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Venusian Probes Subsonic Drag Determination from Flight Data

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Subsonic drag coefficients have been obtained from flight data for the Pioneer Venus multiprobes. The technique used to extract the information from the data consisted of utilizing in situ pressure and temperature measurements. Analysis of the major model parameter error sources indicates overall error levels of 5% or less in the flight values of C_D. Comparisons of the flight coefficients with preflight wind-tunnel test data showed generally good agreement for the five configurations investigated, although all flight-derived values are slightly larger than preflight wind-tunnel test values. Additional wind-tunnel tests were performed on the Sounder descent probe as a control experiment on the data extraction technique. A special attempt was made to accurately duplicate the probe geometry for tests in a high Reynolds number environment in order to achieve as realistic model and flight conditions as practical. Results from this testing in the NASA Langley low-turbulence pressure tunnel produced $C_D = 0.68$ at $\alpha \approx 0$ deg which is within the expected accuracy limits of the flight derived C_D value of 0.72 ± 0.04.

Nomenclature

A	= reference area
b	= reference diameter for rolling velocity and Re_∞
C_A	= axial force coefficient
C_D	= drag coefficient
C_m	= pitching moment coefficient
C_N	= normal force coefficient
g	= gravitational acceleration, $\mu/(R_♀ + h)^2$
h	= altitude
$\dot{h}$	= altitude rate
M	= Mach number
m	= mean molecular gas weight
$\mathfrak{M}$	= vehicle mass
p	= atmospheric pressure
p_v	= rolling velocity
$p_v b/2V$	= nondimensional rolling parameter
R	= universal gas constant
Re_∞	= freestream Reynolds number based on reference diameter
$R_♀$	= radius of planet
T	= temperature
t	= time
V	= velocity, $\lvert\dot{h}\rvert$
X	= model longitudinal station
α	= angle of attack
δ	= real gas correction factor, %
μ	= Venus gravitational constant
ρ	= atmospheric density
ρ_s	= probe mean density

Subscript

0	= initial conditions

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Introduction

THE Pioneer Venus Multiprobe Mission, as part of a series of NASA planetary investigations, sent four instrumented probes into the Venusian atmosphere, which is predominantly carbon dioxide. The purpose of the probes was to gather in situ scientific data in order to advance existing knowledge of Venus and its environment. These 45 deg conical blunt-body entry probes consisted of three identical small entry vehicles (North, Day, and Night) and a large entry vehicle and spherical descent probe combination (Sounder). The probes were directed toward diverse locations on the planet so that comparative atmospheric samples could be obtained. Since the Venusian encounter in December 1978, a continuing analysis and reporting process began using measurements from the Pioneer multiprobe and orbiter experiments. Some of the resulting atmospheric and planetary information was recently reported by the numerous Pioneer Venus scientific teams.[1,2]

One feature of the encounter which offers an excellent opportunity for investigation and verification of atmospheric phenomena is the highly dense Venusian atmosphere, which rapidly decelerated the probes to subsonic speeds. The resulting long descent time (≈ 1 h) in the subsonic flow regime also provides an extensive data base for deriving the subsonic aerodynamic characteristics of the probes in flight for comparison with the results of wind-tunnel investigations. Initial comparative analyses of the flight-derived aerodynamic data with wind-tunnel model data showed generally good agreement. The Sounder descent probe, which was encapsulated by an aeroshell during the high acceleration and heating entry environment, provided an ideal test vehicle for the aerodynamic extraction method. Additional postflight model testing was performed with this configuration as a control experiment since probe geometry and environment are well known. The purpose of this testing was to obtain wind-tunnel data at conditions approaching those obtained in flight with a geometrically similar model to assess the adequacy of the coefficient extraction technique.

During each probe's slow descent to the surface, a multiple of different measurements was made, including pressure and temperature. The pressure instruments on each probe consisted of a double array of six transducers of different ranges to provide both redundancy and accuracy over a wide range of pressure, namely, 0.08-100 bars. Each probe was also equipped with a dual temperature-sensing device. The temperature sensors were multiwire (platinum), resistive-type instruments with two sensing elements configured to extend into the freestream flowfield at subsonic speeds. The two temperature-sensing elements provided both redundancy and independent measurements over a temperature range of 200-800 °K. The redundant pressure and temperature sensors were alternately sampled at regular intervals during the probe's subsonic descent to the Venusian surface. Further design details, descriptions, and achieved accuracies of these sensors and the supporting instrumentation may be found in the existing literature.[3] The technique used to extract the aerodynamic data primarily relies upon the information obtained from these in situ pressure and temperature measurements. This paper presents the technique for processing the dynamically derived subsonic aerodynamic characteristics for each of the probes from flight data, the comparison of these characteristics with wind-tunnel data, and the recently obtained Sounder probe wind-tunnel test results confirming the adequacy of the data extraction technique.

Aerodynamic Determination Method

Configurations

For this study, there are five separate determinations of subsonic aerodynamic coefficients from flight data. These are the three separate determinations for the small probes and two determinations for the Sounder probe; one for the combined parachute and descent probe configuration and the other for the Sounder descent probe alone. Of these configurations, the Sounder descent probe is the most pristine since it was shielded from the entry heat pulse by the aeroshell, which was subsequently ejected. Therefore, this probe is a somewhat rare ideal subsonic test vehicle in excellent condition as compared to an unprotected entry vehicle. A more complete description of the Sounder probe is given in the Wind-Tunnel Investigations section.

Real-Gas Corrections

The atmospheric pressures and temperatures near the surface of Venus are drastically different from those of Earth and Mars, the other two planets sampled by in situ measurements from entry vehicles. The ideal-gas law does not adequately define the state of the gas under conditions presented by Venus. Consequently, real-gas corrections have been applied to the calculations of density. These corrections are based upon the carbon dioxide properties given by Hilsenrath.[4] Figure 1 shows the percent deviation in density from the ideal-gas condition as a function of measured pressure which was used to correct the data from each probe. The corresponding measured temperature profiles used in the calculation are not shown on the figure but are available.[5] At high pressure, corresponding to lower altitudes, each probe measured similar pressure and temperature variations with altitude and, hence, no appreciable deviation in the correction for an individual probe is evident on the figure. As expected, the higher pressures require the larger adjustments, up to about 1%. Although this magnitude is relatively small for aerodynamic extraction purposes, it was deemed reasonable to include these adjustments for completeness.

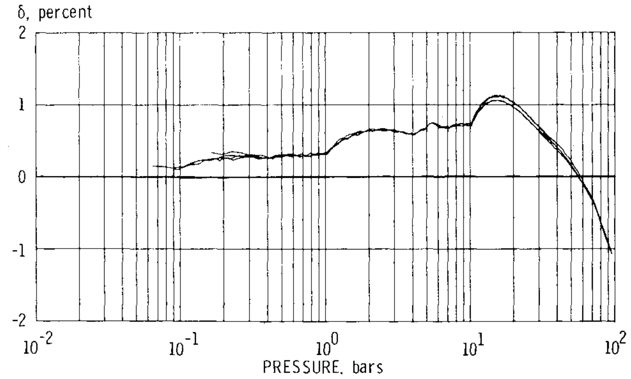

Fig. 1 Density deviation from ideal-gas law for measured pressures and temperatures on each probe.

Coefficient Determination Technique

There are several methods by which the drag coefficient can be obtained from the flight data. As mentioned earlier, the method chosen for this study depends principally upon the pressure and temperature measurements. The step outline to obtain the drag coefficient during subsonic flight is as follows:

1) Calibrated and adjusted pressure and temperature measurements as a function of time are used to calculate the probe's altitude and density profile as first suggested by the Pioneer Venus Atmosphere Structure Team[6] (led by A. Seiff, NASA Ames Research Center). That is,

$$h(t)-h(t_i)=\int_{t_i}^{t}\dot{h}\,\mathrm{d}t\equiv\int_{t_i}^{t}-\frac{\dot{p}}{\rho g}\,\mathrm{d}t \tag{1}$$

where, from the gas law

$$\rho=\frac{\kappa m p}{RT},\qquad \text{where}\qquad \kappa=1+\frac{\delta}{100} \tag{2}$$

At any given time, the above yields $h(t)$ and $\rho(t)$, which define the density altitude profile used in step 2. The integration starts at the surface of the planet and proceeds backward in time to define the altitude profile.

2) From a set of initial conditions (i.e. $h_0, \dot{h}_0$), the probe's physical constants, and the density altitude profile as obtained from the measured pressure and temperature data, the probe's trajectory is calculated from integration of modified standard equations of motion given as

$$\ddot{h}=\frac{C_D A}{2\mathfrak{M}}\dot{h}^2-\left(1-\frac{\rho}{\rho_s}\right)g \tag{3}$$

These equations are modified by the inclusion of buoyancy acceleration factor, ρ/ρ_s since, on Venus, this term is significant. For the altitude regime studied, buoyancy affects the terminal altitude by approximately 500 and 250 m for the Sounder and small probes, respectively.

3) The probe drag coefficient C_D is varied until the altitude profile generated by step 2 agrees with the altitude profile obtained from step 1.

The process to obtain altitude, described in step 1, requires the mean molecular weight and the radius of the planet at the landing site. For the calculations, the mean molecular weight used is 43.44 kg/kmole, corresponding to the measurements from the Pioneer Venus mass spectrometer experiment. The landed radii were based on results from the orbiter mission radar mapping experiment with relative terrain heights determined from surface pressure measurements. The initial conditions required to begin the integration process in step 2 were obtained directly from step 1.

Flight Results

The flight-derived subsonic drag coefficients for each of the five configurations are summarized on Table 1. Included are the flight test conditions, which were calculated from the onboard measurements of pressure and temperature, and the carbon dioxide gas properties given by Hilsenrath.[4] The values listed in the reference area column of Table 1 are based upon the maximum diameter of each of the four probes. The Sounder descent probe diameter includes the beveled ring as discussed in the Wind-Tunnel Investigations section and the

Table 1 Flight derived subsonic drag coefficient summary

Probe	C_D	Reference area, m^2	Mass, kgm	Flight test conditions $Re_\infty \times 10^{-6}$	Mach No.
North	0.775	0.4501	88.559	5.04-12.72	0.107-0.020
Day	0.786	0.4487	87.834	5.17-12.80	0.099-0.020
Night	0.766	0.4494	88.305	5.31-12.84	0.089-0.020
Sounder descent	0.720	0.5979	199.127	8.57-19.44	0.146-0.027
Sounder + parachute	$C_DA = 10.717\ m^2$		207.015	3.33-7.23	0.156-0.042

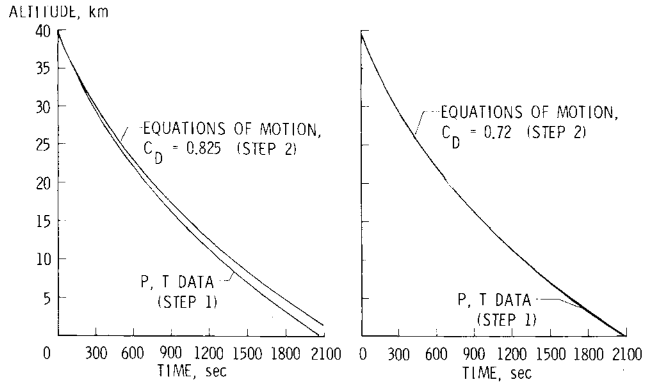

Fig. 2 Sounder descent probe altitude profiles for $C_D = 0.825$ and 0.72.

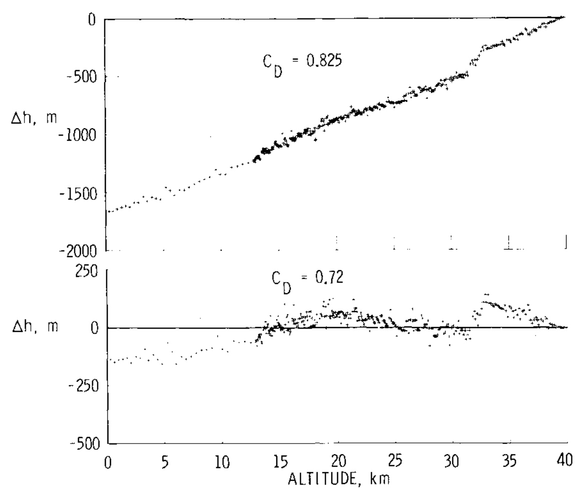

Fig. 3 Sounder descent probe altitude residuals for $C_D = 0.825$ and 0.72.

small probes are the maximum diameters after adjustment for ablation effects. The reference area for each small probe prior to adjustment is 0.4560 m^2. The values listed for the mass of each small probe have also been adjusted to account for ablation. The preadjusted masses are 91.054, 90.873, and 91.299 kg for the North, Day, and Night probes, respectively.

Sounder

Figure 2 displays the altitude profiles for the Sounder probe generated by integration of the equations of motion with $C_D = 0.825$ (an assumed value of subsonic drag coefficient) and the integration of the barostatic equation (step 1) using pressure and temperature measurements. Figure 3 shows the corresponding discrete altitude differences, or altitude residuals, as a function of altitude. It is expected that an accumulating altitude difference would occur upon integration of the equations of motion if the drag coefficient is erroneous. This altitude divergence is readily observed on both Figs. 2 and 3. The altitude disparity at impact exceeds 1500 m.

Figures 2 and 3 also display the results for the Sounder descent probe after iteration to determine the converged value of the drag coefficient. As can be seen from comparison of the two curves in Fig. 3, the altitude divergence is reduced significantly for a value of $C_D = 0.72$ which produces the best match with the altitude derived from the pressure and temperature data. The altitude residuals shown for $C_D = 0.72$ have essentially a zero mean and a spread of about 150 m.

For altitudes below approximately 14 km, the temperature data on all probes departed from the expected behavior due to an (as yet) unexplained malfunction. This occurrence affected other instrumentation as well as the temperature sensors. Thus, below this altitude, the reference data (that is, h from p and T) for comparisons are questionable. Although this is a concern, it poses no serious problems in subsonic drag coefficient determination since this region can be neglected in the iteration process. The signal contained in the residuals requires further identification analysis. However, even on the basis of total spread, the derived value of the drag coefficient is not significantly affected.

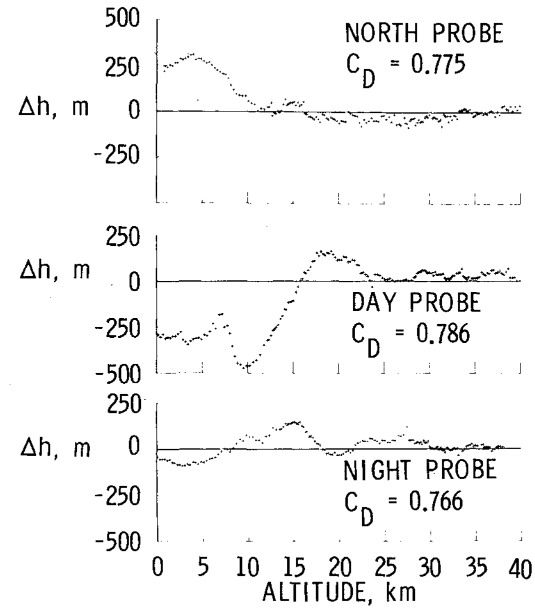

Fig. 4 Altitude residuals for North, Day, and Night probes.

Small Probes

Figure 4 shows the altitude residuals after iteration for the North, Day, and Night probes. The individually determined values for the drag coefficients are 0.775, 0.786, and 0.766, respectively, which represent at most a 3.5% deviation from the nominal preflight drag coefficient of 0.76 for the probes. The probes are basically identical apart from the influence of the atmosphere on probe geometry during the upper entry phase. The derived drag coefficient differences are within the expected accuracy of the experiment as discussed in the error

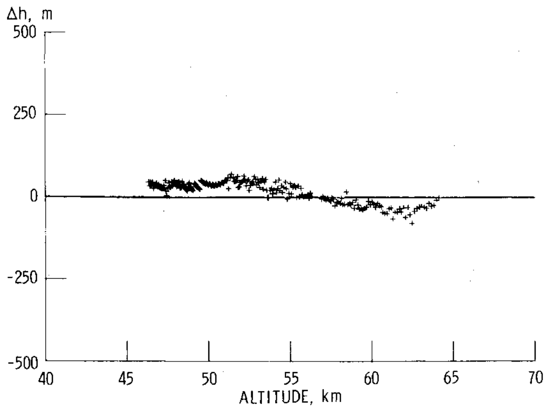

Fig. 5 Parachute/Sounder altitude residuals for $C_DA = 10.717$ m^2.

analysis section. The values for the North and Night probes are nearly the preflight nominals. The deviation for the Day probe is the greatest of the three small probes. This probe also had the shallowest entry path angle, 16.1 and 43.3 deg less than the Night and North probes, respectively. All probes lost temperature measurements below 14 km. However, the residual altitude excursions depicted in Fig. 4 for the Day probe are greater than would be expected by reasonable temperature extrapolations. A comparative examination of the pressure data from each small probe indicates that the Day probe's data are the least well behaved which may be a partial explanation for the residual behavior below 24 km. For this probe, the iteration altitude region was limited to above 24 km. As is seen in this altitude region, the residuals are small, less than 100 m. Both the North and Night small probes have acceptable residual levels considering the error sources in the process.

Parachute and Sounder

The results of the parachute and Sounder configuration are included for completeness. It is recognized that this particular nonrigid combination requires special modeling considerations to describe the dynamic behavior completely. The idea for this study was to select the data segment between when the parachute was known to be fully deployed and before its jettison to see if the scheme used on the probes could adequately describe the combined drag behavior. Figure 5 contains the altitude residual in the full deployment segment for the combined parachute and Sounder configuration after iteration. The value of C_DA obtained from the flight data during this approximate 20 km altitude interval is 10.717 m^2. This value falls within 3% of the preflight value[9] of 10.4 ± 0.74 m^2, a rather good agreement. ¶ The altitude residual level is about 75 m, which is within the expected limitations of the technique and data.

Error Analysis

Model Sensitivity Matrix

The probe's altitude profile from step 2 of the coefficient determination technique is produced by varying only one dynamic parameter, namely C_D. The extent to which errors in model parameters affect the probe's altitude at the time of impact is shown in Table 2. That is, Table 2 is a sensitivity matrix over the altitude interval from 40 km to the surface. Considering the altitude sensitivity to modeling errors, i.e., the second column, Table 2 shows the following:

1) Errors in initial velocity, planet radius, and spacecraft density have negligible effect on altitude over the interval.

2) Errors in C_D and initial altitude have considerable effect on altitude.

Thus, with the aid of Table 2, some conservative estimates can be made on the uncertainty in the determination of C_D in the presence of model errors. For example, the expected uncertainty in altitude determination from step 1 is less than 1% according to the analysis performed by the Pioneer Venus Atmosphere Structure Team.[6] An initial altitude uncertainty of this magnitude produces approximately a 1% uncertainty in the derived value of C_D.

Table 2 Model errors sensitivity matrix

Parameters (p)	$\partial h_{\text{Impact}} / \partial p$
C_D	104 m/%
V_0	−1 m/mps
h_0	275 m/km
$R_{♀}$	8 m/km
ρ_s(Sounder)	−5 m/%
ρ_s(Small probes)	−3 m/%

Other Considerations

There are additional model parameters whose effects on the determination of C_D are not shown in Table 2. These are atmospheric density, vertical winds, and spacecraft angle of attack. In terms of an error source, atmospheric density errors map directly into C_D errors. It is believed that the density is known to within 1%[6]. Error analysis for vertical wind components is not feasible due to the unknown and unpredictable nature of the winds. Nevertheless, independent methods have been used for assessing the vertical winds in the lower atmosphere and preliminary results[7] indicate small magnitudes (<0.5 mps) with no prevailing direction. For the analysis, a zero angle of attack has been assumed. Indications[6] are that the angle of attack for all probes during descent was less than 5 deg. The drag coefficient is essentially invariant for angles of attack less than 10 deg. For the small probes, no appreciable change in probe area or mass due to ablation by the upper altitude heat pulse had been expected. (Current estimates are ~3% for mass loss and ~1.5% for area change.) Although these effects have been incorporated into the calculations, any changes should be somewhat compensatory since the ratio appears in the equations of motion and the area and mass change in the same direction. Effectively, the nonseparable product of $C_DA/\mathfrak{M}$ is solved for in the iteration process described earlier, and consequently, any C_D error arises upon interpretation after the iteration process is complete. Thus, errors in $(A/\mathfrak{M})$ reflect directly into corresponding C_D errors. The flight-derived small probe drag coefficient values included in Table 1 are in good agreement with wind-tunnel data[8] which indicate an axial force coefficient of 0.76 for the small probe configuration at $M = 0.20$, $\alpha \approx 0$ deg, and $Re_\infty \sim 2.25 \times 10^6$. Thus, considering all major error sources, a conservative estimate of the overall error of the derived values of C_D is believed to be less than 5%. This error estimate and validation of the technique has been additionally confirmed by separate postflight testing of the Sounder probe which is discussed next.

Wind-Tunnel Investigations

Sounder Probe

There were many preflight test programs conducted in different facilities to determine the subsonic drag characteristics of the Sounder probe. Many of these tests were done to arrive at a satisfactory design, thus configurations were varied as well as tunnel conditions. The data from these tests

¶The preflight dimensional drag coefficient of the parachute/Sounder was obtained from a combination of verification tests performed at the National Parachute Test Range, El Centro, Calif., and technical exchanges between NASA Ames, Hughes Aerospace, and General Electric (RESD). The estimate arrived at is 10.4 ± 0.74 m^2.

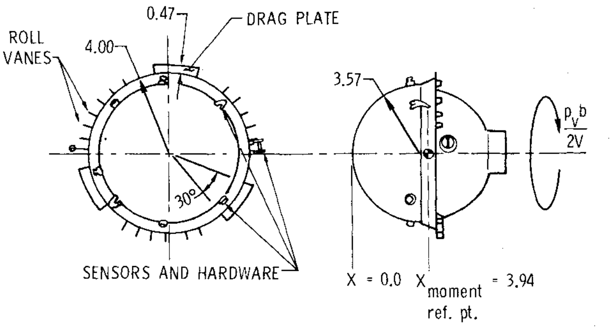

Fig. 6 Schematic of Sounder probe wind-tunnel model (all linear dimensions are in centimeters).

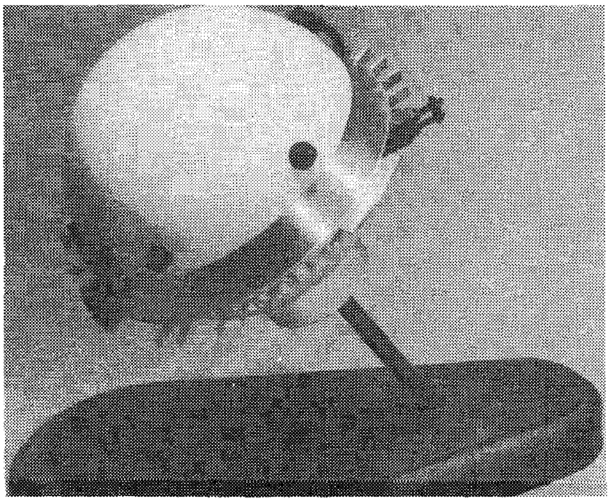

Fig. 7 Photograph of the 0.092-scale Sounder probe model.

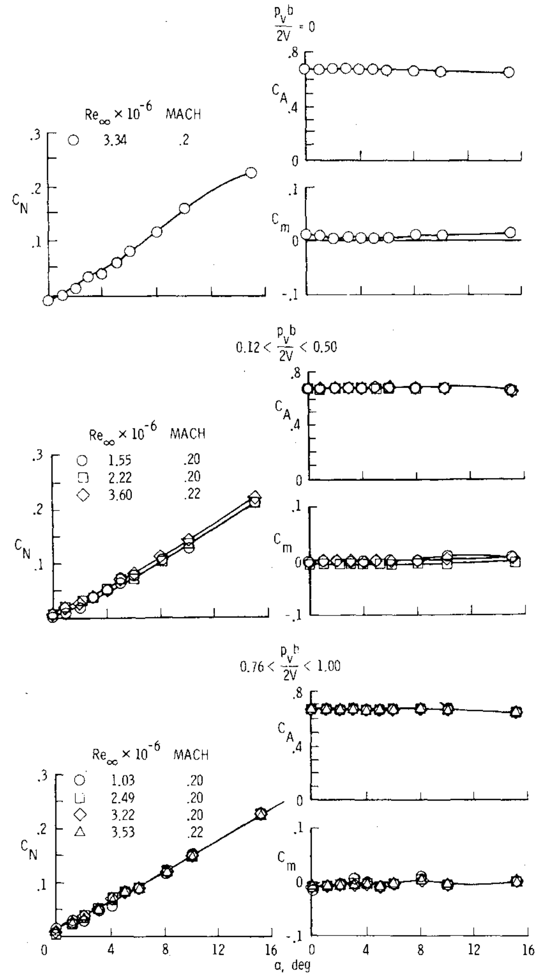

Fig. 8 Longitudinal aerodynamic characteristics of the 0.092-scale Sounder probe model for three sets of nondimensional rolling parameter.

produced a wide range of drag coefficients which, when adjusted for the actual geometry flown, averaged, or extrapolated, produced a good comparison with the value derived from the flight data. However, there were difficulties in obtaining proper documentation since drag test results conducted by the Pioneer Venus Project Office are not in the open literature. Further, all five flight-derived coefficient values are higher than most preflight coefficient values examined. It was felt that the Sounder probe should produce the most reliable coefficient comparison since its geometry and mass is unaffected by the entry heat pulse. Thus, a separate wind-tunnel study was devised to match as closely as possible the configuration of the flight article in an attempt to directly verify the coefficient extraction technique as well as the predicted uncertainty in the technique. For this laboratory experiment, care was exercised to duplicate configuration geometry. In addition, rotational characteristics were included in the wind-tunnel tests at Reynolds numbers approaching the flight Reynolds numbers.

Models and Tests

The postflight Sounder probe aerodynamic study used the 0.092-scale model shown in Fig. 6. The model had a nearly hemispherical forebody joined to a 22 deg beveled ring midfairing with a spherical/cylindrical afterbody. The cylindrical base fairing of the model was the only geometric departure from the flight vehicle and was required to accommodate the three-component electrical strain gage balance used in the wind-tunnel investigation. Three 30 deg windward-facing flat drag plates were equidistantly spaced around the circumference of the 22 deg beveled ring aft surface and extended into the airstream. The plates separated three sets of six roll vanes which were also attached to the aft surface of the beveled ring and extended radially into the freestream at incidence angles to produce the required rolling velocities of the model.

The forebody protuberances on the flight vehicle, consisting of sensors, wiring yolks, and attachment pins, were scaled and attached to the wind-tunnel model (shown in Fig. 7) as were the sampler for the cloud particle-size mass spectrometer and the temperature sensor which were mounted on the afterbody but extended into the airstream. The internally contained strain gage balance was rigidly mounted to a sting and supporting mechanism to allow model angle-of-attack variation and was connected to the model by an adapter and two internally contained roller bearings. The bearings allowed the model to rotate freely about the longitudinal axis of the balance. Rolling velocities were varied by mechanically changing the roll vane incidence angles during the investigation. A magnetic pickup located inside the model was used to indicate the model roll rates.

The wind-tunnel investigation was made in the Langley low-turbulence pressure tunnel at Mach numbers of 0.20 and 0.22. Reynolds numbers for the investigation varied from about 1.0×10^6 to 3.6×10^6 based on the maximum beveled ring diameter. The nondimensional rolling parameter, $p_v b/2V$, and model angles of attack were varied from 0.0 to 1.0 and from 0 to about 15 deg, respectively. The low-turbulence pressure tunnel is a variable-pressure single-return facility having a closed rectangular test section 0.91 m wide by 2.3 m high. Maximum freestream Reynolds number capability of the tunnel is 49.2×10^6/m.

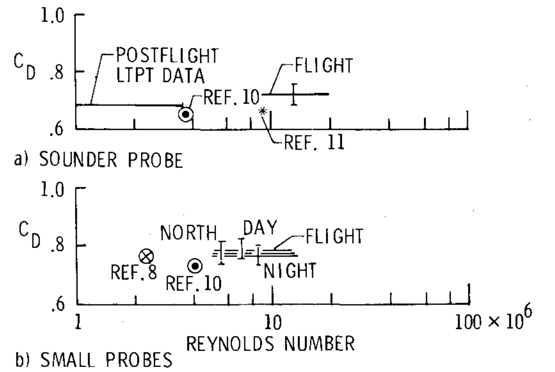

Fig. 9 Reynolds number comparison of flight and wind-tunnel drag data.

Results

Three sets of longitudinal aerodynamic characteristics for the 0.092-scale Sounder probe model are shown in Fig. 8. These data indicate only slight variations in axial force coefficients near 0 deg angle of attack attributable to variations in either Reynolds number or the nondimensional rolling parameter, $p_v b/2V$. The value of the C_A ($C_A \approx C_D$ at low α) obtained from the wind-tunnel study was approximately 0.68 for $p_v b/2V \approx 0.35$, $M = 0.22$, and $Re_\infty = 3.6 \times 10^6$ at low-to-moderate angles of attack. Other observations made from these wind-tunnel data are linear normal force and pitching moment variations noted for the model rolling or at rest at all the Reynolds numbers and rolling velocities investigated.

Small Probes

A summary of the results of preflight testing of the small probe configuration are included for completeness. The probe model used in one preflight aerodynamic study[8] was a 0.367-scale model of the Pioneer Venus undeformed small probe configuration. The small probe external geometry consisted of a spherically blunted, 45 deg half-angle cone forebody with a spherical segment afterbody. Aerodynamic force and moment tests were made in the Langley 8 ft transonic pressure tunnel at $M = 0.20$ and $Re_\infty = 2.26 \times 10^6$, based on the maximum diameter of the model. The resulting data indicate a level of axial force coefficient of 0.76 at low-to-medium angles of attack which agrees well with the values of 0.766-0.786 derived from the small probes subsonic descents.

Flight and Wind-Tunnel Comparisons

In order to summarize the findings of the present investigation, comparisons were made with the dynamically derived drag coefficient flight data for the Sounder probe wind-tunnel data from this study, as well as other tunnel data, and for the small probes with published preflight wind-tunnel data.

Sounder Probe

Figure 9a shows a comparison of the Sounder probe preflight drop tests,[10] preflight wind-tunnel tests,[11] and instrumented subsonic high Re_∞ drag data of the present study as a function of Reynolds number along with the flight-derived data. The flight-derived data are represented as a band to illustrate expected data accuracy. Reynolds numbers for the present wind-tunnel data are shown for which a nearly constant value of 0.68 was found at angles of attack near 0 deg. This value agrees well with the preflight value of 0.685 obtained by the Project Office** with no substantial improvement in agreement with the flight-derived data coefficient value of 0.72 ± 0.04.

Small Probes

Figure 9b shows a comparison of the preflight wind-tunnel and drop test drag data of Refs. 8 and 10, obtained at low angles of attack with the flight-derived data of the present study. The flight data are represented with error bars over the subsonic flight Reynolds number range to account for data accuracy. The level of 0.76 obtained from wind-tunnel studies[8] at $Re_\infty = 2.26 \times 10^6$ and $M = 0.20$, falls within the flight-derived band of the present study. Subsonic flight Reynolds numbers extended from 3.24×10^6 to 10.32×10^6.

Conclusion

The subsonic drag coefficients of the four Pioneer Venus probes have been obtained from flight data to an accuracy within 5% in a predominantly carbon dioxide media. The technique, consisting of matching altitude profiles produced by pressure and temperature measurements with those from integrated trajectories, has also been used to obtain the dimensional drag coefficient of the high-drag combined parachute/Sounder configuration. This method produced agreement to about 3% with preflight estimates for the small probes and the combined parachute/Sounder configuration. Flight results for the Sounder descent probe agreed to within 5% of all the wind-tunnel test results. Flight Mach and Reynolds numbers were calculated from carbon dioxide properties based upon measured values of the encountered atmosphere. The Venus atmosphere produced relatively large Reynolds numbers with respect to present-day tunnel capabilities, although flight drag coefficients were essentially invariant with Reynolds number for this Reynolds number regime. All five flight drag coefficients were consistently higher than wind-tunnel values, although all were within the estimated accuracy of the technique. Separate detailed postflight wind-tunnel testing of the Sounder probe produced essentially no change in the unidirectional scatter. The lack of randomness for this limited sample may be simply coincidence or, perhaps, it may suggest the presence of a small unknown bias.

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**The preflight drag coefficient of the Sounder descent probe is 0.846 ± 0.04 (reference area = 0.4838 m^2) based upon wind-tunnel tests at NASA Ames and NASA Langley. This value corresponds to 0.685 ± 0.04 when converted to the reference area of this report (see Table 1).