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SOME SPHERE DRAG MEASUREMENTS IN LOW DENSITY SHOCK TUNNEL FLOWS

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(6) SOME SPHERE DRAG MEASUREMENTS IN LOW DENSITY SHOCK TUNNEL FLOWS, (7)-(9) NA

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CONTENTS

PAGE

INTRODUCTION	1
FACILITY DESCRIPTION	1
MODELS	2
TECHNIQUE	2
TEST CONDITIONS	3
COMPARISON OF PRESENT RESULTS WITH OTHER DATA	5
CONCLUSIONS	9
TABLE I	10
ACKNOWLEDGEMENTS	11
NOMENCLATURE	12
REFERENCES	13
FIGURES	

ABSTRACT

The free flight technique (1) was extended to low density flows to measure sphere drag at approximately Mach 15 over a free stream Knudsen number range of .0027 to .25.

Comparison of the data obtained with those of other investigators indicates that:

(a) The free flight technique is useful for shock tunnel measurements of aerodynamic forces in non-continuum flows.

(b) There is little to choose from between* ~~Kn_∞, Re_∞, Re_2~~ as a correlating variable for experimental sphere drag coefficients.

c) The parameter $\frac{C_D - C_{D_i}}{C_{D_{fm}} - C_{D_i}}$** yields a useful correlation of sphere drag over a wide range of Mach numbers, Reynolds number and wall Temperatures.

* free stream Knudsen and Reynolds Numbers, and Reynolds Number (at conditions behind normal shock)

~~** (Drag Coefficient (based on Cross Section Area) minus Drag Coefficient (Inv...) divided by (Drag Coefficient (Free Molecule Flow Value) minus Drag Coefficient (Inviscid))~~ [illegible]

INTRODUCTION

In April, 1961, an experimental effort was initiated in the SSL 2"/10" shock tunnel to extend the free flight technique for the determination of aerodynamic forces in shock tunnel flows (1) to non-continuum flows. This effort is described in some detail in Ref. (2).

As part of the program sphere drag data were obtained at approximately Mach 15 over a free stream Knudsen number range of .0027 to .25. This report presents the sphere drag results as well as a comparison of these data with similar data of other investigators. *

FACILITY DESCRIPTION

The 2"/10" shock tunnel in which the present sphere drag data were obtained is driven by a 5 ft. long 2 1/2 I.D. alloy steel, chrome plated bore driver using a multiple spark plug ignition system. The 2" I.D. stainless steel driven tube section consists of one 24 ft. long uninstrumented section followed by two 2 ft. long sections with 2 sets of instrumentation ports and two 6 ft. sections with 7 sets of ports. A 13 7/16 inch long transition section leads to a 15° half cone angle nozzle whose 10 inch exit diameter lies inside a 14 inch diameter, 15 ft. long dump tank which has a side window providing a viewing area. The model support system is independently mounted to the laboratory concrete floor; its main upright member is isolated from the dump tank by a 3 3/4" O.D., 1 1/2" I.D., 1 5/16" thick soft rubber grommet. Scribed primary diaphragms of copper, aluminum, or stainless steel are used in a short, square transition section between the round driver and driven tubes. Scribed aluminum secondary diaphragms are

* These data and the comparisons with other data first appeared as part of Ref. 2.

located in a square transition section immediately upstream of the reflected nozzle face. Straight-through and reflected nozzle operation is available; for this program all work was done with reflected nozzles. A replaceable throat section permits easy variation of nozzle area ratio.

MODELS

Three sizes of spheres were flown in this program:

1) Ping pong balls of 1.500" nominal diameter

2) Solid nylon balls of 1/4 and 3/32" nominal diameter. These were obtained from Industrial Tectonics, Inc., Ann Arbor, Michigan.

Deviations from sphericity was about 2/3 of 1% of the diameter for the ping pong balls and, typically, about .001" for the solid nylon spheres.

TECHNIQUE

In the usual application of the free flight technique in the G. E. SSL shock tunnels (1) the forces generated during starting of the flows are sufficient to break the model supporting strings so that the model is in true free flight during the ensuing quasi-steady flow. However, in the present program involving much lighter models and much lower density flows than heretofore employed, this was not the case. It proved necessary to develop a technique for controlled severing of the nylon model support threads. This was accomplished with an apparatus like that shown in Fig. 1. The horizontal wires across which are draped the nylon model support threads are pulsed with a suitably timed capacitor discharge which melts through the support threads. *

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* The fixture shown in Fig. 1 was developed for use with non-spherical bodies; the one used for the sphere tests was essentially one-half of the fixture shown, i.e., only one wire was required.

In order to minimize the stub length of thread remaining attached to the model (typically about 1/32 of an inch) these wires must be immersed in the flow. Their diameter is .001 so that they were always in free molecular flow (minimum Knudsen number of 4.0) and hence would not be expected to affect the flows about the models. The vertical prongs between which these wires are stretched are also immersed in the flow but are sufficiently far from the models that no disturbance from them intrudes on the model flow fields.

TEST CONDITIONS

Conditions behind the reflected shock are the reservoir conditions for the nozzle flow. Reflected pressures, which vary during the test are measured just before the nozzle entrance. The initial reflected temperature is computed from equilibrium normal shock solutions for the measured shock velocity at the nozzle entrance and the subsequent variation calculated from the varying pressure assuming an isentropic process as an approximation. The test conditions quoted for a particular test are calculated from a time squared (t^2) average condition over the first 4 milliseconds, t^2 being used for the averaging process because the model displacements are essentially quadratic in time.

A typical reflected pressure history is shown in Fig. 2. This non-steadiness of reflected conditions is due to a combination of:

a) flow starting phenomena (first .4 msec.)

b) an incompletely coalesced incident compression wave (next .7 msec. approximately).

c) continued "processing" of the test gas mass by waves reflecting between the nozzle entrance and the advancing contact zone.

d) attenuation of the incident compression wave in the driven section of the shock tube.

Test section conditions are determined by measuring test section impact pressure and assuming an equilibrium "isentropic" expansion from the reflected shock conditions. Reservoir temperatures at the averaged point ranged from 1650 to 1860°K for these tests.

It was interesting to note that as reservoir pressures, and, hence, test section Reynolds number, were lowered there occurred a region of sharp change in the pressure dependence of the test section impact pressure to reservoir pressure ratio, in a manner indicating change of the nozzle boundary layer from turbulent to laminar. In the transition range a total pressure ratio unrepeatibility occurred probably because in this region which type boundary layer initially establishes itself is determined by details of the flow starting processes. Despite this, sphere drag data obtained from such tests proved to be quite consistent with the other data.

Viscosity values used in the Reynolds number and mean free path computations are from a linear extrapolation to the origin from about 79°K, the lowest available experimental data point. At the calculated test section static temperature levels of the present tests such viscosity values are approximately 20% higher than given by the Sutherland equation. The static mean free path, λ_∞, was calculated from the well known equation

$$\mu = .499 \rho \lambda \bar{c}$$

where $\bar{c}$ is the mean molecular velocity, which kinetic theory gives as

$$\bar{c} = \sqrt{\frac{8\,RT}{\pi}}$$

For an ideal gas $a = \sqrt{\gamma RT}$. These equations combine to yield the familiar relation

$$\lambda/L = \frac{1}{.499} \sqrt{\frac{\pi\gamma}{8}}\; M \;/Re_L$$

The test conditions calculated in this manner are presented in Table I along with the experimental sphere drag coefficients.

COMPARISON OF PRESENT RESULTS WITH OTHER DATA

Numerous data of other investigators are available for comparison with the present results. Notable among the more recent additions to the literature are the contributions of Aroesty (3) and Kinslow and Potter (4). The former work contains a thorough survey of theory and experiment and in particular points out certain older experimental results -- Kane (5), Sherman (6), and Jensen (7) -- he deems questionable. In addition, Aroesty presented the first experimental data showing the effects of wall temperature. Kinslow and Potter (4) obtained a large number of data at about Mach 10.5 to very low densities and at different wall to free stream temperature ratios. In addition they presented an analysis of the near-free molecule flow regime in which they calculated the shielding effect upon the incident molecules of the denser gas in the vicinity of the body. They also used their own and others' data to empirically determine the variation with Mach number and temperature ratio of K_1 and K_2 where K_1 and K_2 are defined by the expression

$$C_D = C_{D_i} + \frac{K_1}{\sqrt{Re_2}} + \frac{K_2}{Re_2}$$ and Re_2 is Reynolds number based on sphere diameter and conditions behind the bow shock. This expression has been derived for continuum flow by a number of investigators. The first term is generally considered the inviscid flow pressure drag contribution, the second the effects of skin friction and the third the combined influences of vorticity, slip, temperature jump and large boundary layer thickness. Kinslow and Potter were able to curve fit data to surprisingly low densities.

Chosen for comparison with the present results were the Mach 2.02 data of Sreekanth (8), the Mach 2, 4, and 6 (approx.) data of Aroesty (3) and Mach 4 (approx.) data of Wegener and Ashkenas (9) all at approximately adiabatic wall conditions. The present tests were for relatively cold wall conditions ($\frac{T_w}{T_\infty} \approx 7.2$; $\frac{T_w}{T_o} \approx .18$) so the "cold" wall data of Aroesty ($\frac{T_w}{T_o} = .26$), Kinslow and Potter at Mach 10.5 ($\frac{T_w}{T_\infty} = 2.4$) and Masson, Morris and Bloxsom (10) at Mach 16-21 are included in the comparisons. The data of references 3, 4, and 9 are so numerous that representative points are shown rather than all the data.

In Figures 3 and 4 the data are plotted as C_D vs Kn_∞ and Re_2 respectively. A plot of the data vs Re_∞ shows nothing different and so is not included here. It is evident from these figures that:

a) there is a free stream Mach number effect that is not included in the Knudsen number, which is given by $Kn_\infty \sim \frac{M_\infty}{Re_\infty}$.

b) use of the Knudsen of the free stream near free path seen by a stationary observer as derived by Muckenfuss (13) $[\lambda(M_\infty) \approx k \lambda_\infty M_\infty]$ for high Mach numbers would spread the data points even more than when the conventional Knudsen number is used.

c) There is little to choose between K_{n_∞}, Re_2 and Re_∞ (by implication) correlating parameters. None of them correlate the data especially well and there are not enough data to permit separation (in these presentations) of Mach number and wall temperature effects.

d) The data of reference (10) are quite inconsistent with all others, showing much too sharp a transition from continuum to free molecule flow drag levels.

The parameter resulting from the simple analysis of reference (10), namely $\frac{\lambda \rho_\lambda}{D \rho_\infty}$, which is essentially the ratio of mean free path behind the shock to the shock layer thickness, (admittedly strictly continuum flow concepts and values so calculated) is intuitively appealing to this writer but it does no better a job of correlating the data, as is seen in Fig. 5.

Potter, et al (11), in a presentation of early AEDC Low Density Hypervelocity Tunnel sphere drag data showed that Mach number effects and the wall temperature effects in their own data, at least, (at that time Aroesty's data and the present data were not available) were correlated by plotting not C_D but the quantity $\frac{C_D - C_{D_i}}{C_{D_{fm}} - C_{D_i}}$ Such a presentation of the data is given in Fig. 6.* This correlation is somewhat better than it first appears because the three data points from the present tests for $Re_2 > 100$ should not be taken seriously in this presentation (only) since for these 3 points a three percent error in either the experimental C_D or the value of C_{D_i} used could produce about a hundred percent error in the drag parameter. The data point at $Re_2 \approx 90$ is apparently a "bad data point." For Re_2 greater than about 40.0 this correlation is quite good. At lower Re_2 Mach number and wall temperature effects are apparently present that are not accounted for by the drag parameter used. For example, the drag parameter over-corrects for the wall temperature effects exhibited by Aroesty's (9) Mach 2 and Mach 4 data. This is not surprising since this is a flow regime where continuum flow type viscous effects are large and the drag parameter used here includes Mach number and temperature effects of free molecule flows only. Presumably if experimental data were available at still lower Re_2 they would exhibit in this presentation increasingly smaller Mach number and wall temperature effects as the free molecule flow regime is approached (value of 1.0 of the drag parameter). There are sufficient data in this lower Reynolds number range that one can make reasonable estimates of these Mach number and temperature effects so that overall the correlation in Fig. 6 should permit

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* The values of $C_{D_{fm}}$ were computed from the standard theoretical result for unity accomodation and diffuse reflection, $C_{D_{fm}} = \frac{2S^2+1}{\sqrt{\pi}\, S^3} e^{-S^2} + \frac{4S^4+4S^2-1}{2S^4} \operatorname{erf} S + \frac{2\sqrt{\pi}}{3S}\sqrt{\frac{T_w}{T_\infty}}$ where S is the molecular speed ratio $= \sqrt{\frac{\gamma}{2}}\, M_\infty$. Values of C_{D_i} were taken from the faired data of Hodges (12) as presented in reference (11).

relatively accurate sphere drag predictions for a very wide range of Mach numbers, Reynolds number and wall temperatures.

With the exception of the one above-mentioned data point the present results are quite consistent with the sphere drag data of other investigators. It is concluded, therefore, that the free flight technique can be used in the hypersonic shock tunnel to measure aerodynamic forces in non-continuum flows.

CONCLUSIONS

1) Eleven of the twelve sphere drag data points obtained in the present Mach 15 (approx.) tests over the K_n range .0027 to .25 are completely consistent with the data of other investigators, thus validating the application of the free flight technique in the hypersonic shock tunnel for the determination of aerodynamic forces in non-continuum flows.

2) The drag parameter $\frac{C_D - C_{D_i}}{C_{D_{fm}} - C_{D_i}}$ yields a useful correlation of sphere drag data over a wide range of Mach numbers, Reynolds numbers and wall temperatures. More experimental data are needed to determine more accurately Mach number and wall temperature effects at Re_2 less than about 40.

TABLE I
SHOCK TUNNEL TEST RESULTS WITH SPHERE DRAG

SHOT	945	947	948	949	950	951
Sphere Dia.	1 1/2	3/32	1/4	3/32	1/4	1 1/2
C_D	.92	1.38	1.16	1.39	1.19	.96
Re	8260	551	1380	303	825	5250
Re_2	466	31.2	77.7	17.0	46.0	295
M	15.2	15.2	15.1	15.1	15.1	15.1
Kn $\times 10^2$	.271	4.07	1.62	7.35	2.69	.437

(cont'd)

SHOT	952	955	956	960	961	962
Sphere Dia.	1 1/2	1 1/2	1/4	1/4	3/32	3/32
C_D	.99	.966	1.45	1.35	1.60	1.68
Re	2880	1790	235	429	160	85.2
Re_2	147	89.8	12.6	23.7	8.90	4.50
M	14.3	14.1	14.7	15.0	15.0	14.6
Kn $\times 10^2$	.730	1.16	9.23	5.15	13.8	25.2

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R. W. Garvine, who assisted in early phases of this work.

NOMENCLATURE

a	-	Acoustic Velocity
$\bar{c}$	-	Mean Molecular Velocity
C_D	-	Drag Coefficient Based on Cross Section Area
D	-	Sphere Diameter
K_n	-	Knudsen Number
M	-	Mach Number
P	-	Pressure
r	-	Nose Radius of Blunt Body
R	-	Base Radius, Specific Gas Constant
Re	-	Reynolds Number
S	-	Molecular Speed Ratio, $= \frac{\bar{c}}{2}$
T	-	Temperature
U	-	Gas Velocity
γ	-	Specific Heat Ratio
λ	-	Mean Free Path
ρ	-	Mass Density
μ	-	Dynamic Viscosity

<u>Subscripts</u>

∞	-	Free Stream
o	-	Reservoir Conditions
2	-	Conditions Behind Normal Shock
i	-	Inviscid
fm	-	Free Molecule Flow Value
s	-	Test Section Stagnation Conditions
w	-	Wall

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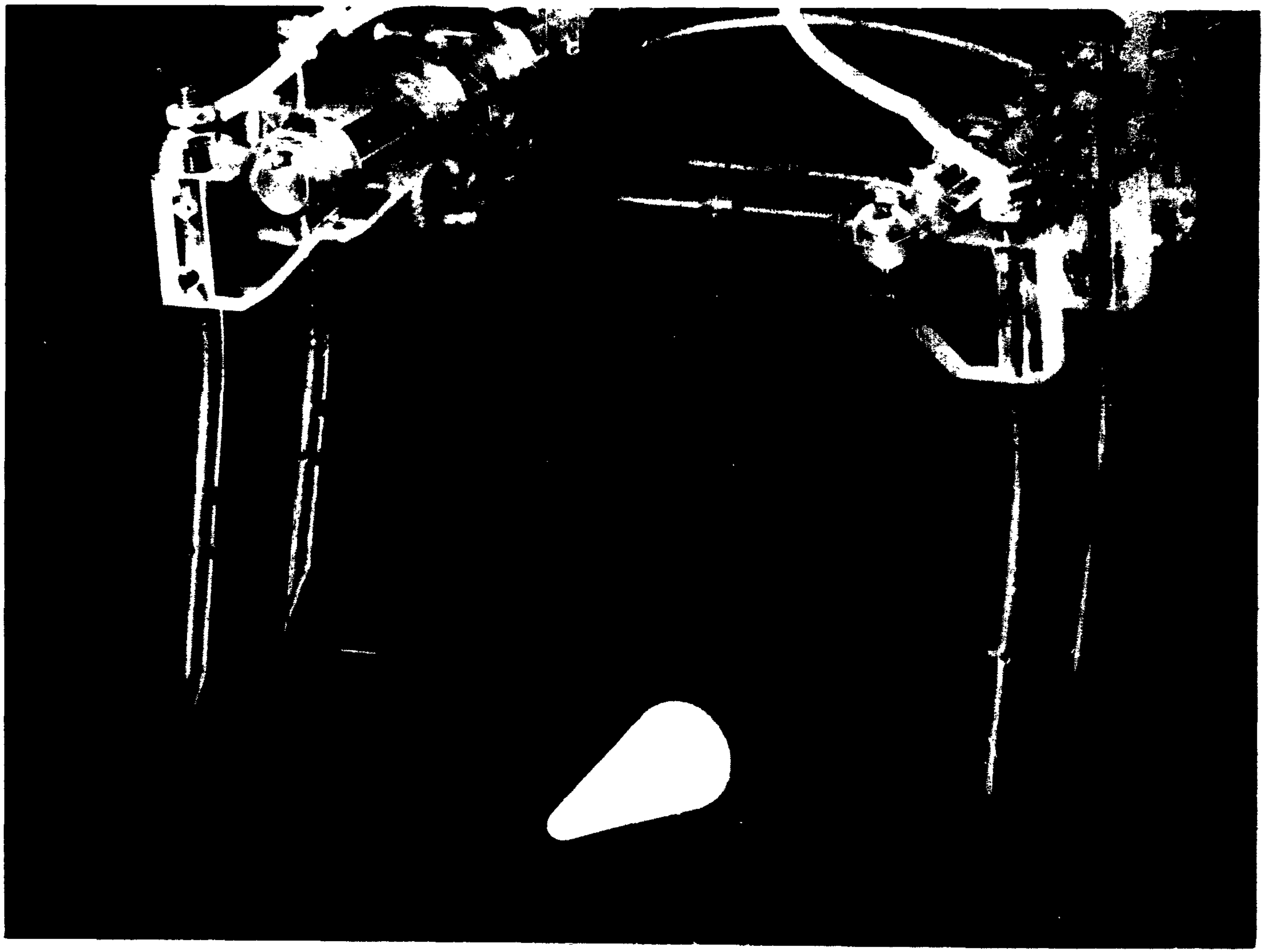

Figure 1. Apparatus for Controlled Severing of Model Suspension Threads

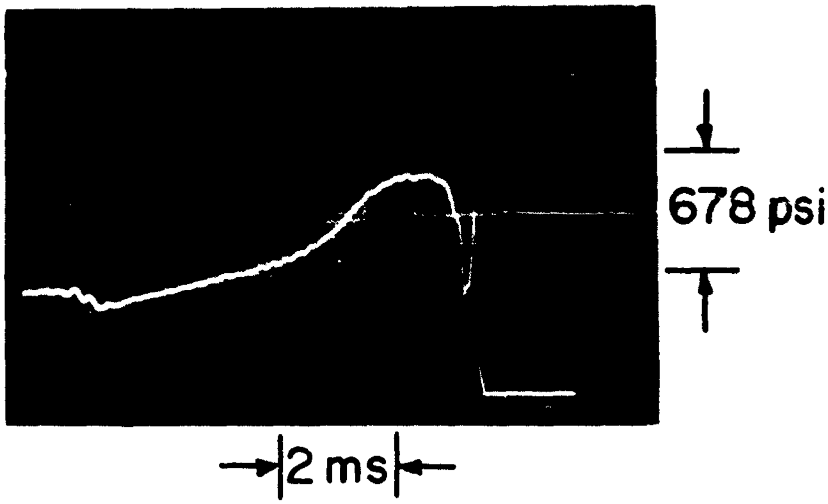

Figure 2. Typical Reflected Pressure

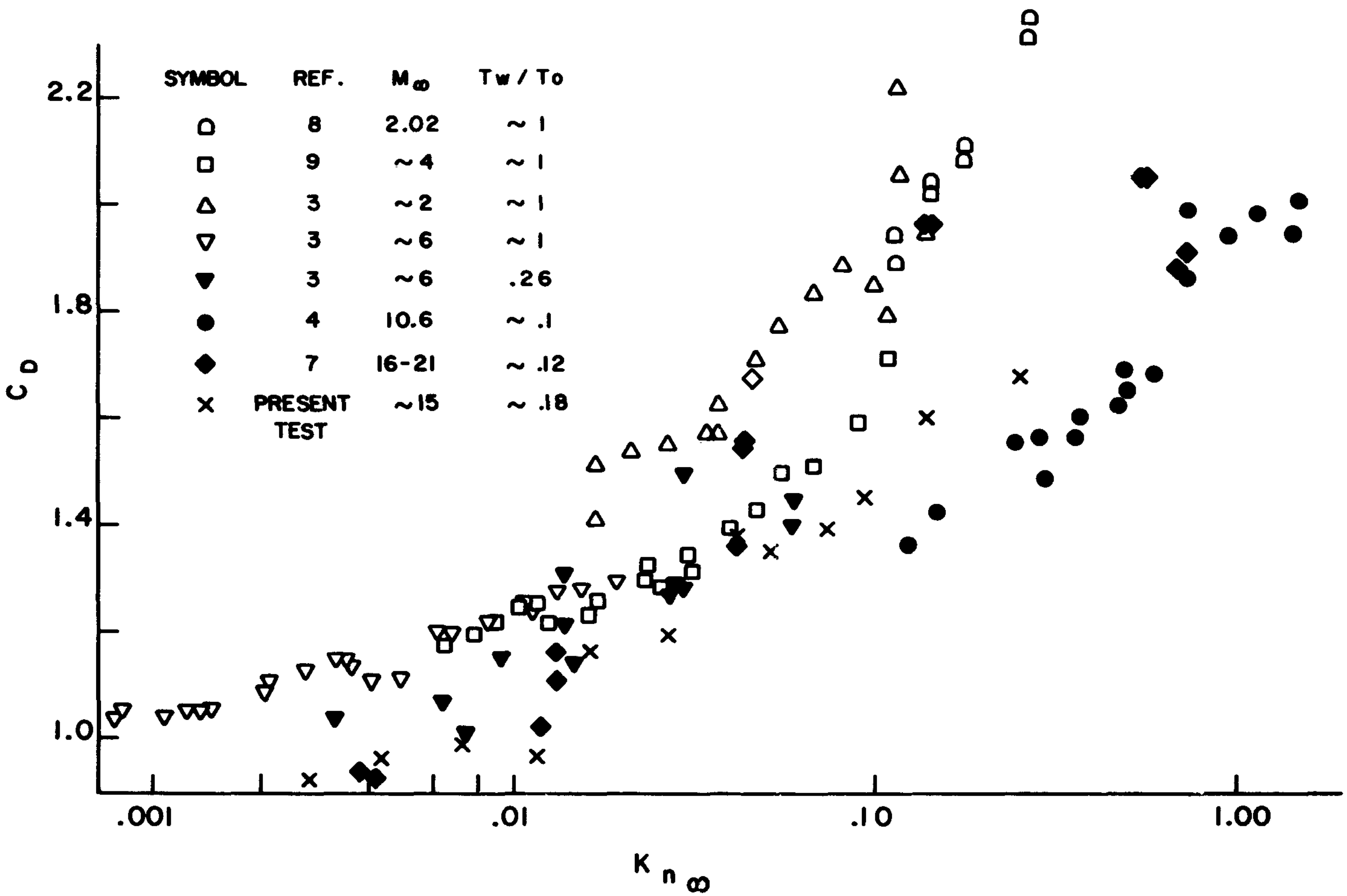

Figure 3. Sphere Drag vs. Free Stream Knudsen Number

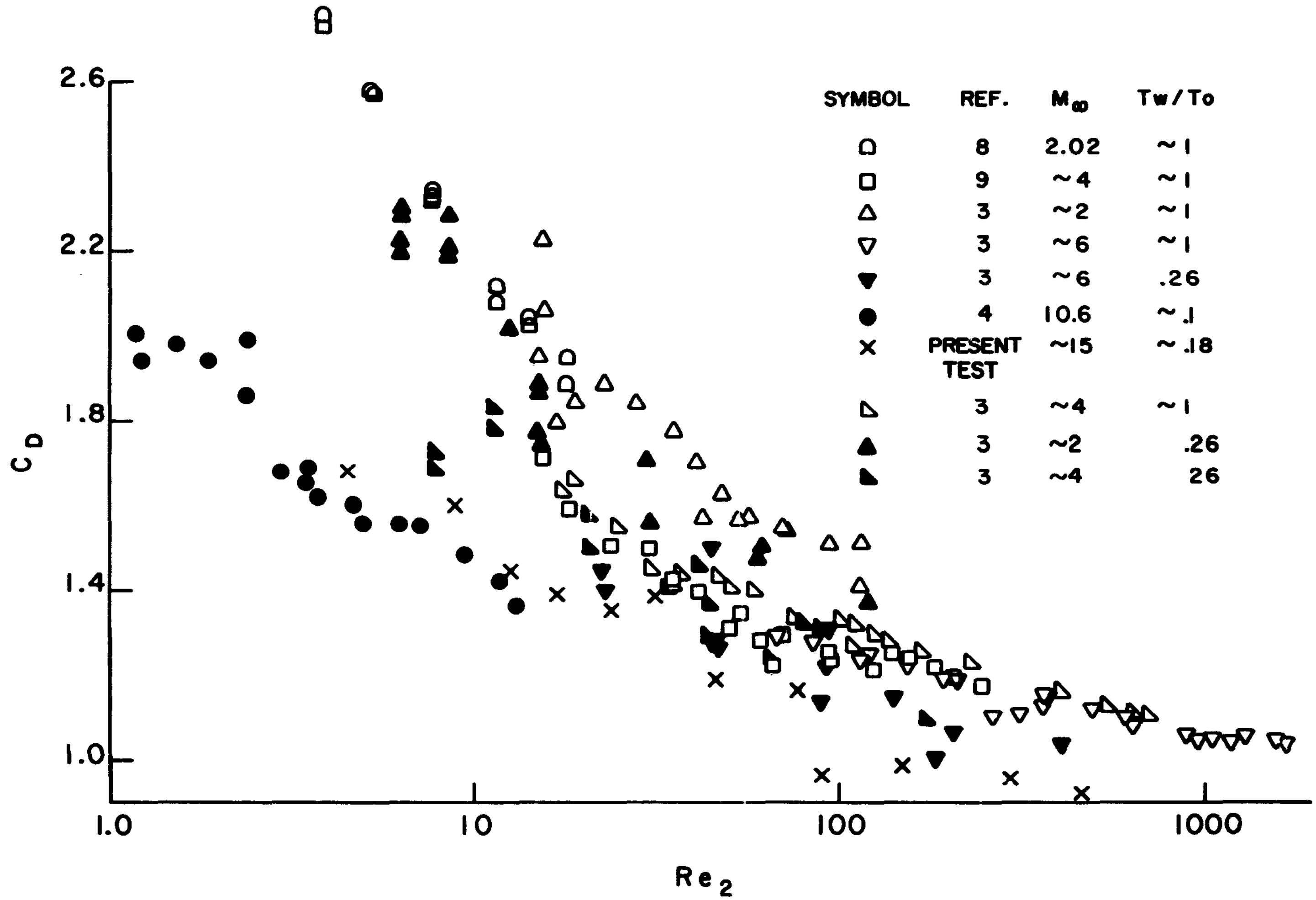

Figure 4. Sphere Drag vs. Re_2

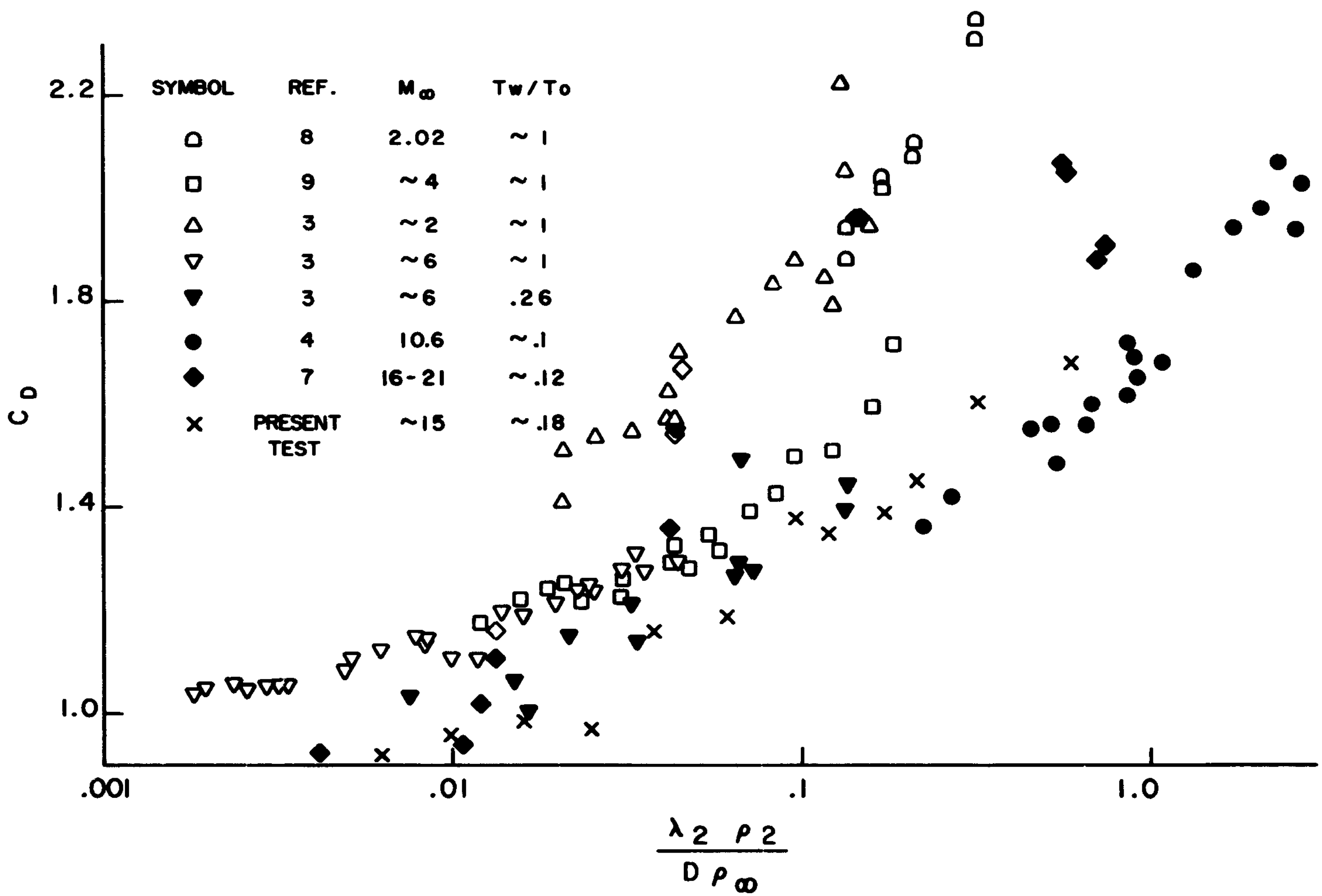

Figure 5. Sphere Drag vs. $\frac{\lambda_2}{D} \frac{\rho_2}{\rho_\infty}$

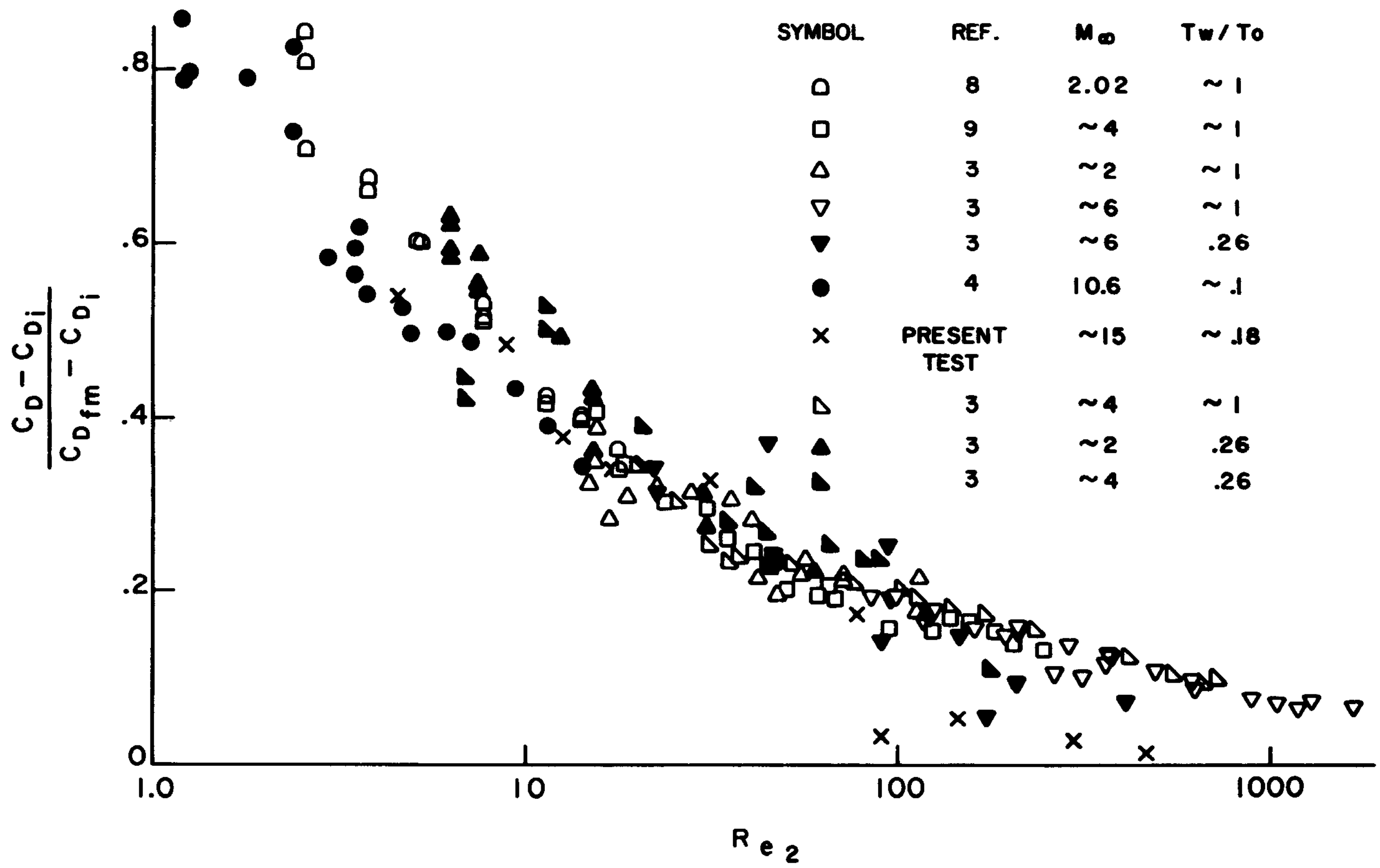

Figure 6. Correlated Sphere Drag

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SUMMARY

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