[12] Freeman, N. C., "Non-equilibrium flow of an ideal dissociating gas," J. Fluid Mech. 4, 407–425 (1958).
[13] Wray, K. L., "Chemical kinetics of high temperature air," Avco Research Rept. 104 (June 1961).
[14] Lin, S. C., Fyfe, W. I., and Neal, R. A., "Rate of ionization behind shock waves in air," Avco Research Rept. 105 (September 1960).
[15] Allen, R. A., Keck, J. C., and Camm, J. C., "Non-equilibrium radiation from shock heated nitrogen and a determination of the recombination rate," Avco Research Rept. 110 (June 1961).
[16] Teare, J. D., Georgiev, S., and Allen, R. A., "Radiation from the non-equilibrium shock front," Avco Research Rept. 112 (October 1961).
[17] Wick, B. H., "Radiative heating of vehicles entering the earth's atmosphere," *The High Temperature Aspects of Hypersonic Flow*, edited by W. C. Nelson (Pergamon Press, New York, 1963), pp. 607–627.
[18] Lobb, R. K., "Experimental measurement of shock detachment distance on spheres fired in air at hypervelocities," Ref. 17, pp. 519–527.
[19] Shih, W. C. L. and Baron, J. R., "Nonequilibrium blunt-body flow using the method of integral relations," AIAA J. 2, 1062–1071 (1964).
[20] Allen, H. J., Seiff, A., and Winovich, W., "Aerodynamic heating of conical entry vehicles at speeds in excess of earth parabolic speed," NASA TR R-185 (1963).

JULY 1965 AIAA JOURNAL VOL. 3, NO. 7

Studies of Wakes of Support-Free Spheres at $M = 16$ in Helium

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A detailed investigation of the flow field behind spheres magnetically suspended in a Mach 16 helium stream has been initiated. Pitot pressure and constant-current hot-wire measurements have been employed to investigate a region from 1 to 50 body diameters downstream of two sphere diameters, 0.75 and 0.375 in., and several body Reynolds numbers from 45,400 to 109,000. Previous data reported in the literature indicated that transition to turbulence should occur within the region of investigation, but hot-wire voltage measurements lead to the conclusion that the wake is probably laminar. Detailed radial and axial pitot pressure distributions are presented and compared with two-dimensional cylinder data at the same Mach number, ballistic-range data, and two theories. The measured rms hot-wire fluctuation voltage was constant at a very low value along the wake axis but showed peaks at the wake edge.

Nomenclature

D = body diameter
D_w = wake diameter
f = frequency
M = Mach number
p = static pressure
P_t = pitot pressure
P_0 = stagnation-chamber pressure
$Re = \rho u/\mu$ = Reynolds number per unit length
T_{aw} = adiabatic recovery temperature
T_0 = stagnation-chamber temperature
T_w = hot-wire temperature
u = velocity
$V_{\rm rms}$ = root-mean-square hot-wire fluctuation voltage
X = radial distance measured from wake axis
Y = radial distance measured from wake axis
Z = axial distance measured from sphere center
ρ = density
μ = molecular viscosity coefficient
τ = hot-wire time constant

Subscripts

℄ = evaluated at wake centerline
e = evaluated at wake edge
∞ = evaluated in freestream
$(\ )_*$ = conditions when flow traversing normal shock at M_∞ has expanded back to p_∞

Presented at the AIAA 2nd Aerospace Sciences Meeting, New York, N. Y., January 25–27, 1965. This study was sponsored by the Advanced Research Projects Agency (Ballistic Missile Defense Office) and technically administered by the Fluid Dynamics Branch of the Office of Naval Research under Contract No. Nonr-1858(37). The program was also partially supported by the Aerospace Research Laboratories, Office of Aerospace Research, U. S. Air Force, Wright-Patterson Air Force Base, Ohio, under Contract No. AF 33(615)-1079.

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1. Introduction

DURING the past several years, the interest in the area of hypersonic wakes has resulted in a large number of both theoretical and experimental investigations of the wake flow region. The key motivation for these studies is the desire to predict the flow properties in the wakes of vehicles reentering the earth's atmosphere as a method of analyzing the long observable trails.

Hypersonic flow fields are generally divided into two classes comprising blunt and slender bodies. The limiting case of an axisymmetric blunt-body flow field is well represented by that of a spherical body (Fig. 1). Curvature of the bow-shock wave results in a highly rotational flow-field downstream of it. The fluid in the viscous boundary layer, which has traversed a strong, nearly normal shock wave, separates from the body and forms a free shear layer. After passing through a compression region known as the "neck," the separated boundary layer forms a hot viscous trail or wake. If the wake is laminar, it grows via molecular diffusion into a region of varying entropy. If the wake is turbulent, growth is accomplished through turbulent diffusion. The hot wake is cooled through two mechanisms: expansion and conduction. The expansion from a relatively high-pressure area around the neck region to freestream ambient pressure causes the temperature of the wake to decrease. This effect is aug-

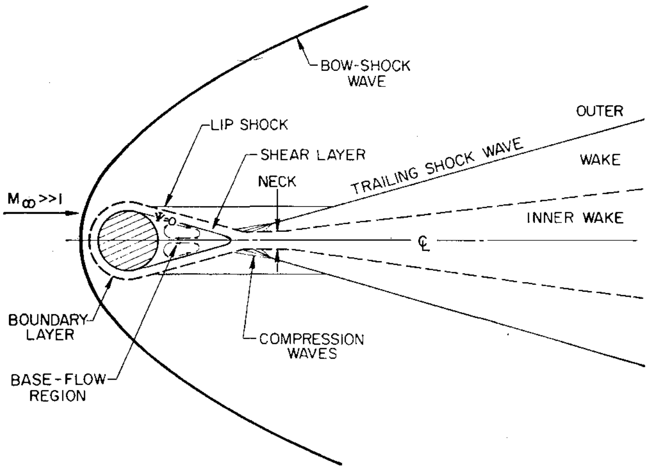

Fig. 1 Schematic drawing of flow field.

mented by the entrainment of the cooler fluid from the inviscid wake into the viscous wake.

Any detailed calculations of the real flow around and behind a high-speed body must, of necessity, start with a calculation of the local pressure and temperature at a point. This is determined by fluid mechanics plus the full chemistry. Following streamlines, step-by-step procedures can be used to calculate the flows, including relaxation and lag times involved in the chemistry. Since the local conditions generated by the fluid mechanics are a key part of this process of calculation, the wind-tunnel studies have been carried out to provide a framework upon which to test the fluid mechanical model in the absence of chemistry. The present investigation was initiated to extend the wind-tunnel studies to high Mach numbers for support-free axisymmetric bodies, particularly spheres. The model was supported magnetically in a helium wind tunnel operating at a Mach number of 16. The wind tunnel operates at conditions where the flows are purely fluid mechanical (no real gas nor ablation effects). The present study was focussed on obtaining detailed information on the fluid mechanical parameters in the wake of two spheres, 0.75 and 0.375 in. in diameter. The studies extended from the body to a distance of about 50 diam downstream of the body. Results are compared with the experimental data from various ballistic ranges and with Ledger's[1] data for a two-dimensional cylinder at the same freestream conditions. Comparisons are also made with calculations using the theories of Lees and Hromas[2] and Zeiberg and Bleich.[3] The theory of Lees and Hromas is an integral method for turbulent wakes, whereas Zeiberg and Bleich use the finite-difference method to solve the laminar boundary-layer equations.

2. Experimental Techniques

Equipment

A conventional wind tunnel of the blow-down variety was employed for the investigation. The tunnel uses helium as a working gas and has a 6- to 8-min testing time. All tests were run at a constant stagnation temperature of 535°R. Stagnation pressures ranging from 100 to 300 psia result in variations of freestream Mach numbers from 14.5 to 16.8, and freestream Reynolds numbers per inch from 60,000 to 160,000 (Fig. 2). The model is located in a 6- to 7-in. diam test section 6 in. downstream of the exit of the contoured nozzle. An inviscid core of uniform flow 2 to 3 in. in diameter extends for 18 in. behind the model location. A drive mechanism capable of moving a probe in three orthogonal directions throughout the region of interest is located just downstream of the test section.

A unique feature of the present investigation is the use of a magnetic suspension system to eliminate model support interference effects. A complete description of the system is given by Zapata and Dukes.[4] Since the magnetic suspension system is an integral part of the present research, a brief description of it will be included.

The system was designed specifically to hold spherical bodies in a hypersonic helium tunnel. Since the only steady-state forces present are the drag of the sphere and the force of gravity, the tunnel was constructed vertically to align these forces and thus reduce system complexity. Because the model is spherical, control in only three orthogonal directions is required (i.e., no attitude controls are needed). Six coils are employed for this purpose, each pair providing appropriate forces in each of the three directions. Detection of the sphere position is accomplished by three light beams, one for each of the three orthogonal directions. Some discussion of sphere movement and positioning can be found in Sec. 3.

The 0.75-in.-diam sphere was made of ferrite and was round to better than 0.001 in. No exact quantitative measurement of surface roughness has been made, but an estimate placed it at less than 12 μin. The 0.375-in.-diam. sphere was a commercially available ball bearing.

Instrumentation

Information about the wake was obtained from measurement of pitot pressure and constant-current hot-wire signals. Position of the probe was measured by means of potentiometers (one for each of the three directions of travel) linear to $\pm 0.1\%$. The potentiometer output was recorded on one axis

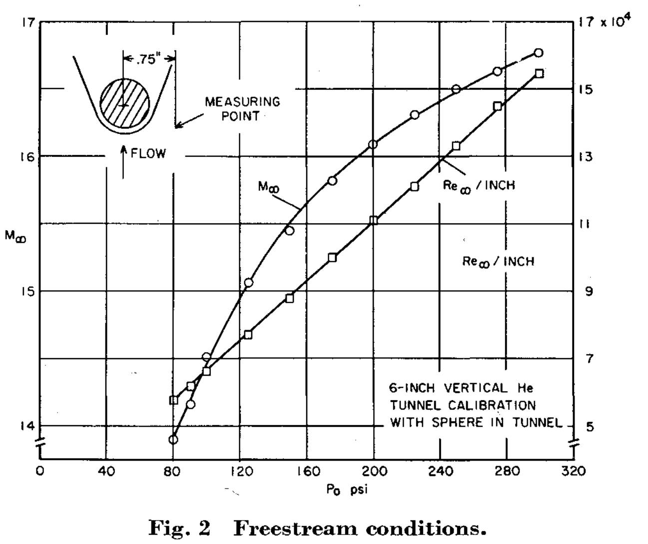

Fig. 2 Freestream conditions.

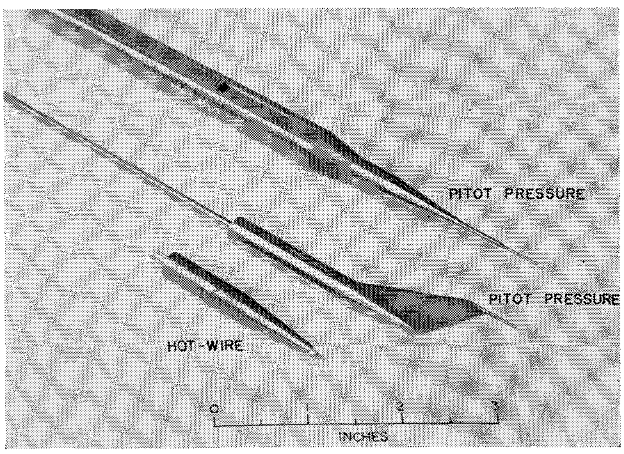

Fig. 3 Wind-tunnel probes.

of a Moseley X-Y recorder, the other axis being used to record the hot-wire or pressure transducer signal.

Two pitot pressure probes were used during the research program (Fig. 3). Both probes had circular orifices of 0.024-in. i.d. and 0.032-in. o.d. The two geometries caused no noticeable differences. Pressures were normally measured by a 2-psia Statham transducer, the output being recorded on the Moseley X-Y recorder. For some tests, where the pressure level was quite low, a 0.5-psia Pace transducer was employed.

Hot-wire probes consisted of two tapered supports (needles) held in a streamlined body which could be plugged into an electrical connector in the sting (Fig. 3). The supports were made of stainless steel to eliminate corrosion and were about 0.150 in. long, about 0.016 in. in diameter at the base, and 0.025 in. apart at the tips. Wollanstan platinum-10% rhodium wire of 0.0001-in. diam. proved to be quite durable. A Shapiro-Edwards Model 50 constant-current hot-wire anemometer system was used in conjunction with the previously described probes. The unit includes a constant-current source, a bridge network, circuits to compensate for the thermal inertia of the wire, and vacuum thermocouples to convert the a.c. signal component to an rms signal. The time constant of the hot wire usually was about 1 to 2 msec. Compensation with the Shapiro-Edwards unit (floor to ceiling ratio of 500) allowed wire response to fluctuations in flow properties to be extended up as far as 40 to 80 kc.

3. Accuracy

Tunnel stagnation-chamber conditions remained quite steady throughout a test with P_0 varying less than ± 1 psia and T_0 changing less than 1°R. Variations of freestream conditions were small throughout the region of testing; M_∞ varied at most by ± 0.2 in the radial (X and Y) directions and ± 0.3 in the axial directions.

Some detailed studies of sphere movement were conducted in order to determine both the frequencies and magnitudes of motion. Typical results are shown in Table 1. The magnitude of the motion was less than the spatial resolution of any of the measurements recorded in the wake. Some spinning of the sphere was also present, and it was always observed to be about 1 to 3 rps. These numbers correspond to peripheral velocities from $\frac{1}{10}$ to $\frac{1}{2}$ fps. Compared with the flow velocities involved ($U_\infty = 5750$ fps), this speed was negligible. The axis of spin was always aligned with the flow direction (Z axis).

Precision of the axial (Z) location of the probe was estimated to be $\pm 0.03D$ for the 0.75-in.-diam. sphere. Errors in the radial (X and Y) locations of the probe were $\pm 0.02D$ for the same sphere. The corresponding errors for the 0.375-in. sphere were double these values.

Pitot pressure measurements were accurate to ± 0.01 psia in most regions of the flow field. In areas where the pressures were low and/or the pressure gradients large, the accuracy decreased to ± 0.02 psia. For this reason, some axial surveys were made with a Pace 0.5 psia transducer.

4. Experimental Results

Introduction

Pitot pressure, mean hot-wire voltage, and fluctuation voltage data were measured in the wake of a 0.75-in. sphere from 1.5–20 diam downstream of the body, and in the wake of a 0.375-in. sphere up to 50 diam behind the model. The majority of data were gathered at one freestream Reynolds number

Table 1

	Movement, in.			Noted frequency		
D, in.	X	Y	Z	X, cps	Y	Z
0.375	±0.002	±0.002	±0.002	10	...	...
0.750	±0.001	±0.0015	±0.001	9	...	...

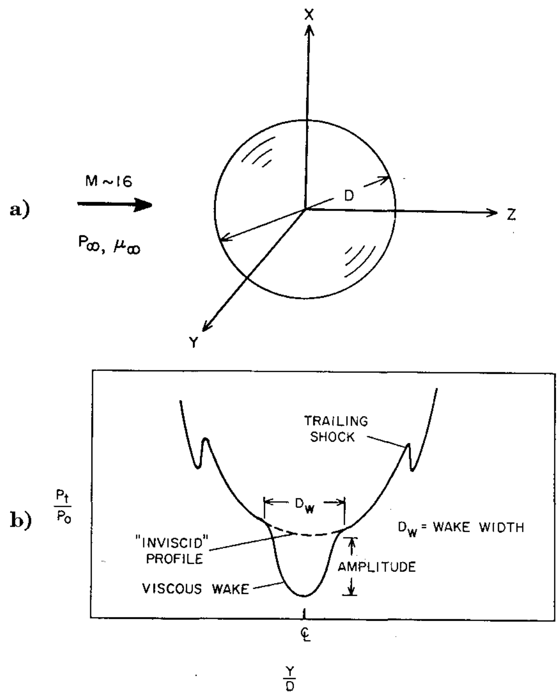

Fig. 4 Nomenclature and definitions.

per inch (i.e., one value of stagnation pressure). Limited amounts of data have been obtained at other freestream Reynolds numbers.

A schematic drawing of the flow field is shown in Fig. 1, and some of the important features are discussed in the Introduction. The coordinate system employed in this report is shown in Fig. 4a. It should be noted that the axial distance (Z) is always measured from the center of the sphere. Some features of the flow field which are recognizable from pitot pressure profiles are labeled in a schematic profile shown in Fig. 4b. The definition of wake edge used throughout this report is defined graphically in Fig. 4b, and is taken as the point where the actual profile diverges from a smooth curve drawn to approximate an "inviscid profile." As shown in Fig. 4b, the pitot pressure has been nondimensionalized by the stagnation-chamber pressure P_0.

Pitot Pressure Profiles

A set of four pitot pressure profiles in the near-wake region from $1\frac{1}{2}$ to 4 diam downstream of the 0.75 in. sphere is shown in Fig. 5. In this region it can be seen that the wake width does not change greatly, and the amplitude remains essentially constant. At $1\frac{1}{2}$ diam, a discontinuity is visible in the region outside the viscous wake. By 2 diam, this discontinuity has become superimposed on the coalescing compression waves from the neck region. The discontinuity is believed to be the separation (lip) shock generated as the boundary layer separates from the body.

A representative group of pitot pressure profiles downstream of the neck region behind the 0.75-in.-diam sphere is shown in Fig. 6. Three profiles in the wake of the 0.375-in. sphere are shown in Fig. 7. Whereas close to the body, $Z/D = 8$, the viscous-wake amplitude is rather large, for $Z/D = 40$, the viscous wake has become almost indistinguishable from the inviscid wake.

To evaluate the effect of Reynolds number variations, pitot pressure profiles have been measured behind the 0.75-in.-diam sphere for several other freestream Reynolds numbers per inch. As shown in Fig. 2, the value of the freestream Mach number, as well as that of the Reynolds number, changes as the stagnation pressure is varied. For this reason, pitot pressures recorded at various stagnation pressure conditions have been nondimensionalized by $P_{t,\infty}$, the freestream

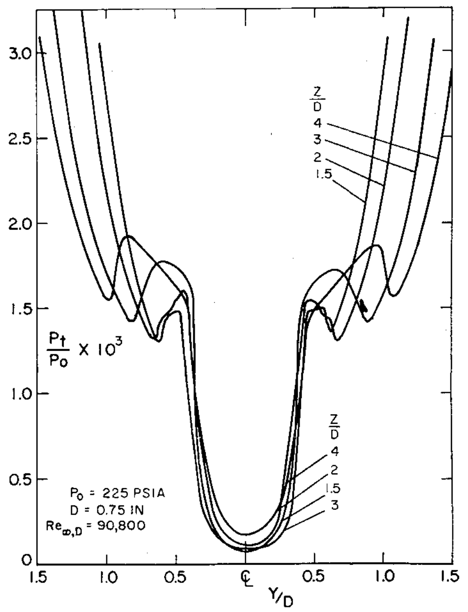

Fig. 5 Pitot pressure profiles near wake.

pitot pressure. Ledger[1] found that this procedure matched the pitot pressure profiles in the inviscid portion of the wake. Since the inviscid region should be unaffected by a Reynolds number change, this procedure seems to provide a better framework in which to study Reynolds number effects.

Pitot pressure profiles obtained at 2 diam behind the 0.75-in. sphere are shown in Fig. 8. The profiles are similar (within experimental accuracy) except in the region at the edge of the viscous wake. At the higher Reynolds numbers, a separation shock is distinguishable from the coalescing compression waves. However, at the lower Reynolds numbers, these two features have merged and are indistinguishable. Similar results were noted by Dewey[5] in his studies of two-dimensional cylinder near wakes.

Three pitot pressure traces 8 diam downstream of the body are shown in Fig. 9. The effects of the two body sizes and two body Reynolds numbers ($\sim 9 \times 10^4$ and $\sim 4.75 \times 10^4$) are shown. Although both the inviscid and viscous portions of the wake are affected, the differences are small.

Constant-current hot wires were used in a fashion similar to that of Demetriades[6, 7] in order to determine whether the wake was laminar, transitional, or turbulent. The wires were operated at a constant current of about 7 ma ($T_w/T_0 \sim 1.2$) and were frequency compensated for some average condition encountered in the wake. The compensated component of

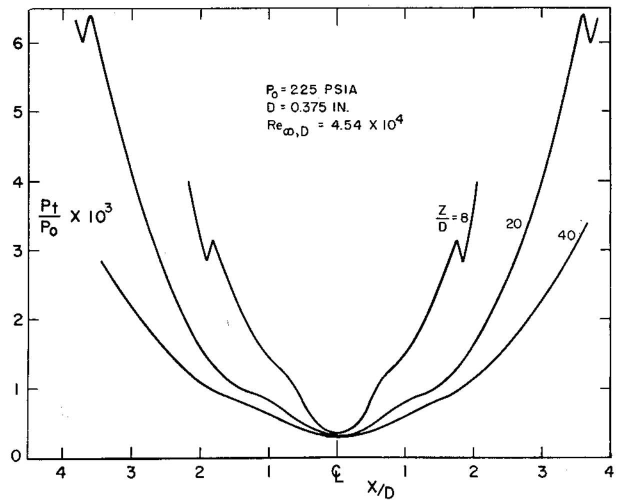

Fig. 7 Pitot pressure profiles, D = 0.375 in.

the hot-wire signal was converted into an rms signal by vacuum thermocouples. At these operating conditions, the rms signal essentially represents an rms mass flow variation.[6] From using techniques similar to those of Dewey,[5] it was evident that the hot wire was operating in a noncontinuum flow regime.

Axial surveys behind both spheres for one freestream Reynolds number per inch (120,000) are shown in Fig. 10. It can be seen that, in both cases, the signal level is about 1.2 times the noise level of the amplifiers and other circuitry. Also, it can be seen that the signal level remains essentially constant with axial distance. There is a small peak of rms voltage about 3 diam behind the 0.75-in. sphere. From viewing the data on a frequency analyzer, this appears to be due to hot-wire vibration and is not a flow phenomenon. It should be mentioned that the signal represents contributions over the wide range of frequencies noted in the figure. No numerical scale has been placed on the ordinate because the signals are only of a qualitative nature. For purposes of reference, an rms voltage signal in the freestream flow ahead of the ball is about 1.3 times the noise level, whereas that in the edge of the boundary layer is greater than 30 times the noise level.

Some surveys across the wake were made at several stations behind the sphere. Two typical profiles, one behind each sphere, are shown in Fig. 11. The rms signal peaks near the edges of the wake were always observed and were consistently

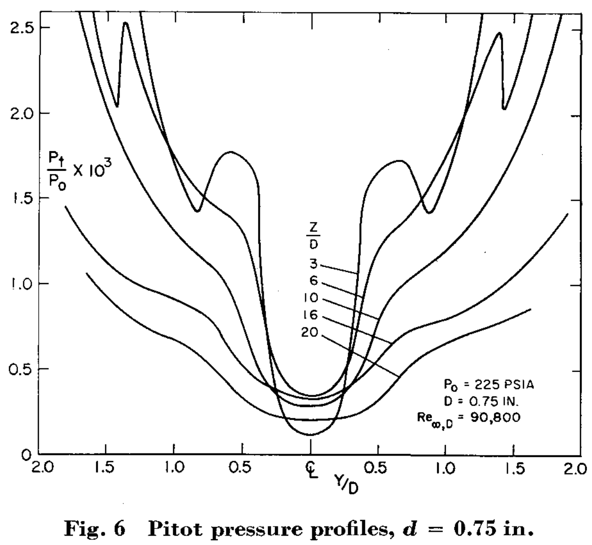

Fig. 6 Pitot pressure profiles, d = 0.75 in.

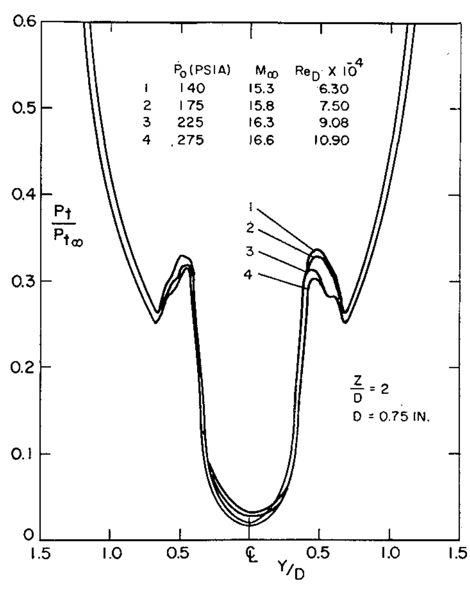

Fig. 8 Effect of body Reynolds number variation.

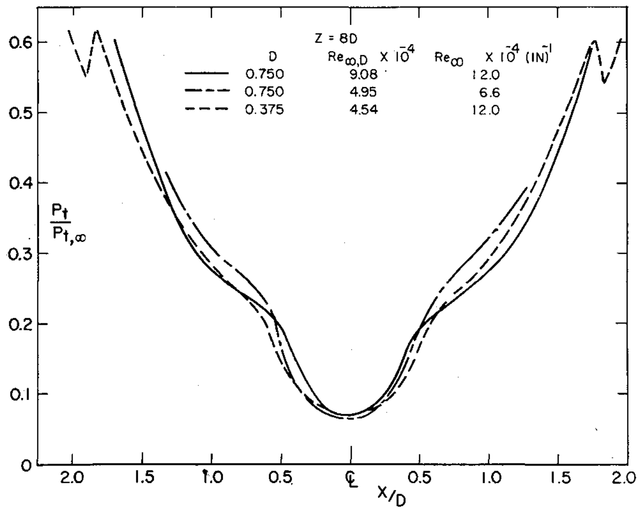

Fig. 9 Effect of body Reynolds number and body size variation.

less pronounced behind the smaller sphere than behind the larger sphere. It is not believed that these peaks are due to wire vibration. A region of low rms signal always existed near the wake centerline. Throughout the region of testing, the radial width of the low center portion was about half a body diameter and remained essentially constant with axial distance. The cause of the region of high rms fluctuation near and outside the trailing shock wave is not clear, but seems to be a characteristic of blunt-body wakes[6] and not slender-body wakes.[7]

5. Discussion

Transition and Mass Flow Fluctuation

Previous correlations of transition distances in the wakes of hypersonic spheres indicate that transition should occur within the region of measurement. Wilson's[8] correlation indicates that transition occurs when $Re_{\infty,\,x}/M_\infty \simeq 8 \times 10^4$ for $M_\infty \geq 10$, where $Re_{\infty,\,x} = \rho_\infty U_\infty x/\mu_\infty$, and x is the dimensional distance behind the body. For the present experiment, Wilson's correlation predicts that X_{tr} is 10.8 in. Lees[9] proposed that the critical Reynolds number below which transition would never occur would be $(Re_{e,\,D})_{\rm crit} = 500$, where $Re_{e,\,D} = \rho_e U_e D/\mu_e$. Cylinder data[9] show this value is closer to 1500. Calculations for the present experiment indicate that $Re_{e,\,D}$ is about 1500 for the 0.375-in.-sphere at 40 diam and about 2400 for the 0.75-in. sphere at 20 diam. Finally, a correlation reported by Demetriades and Gold[10] predicts that the wake should be transitional about 4.5 in. behind the body.

The measured axial rms fluctuation voltages in the present experiment (Fig. 10) are indicative of a laminar wake[6] and show no signs that transition is occurring. The radial rms voltage profiles (Fig. 9) show mass flow fluctuations near the edges of the wake. Demetriades[6, 7] recorded this phenomenon in the laminar portion of the wakes behind two-dimensional cylinders and wedges, but in a truly turbulent region, the rms voltage in the center portion of the wakes was also large.

In the present experiment, the laminar-type profile persists throughout the entire region of testing, even well into the region where transition was predicted to occur. The type of radial mass flow fluctuation profile shown in Fig. 11 is, therefore, not a neck or near-wake phenomenon, but rather a characteristic profile of a laminar wake. The model for such a wake consists of a fluctuating annulus encircling a much more quiescent core, a model not consistent with most analyses and impossible of verification from schlieren or shadow photographs.

Comparison with Theory

It was not known a priori whether the present wakes would be laminar or turbulent, and hence theoretical calculations were performed for both situations. Calculations for the turbulent case were based on the theory of Lees and Hromas[2] and were performed by Hromas[11] of Space Technology Laboratories, Inc. The following assumptions were made in addition to those inherent in the theory: 1) the total temperature in the wake was assumed constant and equal to the freestream total temperature; 2) in obtaining the inviscid pitot distribution, the wake shock was neglected; and 3) the initial conditions ($Z = 8D$) in the viscous wake were matched with the experimental wake-width results.

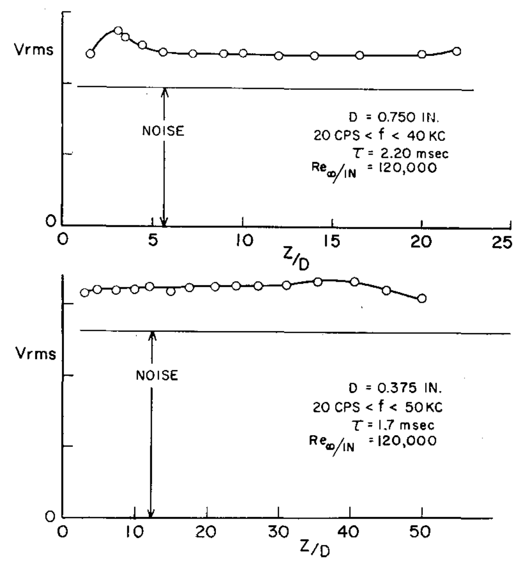

Fig. 10 Axial variation of rms fluctuation voltage.

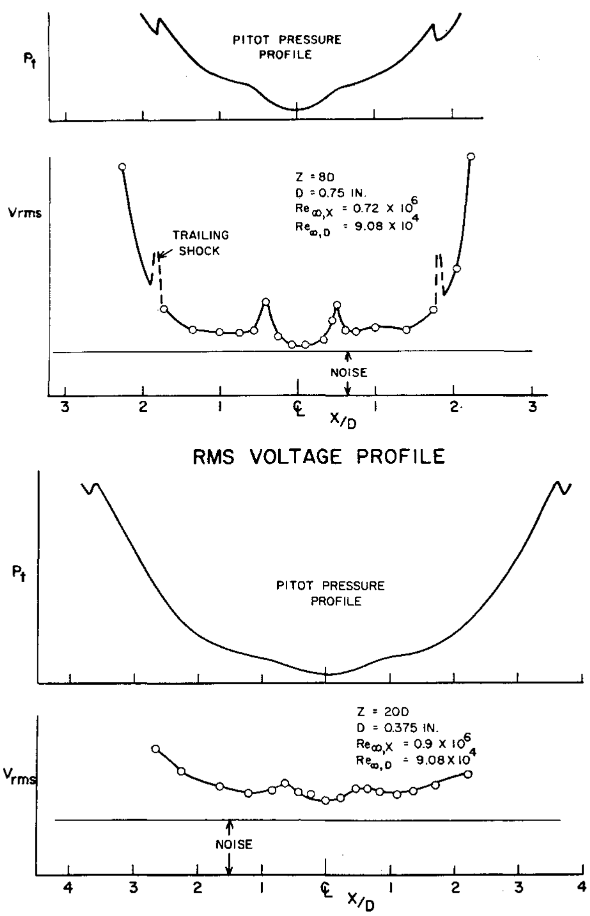

Fig. 11 Radial variation of rms fluctuation voltage.

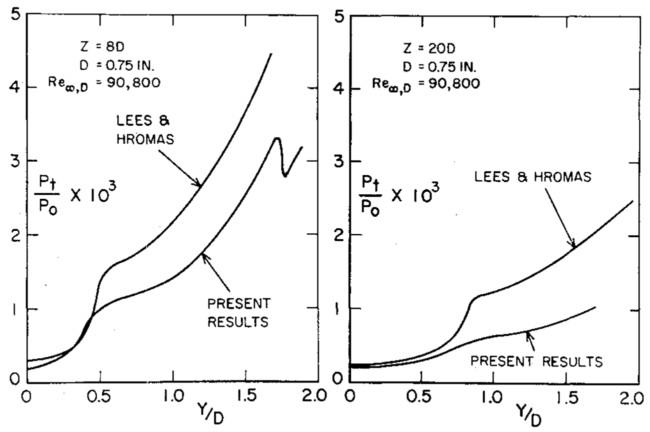

Fig. 12 Comparison of pitot pressure profiles with Lees and Hromas theory.

Calculated and experimental pitot pressure profiles at two axial locations behind the 0.75 in. diam sphere are shown in Fig. 12. The profiles are in close agreement in the center portion of the wake. The shapes of the calculated inviscid profiles appear to be quite good, but the magnitudes are considerably larger.

The theory of Zeiberg and Bleich[3] was used to predict the results for a laminar wake. Calculations were performed by Siedman and Zeiberg[12] of General Applied Science Laboratories.§ The foregoing assumption 1 was invoked. Conditions in the inviscid region downstream of an initial value line were calculated in two ways: 1) the entire flow field was calculated using the method of characteristics; and 2) the streamlines were calculated as in 1, but a blast wave pressure decay law was assumed to hold along each streamline (modified characteristic).

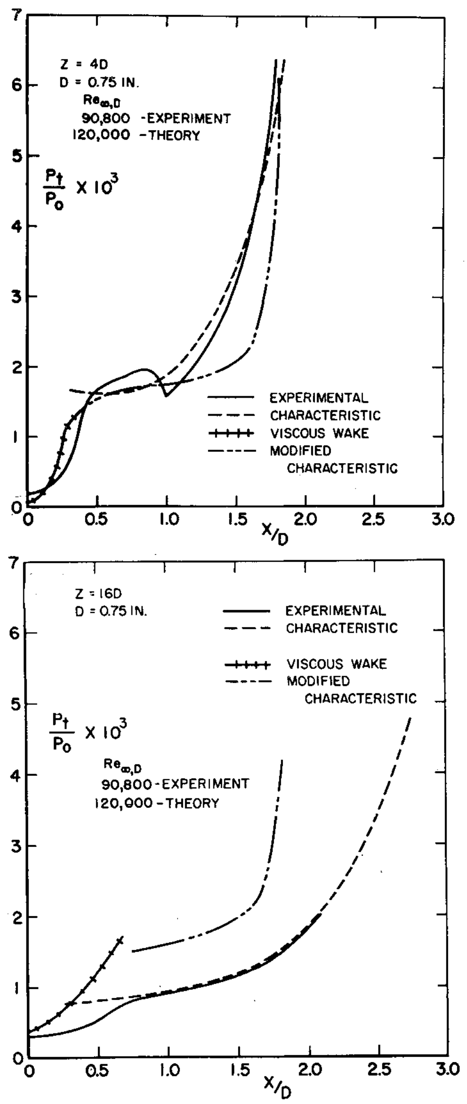

Fig. 13 Comparison of pitot pressure profiles with Zeiberg and Bleich theory.

Experimental results are compared with Zeiberg and Bleich's[3] theory in Fig. 13. In the inviscid portion of the wake, the data are in excellent agreement with the characteristic calculations. Agreement with the modified characteristic calculations is not good. The viscous wake was calculated to match the modified characteristic values and hence does not agree with the experimental data. Seidman and Zeiberg[12] point out that a shift of the viscous-wake results to match the characteristics might be more representative of the actual results. However, they also point out that this shift would imply only a 2% change of velocity. This points out the extreme sensitivity of the pitot pressure data and, considering the accuracy of calculation of both theories, indicates a reasonable check of the experimental results.

The experimental variation of edge pitot pressure with axial distance behind the sphere together with some calculations from Lees and Hromas'[2] theory is shown in Fig. 14. Experimental results indicate a rising portion for the first 3 diam because of deceleration of the flow in the neck region. Downstream of 3 diam, the pitot pressure monotonically decreases to the line labelled $(P_t/P_0)_*$. This is the value of pitot pressure which would be measured if the flow behind a normal shock at the freestream Mach number were isentropically expanded back to freestream ambient pressure. As can be seen, the edge pitot pressure is quite close to this value at 40 diam behind the body.

Two calculations performed by Dr. Hromas[11] are shown. The curve labeled "wake edge" is self-explanatory. As was noted previously, these values are larger than the experimental results. A curve labeled "axis inviscid values" is also included. These pitot pressures were calculated by assuming the flow had traversed a normal shock at the freestream Mach number and then isentropically expanded to the axial static pressure calculated for that location. The latter curve provides a good fit to the measured edge pitot pressures.

Because of the low pitot pressure on the wake axis, some special tests were conducted employing a more sensitive pressure transducer. During these tests, the probe was only moved axially, and individual data points were recorded. This procedure was necessitated by the larger lag times encountered. Figure 15 presents the data obtained in this manner together with calculations from the two theories. The experimental results show that, in the first five body

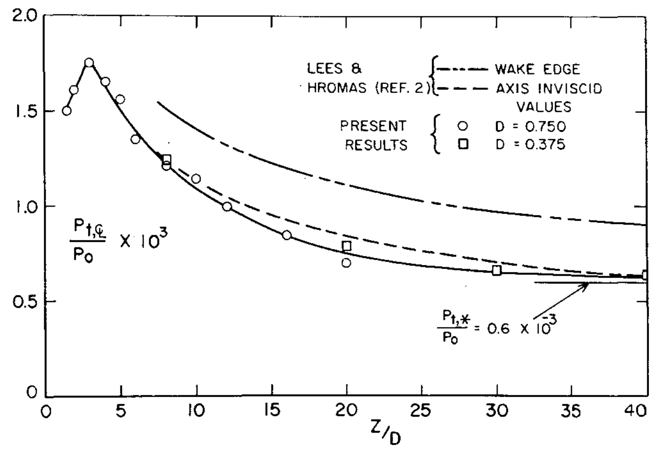

Fig. 14 Edge pitot pressure variation.

§ Sponsored under Advanced Research Projects Agency Contract No. SD-149.

diameters, the pitot pressure rises quite rapidly. Downstream of this point, the pitot pressure variation is seen to be dependent on the body size. The smaller sphere indicates a peak of 6 diam followed by a portion of nearly constant pitot pressure. Behind the larger sphere, however, the pitot pressure continues to rise until 10–12 diam and then begins to decrease with axial distance. This dependence on body geometry has also been noted for cylinders.[13]

In the first few body diameters downstream of the neck, the local Mach number is rapidly increasing. Thus, the rise of pitot pressure in this region must be due to an increase of the local stagnation pressure. In this region of the wake, the *radial* gradients of both stagnation pressure and velocity have large positive values. Thus, the increase of stagnation pressure on the centerline can be explained by either laminar or turbulent transport of momentum to the axis.

It is interesting to note that the calculations of Seidman and Zeiberg[12] predict this initial rise, whereas the integral theory of Lees and Hromas[2] does not. The latter result shows a continually decreasing pitot pressure due to the increasing Mach number. The former calculations reveal a peak further downstream followed by a region of decreasing pitot pressure. Both the experimental results and the theoretical calculations indicate that the asymptotic value of $(P_t/P_0)_{℄}$ is below $(P_t/P_0)_*$ in the region studied.

Wake Growth

Wake widths were measured from pitot pressure profiles, mean hot-wire voltage traces, and rms voltage profiles. The results are plotted in Fig. 16a together with predictions calculated from the two theories under consideration. The experimental data indicate that the three forms of measurement are in good agreement. The widths of the wake behind the 0.375-in.-diam sphere seem to be a little larger than those of the 0.75-in. sphere at 5 and 8 diam. Further downstream, the widths are the same. Calculations using the theory of Lees and Hromas[2] (matched with experimental results at an axial distance of 8 diam) are in good agreement with the data in the region studied. Calculations using the theory of Zeiberg and Bleich[3] are somewhat low, but this is most probably a result of the higher stagnation pressure used. (Some calculations using $P_0 = 100$ psia fall above the present data.) It is evident from Fig. 16a that the growth of the initial portion of the wake is insensitive to whether the wake is laminar or turbulent.

Comparison of the present data with some available ballistic-range data[13–16] for turbulent wakes of nonablating spheres is shown in Fig. 16b. The results from the ranges at General Dynamics,[14] Canadian Armament Research and Development Establishment,[15] and Ballistic Research Laboratories[14] lie considerably below the remaining data. These three experiments were conducted at lower Mach numbers than the

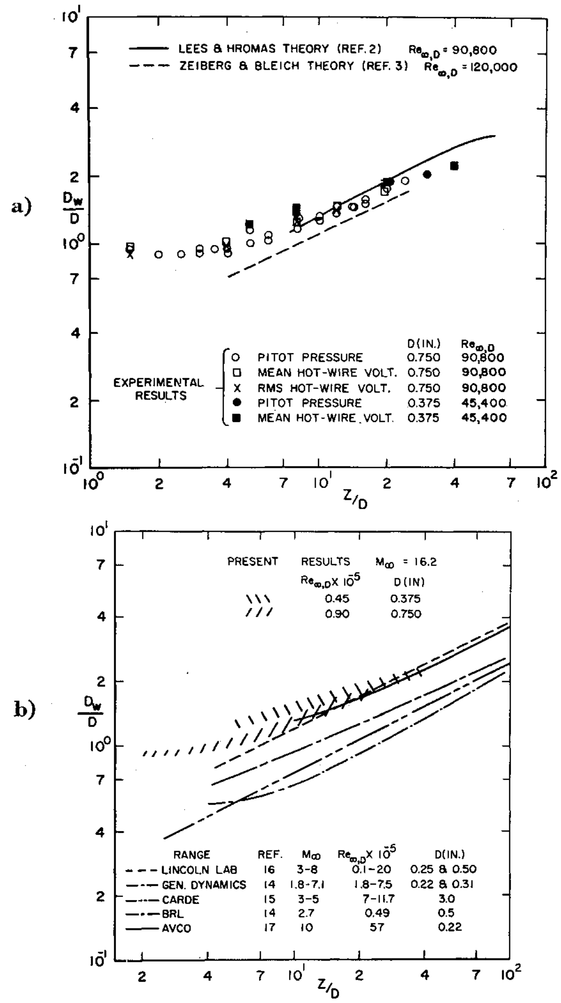

Fig. 16 Wake-growth data and theory.

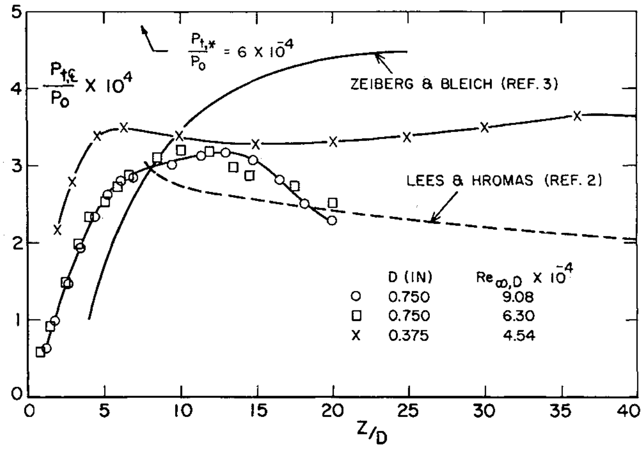

Fig. 15 Centerline pitot pressure variation.

Lincoln Laboratory[16] and Avco-Everett Research Laboratory[17] tests. The latter two sets of data agree quite well with the present results. There seems to be no consistent variation in either sphere diameter or body Reynolds number which would result in the foregoing ordering of data. Tentatively then, one concludes that the higher Mach number data fit together, and wake widths are insensitive to Mach number variations above about Mach 8. This result was previously noted by Fay and Goldburg.[17]

Comparison of Sphere and Cylinder Data

The present investigation has afforded an opportunity to compare two-dimensional cylinder data and sphere data obtained under essentially indentical experimental conditions. Ledger's data behind cylinders were obtained at the same laboratory in a helium tunnel having the same flow conditions as the present tunnel. Comparisons between the two sets of data serve to provide a linkage between two-dimensional and axisymmetric data. Although the body Reynolds number for the cylinder is less than half that for the sphere, the free-stream conditions are the same.

Wake growths, edge pitot pressure, and centerline pitot pressure variations for the two experiments are presented in Fig. 17. Simple reasoning from mass conservation principles dictates that the axisymmetric flow field should expand more rapidly than the two-dimensional one. This effect is readily discernable in Fig. 17.

Figure 17a shows that, although the sphere edge pitot pressure $(P_t/P_0)_e$ is almost equal to $(P_t/P_0)_*$ at 40 diam, the cylinder data are still considerably above this value. It is interesting to note that the cylinder centerline pitot pressure is about

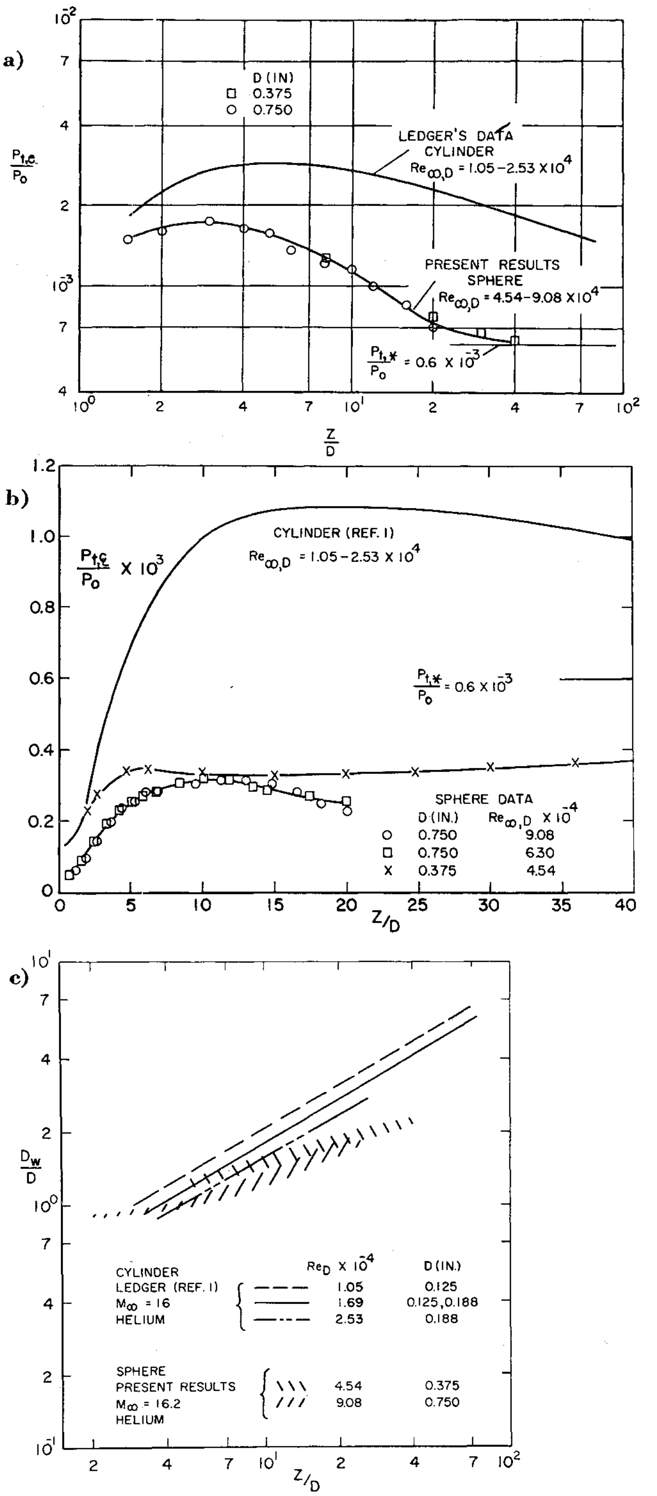

Fig. 17 Comparison of cylinder and sphere wake pitot pressure data.

three times higher than the sphere data (Fig. 17b). The quantity $(P_t/P_0)_*$ lies below the cylinder data. The wake growth for the cylinder is larger than for the sphere, as shown in Fig. 17c.

6. Conclusions

On the basis of the exploratory tests carried out with two sphere sizes at a nominal Mach number of 16 in helium, and comparison with theories and other experiments, the following tentative conclusions have been reached.

Pitot pressure profiles and wake growths are in reasonable agreement with the calculations using theories of Lees and Hromas[2] and Zeiberg and Bleich[3] in spite of the fact that one was for laminar flow, whereas the other was for turbulent flow. Experimental results reveal that there is a body size effect in the axial pitot-pressure data which is not understood. Wake-width data agree well with the ballistic-range results at Mach 8–10 and are substantially above the ballistic-range data obtained at lower Mach numbers.

Axial and transverse rms hot-wire voltage surveys reveal some interesting new features about the laminar wake structure. The rms voltage remained constant along the axis throughout the region studied. The axial value was quite low (less than freestream). Profiles across the wake showed that the rms voltage was largest in a region near the wake edge and quite low in a region about the wake axis. This latter region always had a diameter about half that of the body, even for the station furthest downstream. Transition correlation information available in the literature indicates that the transition should be occurring in the present wake, but no indication of this was found. These preliminary results suggest a model of the wake which has an annulus of larger scale turbulence surrounding a nearly quiescent cylindrical core of nearly constant diameter.

References

[1] Ledger, J. D., "An experimental investigation of the wake of a circular cylinder at Mach 16," Princeton Univ. Master of Science and Engineering Thesis, Dept. of Aerospace and Mechanical Sciences (1963).

[2] Lees, L. and Hromas, L., "Turbulent diffusion in the wake of a blunt-nosed body at hypersonic speeds," IAS Preprint 62-71 (January 1962); also J. Aerospace Sci. **29**, 976–993 (1962).

[3] Zeiberg, S. L. and Bleich, G. D., "The blunt body hypersonic wake," General Applied Sciences Laboratories TR 451 (July 1964).

[4] Zapata, R. N. and Dukes, T., "Electromagnetic suspension system for spherical models in a hypersonic wind tunnel," Princeton Univ. Dept. of Aerospace and Mechanical Sciences Rept. 682 (July 1964).

[5] Dewey, C. F., Jr., "Measurements in highly dissipative regions of hypersonic flows," California Institute of Technology Ph.D. Thesis (1963).

[6] Demetriades, A., "Some hot-wire anemometer measurements in a hypersonic wake," *Heat Transfer & Fluid Mechanics Institute Proceedings* (Stanford University Press, Stanford, Calif., 1961).

[7] Demetriades, A., "Hot-wire measurements in the hypersonic wakes of slender bodies," AIAA J. **2**, 245–250 (1964).

[8] Wilson, L. N., "Body shape effects on axisymmetric wakes," General Motors Defense Research Labs. TR 64-02K (October 1964).

[9] Lees, L., "Hypersonic wakes and trails," AIAA J. **2**, 417–428 (1964).

[10] Demetriades, A. and Gold, H., "Transition to turbulence in the hypersonic wake of blunt-bluff bodies," ARS J. **32**, 1420–1421 (1962).

[11] Hromas, L., private communication, Space Technology Laboratories, Inc., Redondo Beach, Calif. (October 1964).

[12] Seidman, M. H. and Zeiberg, S. L., private communication, General Applied Sciences Laboratories, Westbury, N.Y. (November 1964).

[13] Murman, E. M. and Hurlburt, R. L., "Experimental investigation of the wake of a circular cylinder at $M = 9$, part I," Princeton Univ. Dept. of Aerospace and Mechanical Sciences, Gas Dynamics Lab. Internal Memo. 1 (1964).

[14] Dana, T. A. and Short, W. W., "Experimental studies of hypersonic turbulent wakes," General Dynamics/Convair Rept. ZPH-103A (August 1961).

[15] Knystautas, R., "The growth of the turbulent inner wake behind a 3 inch diameter sphere," Canadian Armament Research and Development Establishment TR 488/64 (February 1964).

[16] Slattery, R. E. and Clay, W. G., "The turbulent wake of hypersonic bodies," ARS Preprint 2673-62 (1962).

[17] Fay, J. A. and Goldburg, A., "Vortex shedding, transition and growth of luminous wakes behind spheres at Mach 15 to 25," Avco-Everett Research Lab. Research Note 295 (April 1962).