the axisymmetric wake these scaling parameters vary as powers of x: $L_c/D \sim [(x - x_0/D)]^{1/3}$ and $U_c/U_\infty \sim [(x - x_0/D)]^{-2/3}$ where x_0 is the virtual origin of wake similarity. The decay of turbulence in the region of similarity follows a power law; for the axisymmetric wake, $(u/U_\infty) \sim (x/D)^{-2/3}$. The axial component of the turbulence intensity along the wake centerline has thus been shown as a function of x/D in Fig. 2. The straight line for $x/D > 5$ indicates similarity beyond that point. The virtual origin is found to coincide with the actual origin, in contrast to the results of Uberoi and Freymuth[3] who found $x_0 = 12D$ and similarity for $x/D > 50$ at a Reynolds number of 8,600.

Further evidence that similarity is attained within the first few diameters may be found by normalizing the centerline defect velocity, $U_0 = U_\infty - U$, and turbulence intensity, u_0, with the characteristic scale velocity as shown in Fig. 3. The lack of variation for $x/D > 5$ again shows similarity.

Wake Intermittency

Measurements of the intermittency factor made on the axis of the wake revealed that the fully turbulent core is confined to approximately the first five sphere diameters downstream. Beyond this distance the corrugation amplitude of the turbulent front has increased to the point where it is on the order of the wake radius, causing periods of laminar flow on the axis. This feature of sphere wakes was first

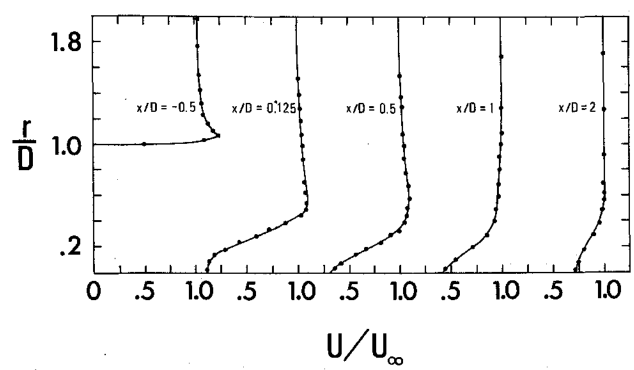

Fig. 1 Mean velocity profiles in the recirculation region.

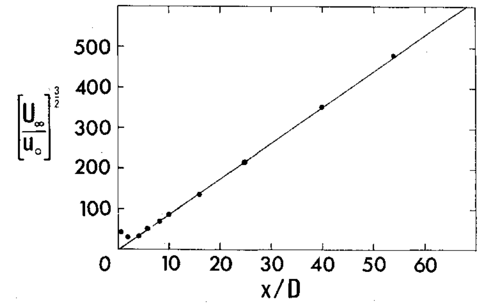

Fig. 2 The virtual origin of wake similarity shown by the axial turbulence intensity.

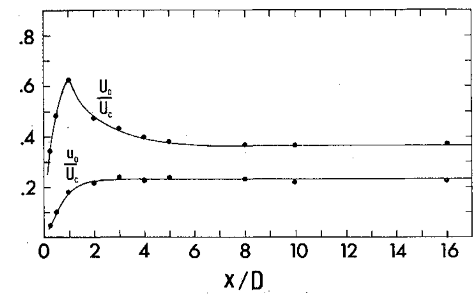

Fig. 3 The approach to similarity of the defect velocity and turbulence intensity on the wake centerline.

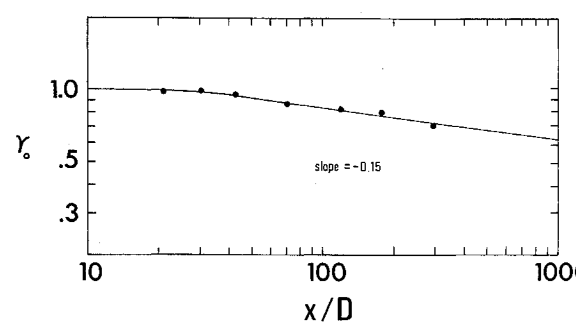

Fig. 4 The axial variation of the intermittency factor on the wake centerline.

Received February 16, 1971; revision received March 22, 1971.

* Graduate Research Assistant; now at the Royal Thai Air Force Academy, Thailand.

† Graduate Instructor in Research. Student Member AIAA.

‡ Professor of Aeronautics, Astronautics and Engineering Sciences. Associate Fellow AIAA.

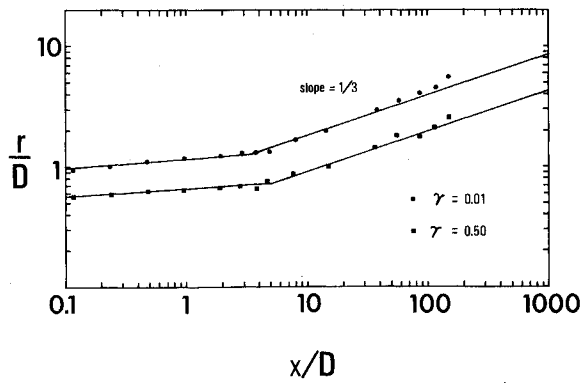

Fig. 5 Wake growth defined by the mean boundary location ($\gamma = 0.5$) and by the farthest spread of the turbulence ($\gamma = 0.01$).

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.

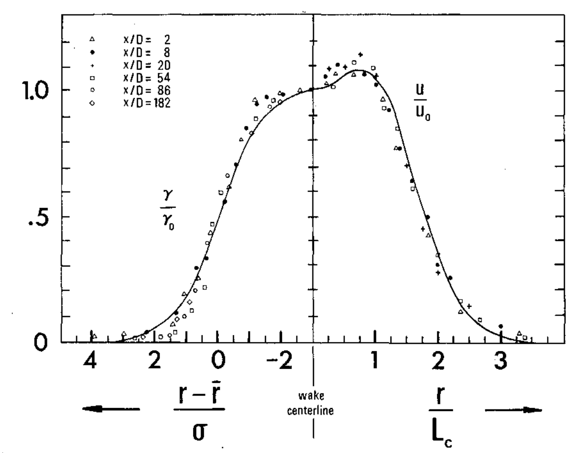

Fig. 6 Similarity profiles for the intermittency factor and turbulence intensity in the wake of a sphere.

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_{DFM}	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.