Sphere Drag Coefficients for a Broad Range of Mach and Reynolds Numbers

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The purpose of the present investigation was to establish accurate values of sphere drag coefficient in the flight regime $0.1 < M_\infty < 6.0$ and $2 \times 10^1 < Re_\infty < 10^5$ for $T_w/T_\infty \approx 1.0$. To this end, an extensive series of measurements was made in a ballistic range. These measurements, together with other published data, permit the derivation of sphere drag coefficients with an uncertainty of $\pm 2\%$ in this flight regime. In addition, sufficient information is presented such that reasonable estimates of sphere drag coefficient can be made for $T_w/T_\infty \neq 1.0$, $0.05 < M_\infty < 20.0$, and $2 \times 10^{-1} < Re_\infty < 10^6$.

Introduction

FOR many years[1] there has been an interest in the drag of a sphere moving through a fluid. At this time there are several test programs[2-4] which require an accurate knowledge of sphere aerodynamics over a wide range of Mach and Reynolds numbers. The flight regime of interest ranges from continuum to near free-molecular flow and from subsonic to hypersonic speeds. Sherman[5] indicates that a single wind tunnel does not have sufficient operational flexibility to cover this entire flight regime.

Ideally, a test facility is required which can measure drag over the entire Mach number Reynolds number range to the same degree of accuracy. An aeroballistic range would appear to be well suited to this particular measurement, provided the deceleration of the sphere at low ambient pressures can be measured accurately. Bailey and Koch[6] developed a technique for manufacturing and launching spheres having densities as low as 1 lbm/ft^3 to speeds of 16,000 fps. A limited number of sphere drag measurements have been made using this technique over the velocity and Reynolds number range from 3,000 to 12,000 fps and 10 to 3×10^6, respectively, with an estimated accuracy no worse than $\pm 4\%$ at the lowest Reynolds numbers.[7] These tests demonstrated that for a wide range of operating conditions it is possible to 1) study the initial departures of sphere drag coefficient from the high Reynolds number, continuum level; and 2) make measurements at freestream Knudsen numbers approaching 1.0 in an aeroballistic range.

Lawrence[8] has shown that accurate (i.e., $\pm 2\%$) measurements of sphere drag at Reynolds numbers ranging from 185 to 11,600 for Mach numbers ranging from 0.17 to 0.99 can be made in an aeroballistic range. As a result of these studies,[6-8] it was concluded that an aeroballistic range would be a suitable facility to make measurements of sphere drag coefficient in the Mach number and Reynolds number range of interest.

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Index categories: Subsonic and Transonic Flow; Supersonic and Hypersonic Flow; Rarefied Flows.

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Experimental Equipment

The present sphere drag investigation was undertaken in the Hyperballistic Range (K) of the von Kármán Gas Dynamics Facility (VKF) of Arnold Engineering Development Center (AEDC). This range is a variable-density, free-flight test unit that can be used for either aerophysical testing or classical aerodynamic tests. A complete description of the range, together with an evaluation of the accuracy of the distance, time, velocity, deceleration, mass, diameter, temperature, pressure, drag coefficient, Reynolds number, and Mach number measurements, is contained in Ref. 9.

Results

Aeroballistic Range Data

A complete listing of the results of this test program is contained in Ref. 9. Some examples of the basic data contained in this report are shown in Fig. 1. Also shown are the results of sphere drag measurements presented in Refs. 7, 8, and 10–14. These data were selected because $T_w/T_\infty \approx 1.0$, as is the case for the ballistic range data contained herein. The present data are in good agreement with these earlier measurements.

Curves have been faired through all of the available data at the discrete Mach number intervals shown in Fig. 1. An average Mach number has been assigned to each of these Mach number intervals (e.g., for interval $0.19 < M_\infty < 0.27$, $M_\infty = 0.23$), and cross plots of C_D vs Mach number have been derived at fixed Reynolds numbers (Fig. 2). If more accurate values of C_D are required, the reader should refer to Ref. 9. As a result of an examination of the measurement errors discussed in Ref. 9 and the consistency of the experimental data, it has been concluded that the total errors in sphere drag coefficient derived from the faired curves are no greater than $\pm 2\%$.

Sphere Drag Coefficients at Subsonic Speeds

Before 1930, many measurements of the drag of a sphere falling through various fluids were made, and a body of information was generated for $10^{-1} < Re_\infty < 10^6$. It was considered that these data gave the level of the incompressible drag coefficient of a sphere in steady nonturbulent flow. Usually these data, which have a significant degree of scatter, are represented by a single line which is called the "standard" drag curve. This curve has appeared in many textbooks and reports at least as far back as 1931.[15] This standard drag curve is shown in Fig. 3. Also shown in this figure are two examples of the early data upon which this curve has been based.[16,17]

Heinrich, Niccum, and Haak[18] made some sphere drag measurements in a wind tunnel for $0.078 < M_\infty < 0.39$ and $2 \times 10^3 < Re_\infty < 2 \times 10^4$. These data are compared with the

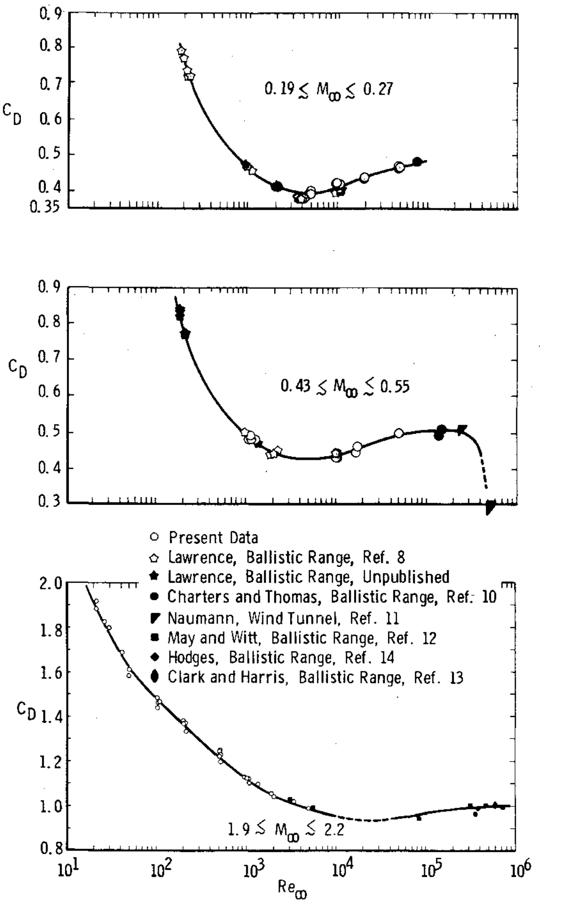

Fig. 1 Variation of sphere drag coefficient with Reynolds number and Mach number.

standard drag curve in Fig. 3 and are shown to be significantly higher than the standard values. Sivier[19] has measured the drag of magnetically supported spheres in a wind tunnel with a freestream turbulence intensity up to 8%. These sphere drag values (cf. Fig. 3) are also significantly greater than the standard drag values. Zarin[20] refined the magnetic balance system used by Sivier[19] and varied the freestream turbulent intensity level. He obtained some sphere drag measurements at freestream turbulent intensity levels of less than 1% (cf. Fig. 3). For $Re_\infty > 10^3$, these values are still significantly greater than the standard values. For $Re_\infty < 10^3$, these values are in good agreement with

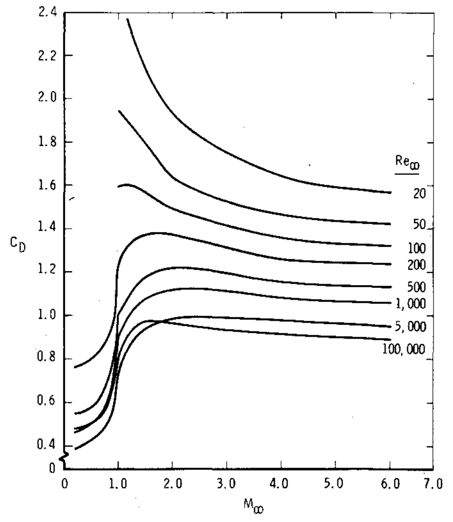

Fig. 2 Variation of sphere drag coefficient with Mach number at subsonic and supersonic speeds and $T_w/T_\infty \approx 1$.

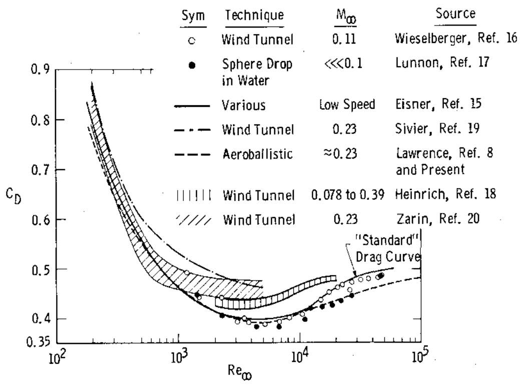

Fig. 3 Comparison of sphere drag measurements at low speeds.

the standard values. From this study, Zarin concluded that small degrees of freestream turbulence were the cause of his higher-than-standard drag values.

Also shown in Fig. 3 are the present drag values. It can be seen that these values are in good agreement with the standard values for $5 \times 10^2 < Re_\infty < 10^4$. It is reasonable to assume that the ballistic range data are representative of a freestream turbulent intensity level approaching zero.

Effects of Compressibility on Sphere Drag Coefficients

As was the case for subsonic velocities, there is a generally accepted curve (Fig. 4) which has been used to indicate the effects of compressibility upon sphere drag coefficient. This curve appears to have originated with Hoerner[21] and has been repeated in several references since (e.g., Refs. 4, 19 and 20). The form of the variation of sphere drag coefficient with Mach number[21] was based upon several sets of data for $0 < M_\infty < 1.0$ obtained before 1946 (including, for example, the ballistic range data of Ref. 10). The curve is characterized by a pronounced dip in the drag coefficient at $M_\infty = 0.85$. Unfortunately, the ballistic range test[10] did not obtain data for $0.65 < M_\infty < 0.85$. An inspection of the remaining data[21] upon which this curve (Fig. 4) was based indicates that the curve fitted to the data may not, in fact, be the best fit to the data. This is confirmed to some extent when Naumann's[11] data are considered in Fig. 4. It can be seen (Fig. 4) that these data agree with Charters' and Thomas'[10] data and do not show a dip in drag coefficient at $M_\infty = 0.85$.

The reason for presenting the foregoing discussion is to examine the validity of the dip in light of the present results. If the form of Hoerner's curve is accepted, then to some extent his explanation for the reason for the dip is accepted. Hoerner's explanation for the dip is that it is attributable to "a favorable interaction between the local supersonic field of flow existing at and behind the location of the cylinder's (sphere's) maximum thickness and the flow pattern within its wake." If this reasoning is accepted, then for lower subcritical Reynolds numbers a curve with similar characteristics would be expected. None of

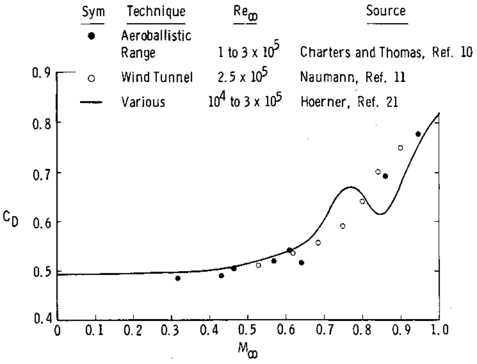

Fig. 4 Variation of sphere drag coefficient with Mach number (pre-1970 data).

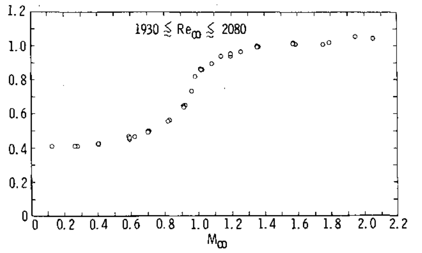

Fig. 5 Variation of sphere drag coefficient with Mach number (present data).

the summary curves shown in Fig. 2 indicated that this occurs. To indicate that the effect has not been obscured by the smoothing procedure used in deriving the summary curves, the data obtained for $1930 < Re_\infty < 2080$ are shown in Fig. 5. These and Naumann's[11] data are sufficiently well defined to state with some certainty that there is no dip in the C_D vs M_∞ curve for $M_\infty \approx 0.85$.

Transonic Sphere Drag Coefficients

There are very few experimental measurements of sphere drag in the transonic speed regime. The data contained in the summary curve in Fig. 2 represent the most comprehensive set of results in this speed regime. From a consideration of the data presented in Fig. 2 for $2 \times 10^1 < Re_\infty < 10^6$, it is apparent that the form of the C_D vs M_∞ variation at $0.9 < M_\infty < 1.1$ is a function of freestream Reynolds number. For high Reynolds numbers (i.e., $Re_\infty > 10^5$), there appears to be a smooth transition from subsonic to supersonic drag values. For $2 \times 10^2 < Re_\infty < 10^4$, there is not a smooth transition from subsonic to supersonic drag values. For $2 \times 10^1 < Re_\infty < 2 \times 10^2$, the change from subsonic to supersonic drag values is accompanied by relatively large changes in C_D for small changes in M_∞.

The significance of these results is that they indicate a basic difficulty in measuring sphere drag at $M_\infty \approx 1.0$ in a short ballistic range such as the VKF 100-ft Range K. The reason for this is that a velocity drop of at least 10 fps is required to derive an accurate drag coefficient at $M_\infty = 1.0$. This means that for $M_{\infty avg} = 1.0$ the Mach number varies from 0.996 to 1.004. At low Reynolds number in this speed regime, it is not completely valid to assume that C_D is constant, and a facility such as the VKF 1000-ft range (Hyperballistic Range G) with its considerably greater velocity measuring accuracy would be required in order to detect the C_D change for a ΔV of less than 10 fps.

Supersonic Sphere Drag Coefficients

It is of interest to consider the form of the C_D-Re_∞ curve shown in Fig. 1 for $1.9 \lesssim M_\infty \lesssim 2.2$. The total drag coefficient of a sphere can be written as the sum of drag components attributable to forebody pressure, afterbody pressure, and friction, viz

$$C_D = C_{DPF} + C_{DPB} + C_{DF}$$

The forebody pressure drag (C_{DPF}) of a sphere can be derived from the pressure distribution over a hemisphere.[21,22] Clark has derived a simple expression for forebody drag

$$C_{DPF} = 0.901 - 0.462/M_\infty^2$$

Sherman's[23] measurements of stagnation pressure on source-shaped bodies indicates that this pressure term would be constant for $Re_\infty > 3 \times 10^2$.

Lehnert[24] has measured the afterbody pressure drag of a sphere over a range of Reynolds numbers. For low supersonic Mach numbers, he shows that C_{DPB} decreases with decreasing Reynolds number. More recent measurements[25] of C_{DPB} are in good agreement with Lehnert's (cf. Fig. 6).

Also shown in Fig. 6 is the summation of the two terms C_{DPF} and C_{DPB} compared with the ballistic range values of total drag. The small difference between these two curves is representative of the friction drag component which for a sphere at $Re_\infty \approx 10^6$ would be expected to be small.

At supersonic speeds and for $10^4 < Re_\infty < 10^6$, the sphere drag coefficient decreases as the Reynolds number decreases

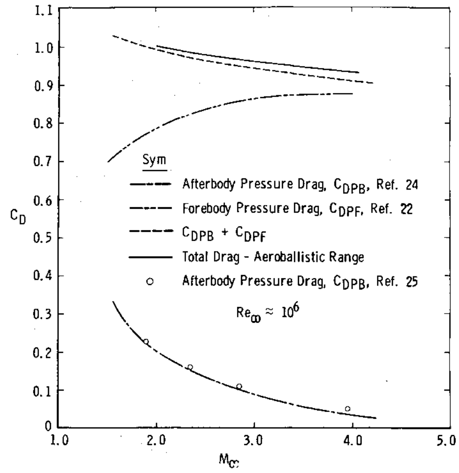

Fig. 6 Total drag as a function of Mach number.

from 10^6 to 10^4, e.g., Fig. 1. As noted earlier, the value of C_{DPF} is substantially constant over this range of Reynolds numbers. With decreasing Reynolds number, the friction drag component, C_{DF}, increases. Thus, the decrease in C_{DT} must be explained in terms of a decreasing value of C_{DPB}. This is in agreement with Lehnert's[24] measurements of C_{DPB} in the wind tunnel, which show a similar variation with Reynolds number.

Effect of Sphere Wall Temperature

In determining the correct drag coefficient to use in the supersonic-hypersonic speed regime, attention must be paid to the wall temperature of the sphere. The effect of wall temperature upon the viscous drag of a sphere at near-continuum flow conditions has been theoretically demonstrated by Davis and Flügge-Lotz.[26] Hayes and Probstein[27] present equations showing the effect of wall temperature on drag coefficient for free-molecule flow conditions. On the basis of this information and several experimental studies, it is apparent that the drag coefficient in the transition regime between free-molecule and continuum flow conditions must be a function of wall temperature.

The ballistic range data obtained both here and elsewhere for $1.0 < M_\infty < 6.0$ have been obtained over relatively short flight distances, and consequently no appreciable model heating would be expected. Therefore, it has been assumed, on the basis of approximate calculations of the heating rates, that the ballistic range data correspond to the condition where $T_w/T_\infty \simeq 1.0$. To determine whether small changes in wall temperature affect the drag coefficient significantly, a study was made of several sets of data,[28-37] where $T_w/T_\infty \neq 1.0$. Some of these data are shown in Fig. 7. The data are plotted with C_D as a function of Re_2 where Re_2 is considered to be a better parameter for comparison than Re_∞ when $M_\infty > 1$. A more complete summary of these data is presented in Ref. 9. Figure 7 demonstrates the consistency of measurements from a variety of sources.

All of these data (Refs. 28–37) show that at a fixed Reynolds number, the drag coefficient increases as T_w/T_∞ increases. To

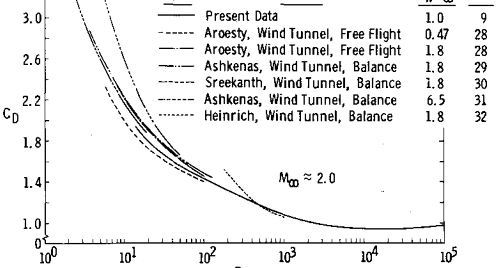

Fig. 7 Variation of sphere drag coefficient with Reynolds number and wall temperature.

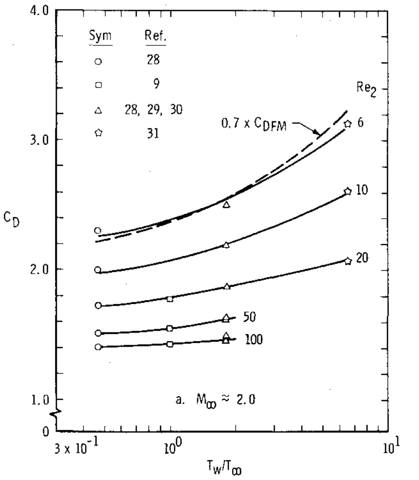

Fig. 8 Variation of sphere drag coefficient with wall temperature.

illustrate this effect more clearly, the data contained in Fig. 7 have been replotted as C_D vs T_w/T_∞ at various discrete values of Re_2 in Fig. 8. The variation of drag coefficient with velocity and wall temperature has been defined theoretically (cf. Ref. 27) in the free-molecule limit. As the free-molecule limit is approached, the form of the variation of drag coefficient with wall temperature should approach that which exists in the free-molecule limit. The $M_\infty \approx 2.0$ data contained in Fig. 8 is the most complete set of data from which to establish the effect of wall temperature. It is evident from these data that when $C_D \gtrsim 0.7\, C_{DFM}$, the temperature effects upon drag coefficient approximate those which are predicted theoretically in the free-molecule limit.

Drag Coefficient at High Speeds

All the available drag coefficient data for $2 \lesssim M_\infty \lesssim 19$ and $T_w/T_\infty \approx 1.0$ contained in Refs. 7 and 9 have been summarized in Fig. 9. Also shown in Fig. 9 are some measurements made on 1) microscopic spheres in free flight[38,39] and 2) full-scale spheres re-entering the Earth's atmosphere.[40] For $M_\infty > 10.0$ and $0.5 \lesssim Re_\infty \lesssim 10^4$, the measurements obtained from these three sources indicate that C_D increases with increasing Mach number at a fixed Reynolds number. Knudsen number ($\approx M_\infty/Re_\infty$) is a more realistic indicator of the approach to the free-molecule limit than Reynolds number. However, plotting C_D vs M_∞ for fixed values of M_∞/Re_∞ does not significantly alter the form of the plot shown in Fig. 9. Kussoy[41,42] has made measurements of sphere drag coefficient for $10 < M_\infty \lesssim 27.2$, $10 \lesssim Re_\infty \lesssim 8 \times 10^3$, $1.5 \lesssim T_w/T_\infty \lesssim 4$. These data exhibit the same trends as do those shown in Fig. 9. This type of variation has also been recognized by Whitfield and Smithson.[43] As a result of their analysis of the data, they suggest that wall surface temperature is not the relevant temperature to determine the effects of temperature upon drag coefficient in high enthalpy flows. Using a reference temperature which is an average of the temperature of the incident and reflected molecules, they are able to correlate some of the high enthalpy data (e.g., Refs. 33, 36, 41, and 42). It is suggested that until this phenomenon is better understood the sphere drag coefficients shown in Fig. 9 are those appropriate for full-scale free-flight conditions where $T_w/T_\infty \approx 1.0$.

The experimental data presented in Refs. 38, 41, and 42 indicate that at low Reynolds numbers drag coefficient is greater than the generally accepted free-molecule flow value. It must be emphasized that the present free-flight data, delineated by solid lines in Fig. 9, do not indicate this. Furthermore, extrapolation of these data to flow conditions outside of the range of the test variable may lead to erroneous answers.

Summary of Sphere Drag Coefficient Measurements

Crowe et al.[44] have made measurements of sphere drag for $0.1 < M_\infty < 2.0$ and $Re_\infty < 10^2$ in a microballistic range. These results and those discussed earlier in this report have been combined to produce Fig. 10. This curve illustrates clearly the changes in the form of $C_D \sim M_\infty$ that occur as flow conditions change from continuum to free-molecular. The primary purpose of Figs. 9 and 10 is to illustrate the variation of C_D vs M_∞ and Re_∞ over a wide range of these variables.

Conclusions

Measurements have been made such that reliable values of sphere drag coefficient may be derived for any value of M_∞ and Re_∞ for $T_w/T_\infty \approx 1.0$ within the bounds $0.1 < M_\infty < 6.0$ and $2 \times 10^1 < Re_\infty < 10^5$ with an uncertainty no larger than $\pm 2\%$ Based on these and other published data, there is sufficient information contained herein to predict the effect of wall temperature on C_D when $T_w/T_\infty \neq 1.0$ for $2.0 < M_\infty < 6.0$.

There is reasonable agreement between the present low-speed data ($M_\infty < 0.25$ and $Re_\infty < 10^4$) and the classical data which have resulted in the derivation of the "standard drag curve". Any differences in the two sets of data may be explainable in terms of velocity differences in the basic data.

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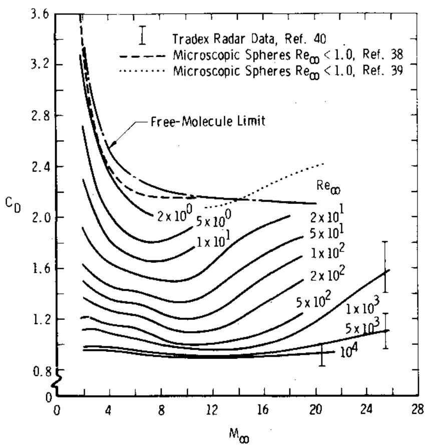

Fig. 9 Variation of sphere drag coefficient with Mach number at hypersonic speeds and $T_w/T_\infty \approx 1$.

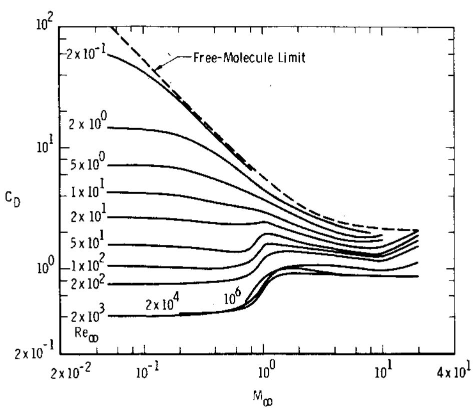

Fig. 10 A summary of sphere drag coefficient measurements ($T_w/T_\infty \approx 1.0$).

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