Tether Satellite Potential for Rarefied Gas Aerodynamic Research

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Applications of the tether satellite in aerodynamic research under conditions of low-density hypervelocity flow are described. The satellite is envisioned as a spheroidal nose, slab-sided cylinder with variably swept wing, tethered to the shuttle orbiter and deployed to altitudes of about 95 km and above. Suggested experiments reflect requirements for new understanding of low-density flows and include the direct measurement of normal and tangential stress on representative aerospace surfaces, the measurements of vehicle lift, drag and pitching moment, ambient gas density and composition, surface temperatures, and wall tap and impact probe behavior. Also suggested are measurements of gas densities above the wing surfaces and on or near the stagnation line using electron-beam fluorescence methods and, where applicable, free-molecule orifice probes. Experiments proposed may be implemented without significant development of new technology.

Nomenclature

A = area of test surface
C_D, C_L = coefficient of aerodynamic drag and lift, respectively
F_L = lift force
F_x = force along surface tangent
F_{-y} = force on surface along inward surface normal
R = mixture gas constant
S_∞ = speed ratio, $U_\infty/\sqrt{2RT_\infty}$
T_∞, U_∞ = freestream temperature and velocity, respectively
X, Y = coordinates tangent and normal to surface, respectively
ρ_∞ = freestream density
θ = angle, freestream axis to surface tangent

Introduction

ENGINEERS closely linked with the design of aerospace vehicles recognize the need for new knowledge of aerothermodynamic processes in hypervelocity flight. They recognize also that such knowledge must come from experimental sources. A remarkably tiny fraction of direct flight experimentation has been organized to provide data on flows in rarefied regimes yet, except for these data, we have acquired very little experimental information recently that is directly applicable to re-entry gas dynamics.[1] In part, the reason for this may be very simply stated; there are no ground-based facilities in which to duplicate flow velocity, gas composition, and rarefaction appropriate to the flight condition. We know too that experimental measurements undertaken during ascent or re-entry are severely constrained by time and, in consequence, are of limited utility. On the other hand, the tether vehicle at its station within the correct flight environment would seem to provide that steady-level platform required for significant technical observation. These familiar remarks are repeated here to sketch again the rationale for aerodynamic experimentation supported by tethered satellite.

Although the possibility of such work has been discussed for a number of years, not until rather recently have space agencies become seriously involved. Two major programs have emerged. The first is an international undertaking in which NASA, together with the Italian aerospace agency, will develop the TSS, or Tether Satellite System.[2] Two flights using the TSS-1 and TSS-2 are scheduled for the early 1990's. Both have objectives relating primarily to atmospheric science. The second, more recent in origin, is known as STARFAC or Shuttle Tethered Aerodynamics Research Facility.[3] STARFAC is supported by NASA and will undertake both aerothermodynamic and atmospheric science studies. As the title of this paper suggests, I will be concerned principally with the potential for aerothermodynamic investigations that might be accommodated within the logistic constraints of the STARFAC program. In the flight environments appropriate to this discussion, we deal with rarefied or low-density hypervelocity flows, which, following Potter,[4] will be referred to as LDH flow. The effects of rarefaction are felt by the space transportation system (STS) orbiter at altitudes as low as 70 km, but aerodynamic heating and vehicle drag impose a low-altitude limit for tether deployment of about 90 km. In this region and above, our current understanding of the gas/wall boundary interaction including surface catalyticity is slight, as is our understanding of the nonequilibrium chemistry of the shock layer. Design application of direct simulation by Monte Carlo (DSMC), which seems at present to be the only effective computational method for LDH flows, is in consequence severely limited. The matter can be put more optimistically; DSMC will be able to supply flowfield descriptions, stability coefficients, heat-transfer coefficients, and so on throughout the transition from continuum to free-molecule flow once suitable experimental information is in hand.

The author has recently shown[5] through DSMC that the density, velocity, and temperature fields above a flat plate in hypersonic rarefied flow are strongly influenced by the nature of the wall/gas interaction. This point will be developed further in another section of this paper. The strong implication of these studies is that flowfields about many kinds of bodies in LDH flows will also be influenced, as will surface heating, stability coefficients, and wake characteristics.

The tether vehicle is well-suited to support experimental work on both the wall/gas interaction and on the flowfield—work that would yield physical data of extraordinary value in design and analysis. My purpose here is to describe possible forms of such experiments and to show how they might be useful. Specifically, I shall examine first an ex-

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perimental system for the direct determination of normal and tangential stresses on flat surfaces at angle of attack under conditions of free-molecule flow.

It should be noted that certain housekeeping experiments such as the measurement of the incident momentum flux, the total incident energy flux, or the measurement of the local species composition are needed to supplement direct aerodynamic observation. A dual purpose is served since the measurement of such quantities will also contribute to our general knowledge of atmospheric science. These and other experiments appropriate to the flight conditions will be examined including experiments involving the noninvasive observation of density fields about a sphere nose cylindrical body with swept wing. These experiments will use the method of electron-beam fluorescence.

The order in which these experiments has been introduced suggests the order of priority in which the studies should be approached. Thus, the most fundamental work, that which is most generally applicable and most directly interpretable, should be undertaken first. Later experiments can base a more complete understanding upon those that have gone before. At levels of sophistication which will be suggested here, proposed experiments, except as noted, can be implemented within the current experimental art. I have elected to discuss potential experiments in association with a somewhat more complex vehicle than an early conceptual picture of STARFAC would suggest. I have done so to accommodate the storage and deployment of experimental packages, to provide the required capability for dynamic control of orientation, and to make possible vehicle aerodynamic measurement.

Free-Molecule Shear and Normal Stress

Measurement of stresses arising from wall/gas momentum transfer has not been undertaken directly, either aboard the shuttle orbiter or on other satellites in low Earth orbit. However, certain useful inferences have been drawn from the observation of orbital or spin decay of satellites and more recently, from records of shuttle flight performance. Unfortunately, observations on orbital decay of complex shapes do not lead to definitive models of scattering behavior although important insight may be gained. For example, Moe[6] examined the recorded spin-decay rate of the Explorer VI. This spin-stabilized satellite resembled a large four-bladed propeller set in rotation against the incoming stream. About 60% of its surface was coated with silica and the rest with a black paint. Results could not support a particular scattering model, but it was clear that gas molecules retained some fraction of their incident velocity upon scattering from the surface. The re-emitted momentum flux was sufficient to induce decay in the rotational frequency a factor of ten more rapidly than if the molecules had been diffusely re-emited at the surface temperature (Maxwellian re-emission). In a much more recent study, Blanchard,[7] using accelerometer records for six shuttle orbiter missions, found free-molecule lift-to-drag ratios significantly higher than predicted assuming diffuse scattering. When 8.5% of the incident flux was assumed to be specularly reflected, Blanchard calculated values of the lift-to-drag ratio to be 0.13, agreeing with the mean of observed values at 160 km where the shuttle would be in free molecular flow. Such observations, although showing that the incident momentum is not fully absorbed at the surface, also show clearly the need for direct experimental studies of momentum transfer under re-entry conditions.

Let me propose an experimental system that would be supported by the tether satellite and that would yield tangential force and normal force data on planar surfaces. These surfaces would be rotated with respect to the freestream through a suitable range of incident angles. It is useful to note that the surfaces of the shuttle orbiter are of two general sorts, the larger fraction being of glass on a substrate of silica fiber tiles. The nose cap and elevons, constructed of carbon-carbon, constitute the smaller fraction. Research or communication satellites similarly may have a large fraction of surface devoted to silica-coated solar panels, the remainder of the surface being polymer-based paint or oxide-coated metals. Extended space structures may employ polymers such as Kapton with overlays of protective coatings. Accordingly, the surfaces that we propose to test are those representative of the surfaces of flight vehicles.

The measurement of normal and shear stresses on surfaces will be accomplished by the concurrent measurement of the two components using a pair of balances for each material. Since we are dealing with large areas of technical surface, we may assume isotropic properties so that both surfaces of a pair will be essentially identical. In our view, for what must be considered relatively small forces, a dual single-component system will prove to be preferable to those using two-component balances.

A schematic showing elements of a dual single-component system is given in Fig. 1. A light frame supports a thin layer of the surface under test. Arms from the frame lead to a torsion wire that supports the frame and provides a variable restoring torque through rotation applied to one end. This fragile construction benefits from the "zero gravity" environment and from the absence of local vibrational disturbances. Provision is made for optical null sensing, null balancing, damping, and caging. Shear and normal force balances are seen to differ only in the arrangement of supports.

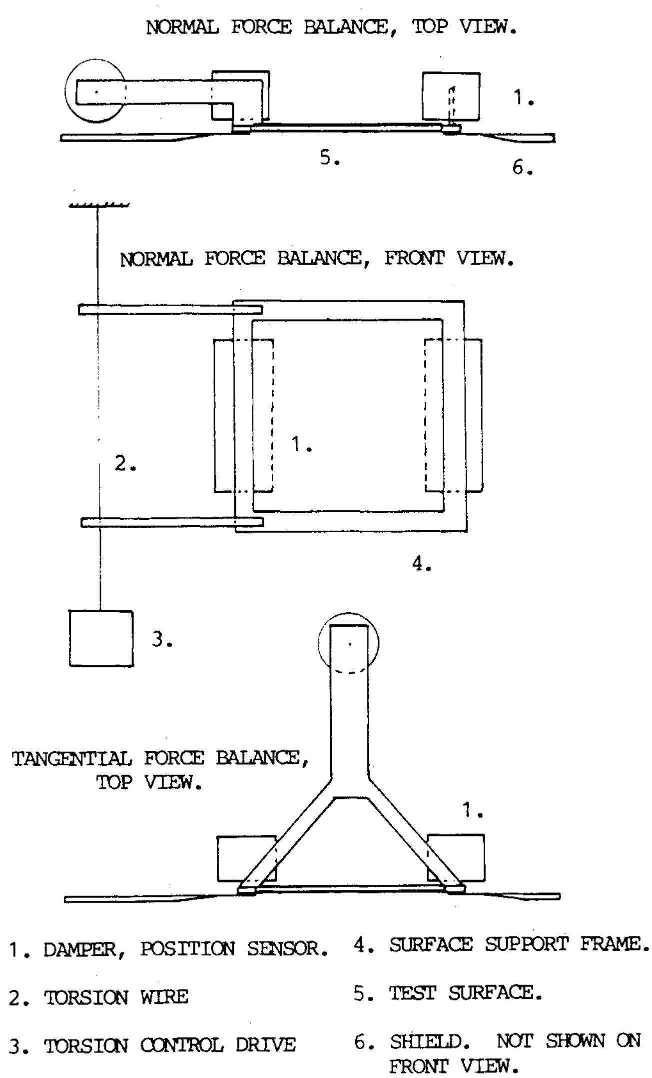

Fig. 1 Schematic of balance system for force measurements in free-molecule flow.

Several such balance pairs would be stacked upon a rotatable pylon and housed within a single shield. An assembly of four dual-balance systems together with one nonrotating momentum trap might appear as shown in Fig. 2. The momentum trap, which has a deeply fissured or cellular surface, ensures that incident molecules make a number of wall collisions before emerging. The test surfaces are isolated by a shield from molecules that have become scattered from the satellite body or from a shock layer just ahead of the vehicle.

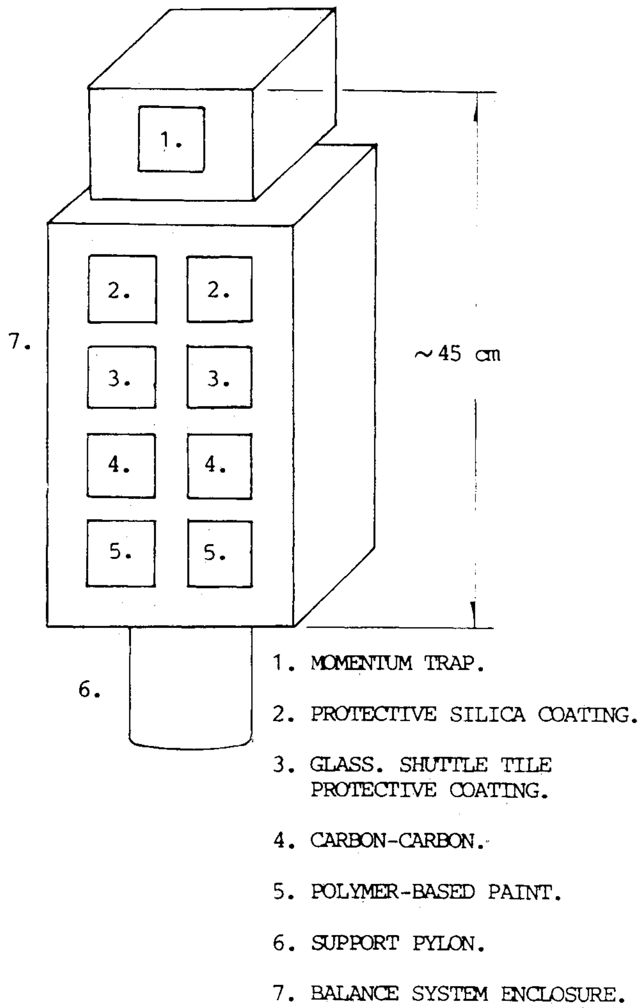

Fig. 2 Typical balance array.

One can characterize the degree of rarefaction using the Knudsen number Kn, where $Kn = \lambda/d$. Molecular collision in the gas phase becomes of negligible importance as the value of Kn becomes somewhat larger than unity. Atmospheric densities and molecular mean free paths are plotted as a function of altitude in Fig. 3. At 110 km, the molecular mean free path is approximately 1 m giving a value Kn of 2 or larger for the balance system proposed. Measurements would be made under essentially free-molecule conditions at all altitudes down to about 110 km.

Estimates of maximum normal force assuming diffuse scattering are also plotted as a function of altitude in Fig. 3. At 110 km, the normal force on a 25-cm^2 surface would amount to a comfortable 1.4 g, but at 200 km would have fallen to a few milligrams. Since the normal force falls off as the angle of incidence, as measured from the surface tangent, is reduced, a practicable operating limit for a balance of this size would probably lie somewhat below 200-km altitude.

It is useful at this point to consider what distributions of shear and normal stress are likely to be observed and how these would be used. A schematic diagram is shown in Fig. 4 in which the entering freestream from the left strikes a surface at an angle as measured from the surface tangent. At 110 km, the freestream molecular speed ratio S_∞ has a value of approximately 19. The quantity S_∞ is defined by the expression

$$S_\infty = U_\infty / (2RT_\infty)^{1/2} \tag{1}$$

in which U_∞ is the freestream velocity relative to the vehicle, R is the species gas constant, and T_∞ is the freestream temperature. Since S_∞ is quite large, the freestream molecules can be considered to have a common speed and direction. If we assume the incoming particles to be completely absorbed, then desorbed diffusely with negligible velocity (one of the frequently applied limiting forms of gas/wall interaction), we may immediately write the normal force imparted to the surface F_{-Y} as

$$F_{-y} = \rho_\infty A (U_\infty \sin\theta)^2 \tag{2}$$

while the tangential force F_x is given by

$$F_x = \rho_\infty A (U_\infty^2 \sin\theta \cos\theta) \tag{3}$$

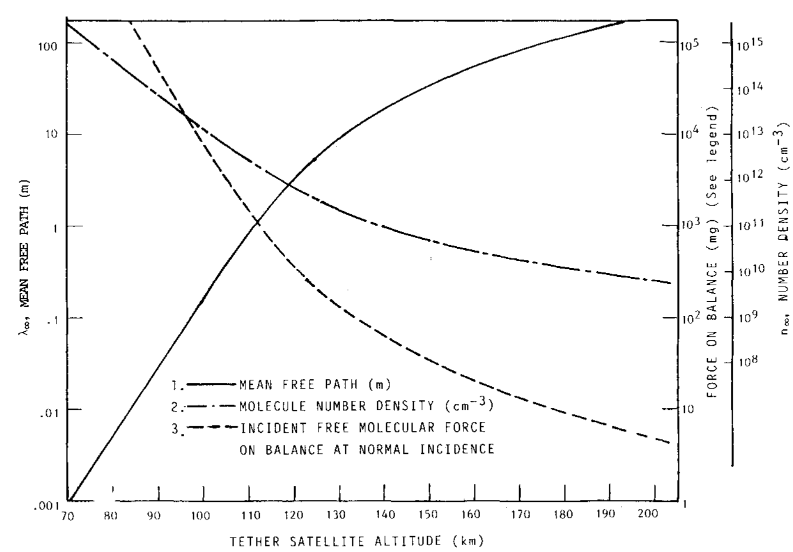

Fig. 3 Molecule number density, mean free path, and normal force to balance surface (70–200 km).

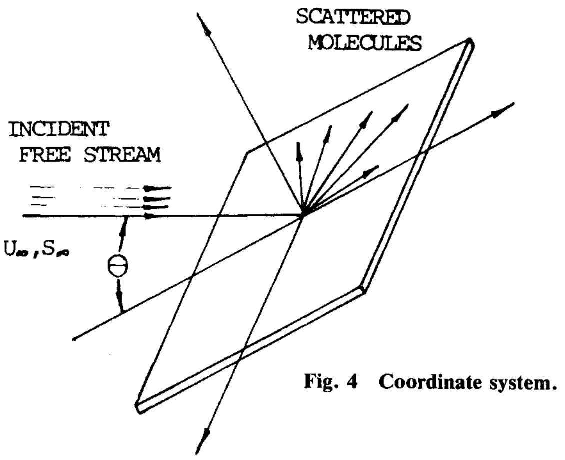

Fig. 4 Coordinate system.

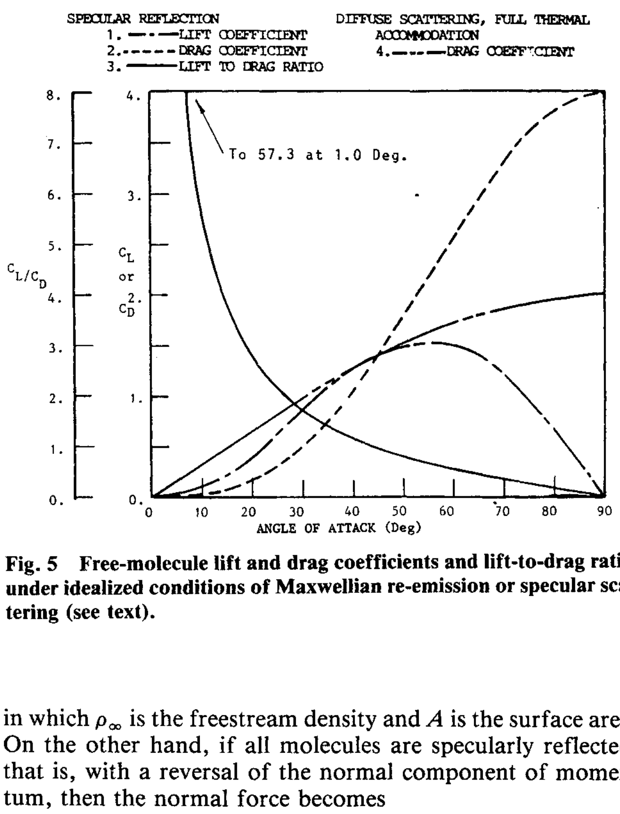

Fig. 5 Free-molecule lift and drag coefficients and lift-to-drag ratios under idealized conditions of Maxwellian re-emission or specular scattering (see text).

in which ρ_∞ is the freestream density and A is the surface area. On the other hand, if all molecules are specularly reflected, that is, with a reversal of the normal component of momentum, then the normal force becomes

$$F_{-Y} = 2\rho_\infty A(U_\infty \sin\theta)^2 \tag{4}$$

while the tangential force is zero. Forces of drag and lift are found directly from the foregoing expressions to be given by

Diffuse scattering:

$$F_D = A\rho_\infty U_\infty^2 \sin\theta \tag{5a}$$

$$F_L = 0 \tag{5b}$$

Specular scattering:

$$F_D = 2A\rho_\infty U_\infty^2 \sin^3\theta \tag{6a}$$

$$F_L = 2A\rho_\infty U_\infty^2 \sin^2\theta \cos\theta \tag{6b}$$

The coefficient of lift C_L and the coefficient of drag C_D are readily calculated using the foregoing relations. In Fig. 5, C_L, C_D, and C_L/C_D are plotted as functions of the incident angle.

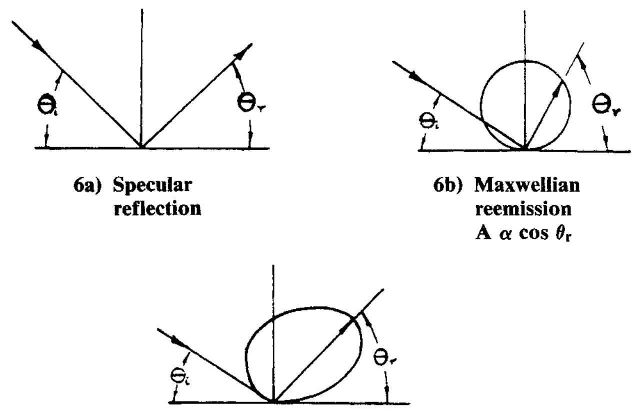

Fig. 6 Representative density distributions of molecules scattered from a wall.

The very large values of the lift/drag ratio at low angles of attack are primarily caused by the low values of drag coefficient resulting from our assumptions. A more careful discussion of these limiting cases appears in Ref. 8 in which the thermal velocities of incident and reflected particles are correctly accounted for. The familiar approximations of Eqs. (5) and (6) are introduced again here to illustrate the wide differences in momentum transfer that may result within assumptions frequently applied in simulation studies.

In LDH flight, we do not anticipate either pure specular reflection as illustrated in Fig. 6a, or Maxwellian re-emission, Fig. 6b. We believe, instead, that scattered molecules will have density distributions of lobular form as suggested in Fig. 6c, and mean speeds that increase, with certain fluctuations, from directions near the surface normal to those near the surface tangent. These distributions will show substantial remnants of the freestream momentum. Currently, our knowledge of velocity and molecular density distributions is derived from the use of molecular beams and that which is currently available is severely limited both in quantity and applicability to problems of LDH flows. Still such measurements lend strong support to the foregoing assertions. Accordingly, our measured distributions of aerodynamic forces will differ from those of the limiting cases (see Fig. 5), and in particular will exhibit both lift and drag at all angles of incidence.

It is regrettable that distributions of the molecular velocities themselves will not be given by these balance measurements but such determinations would be more appropriate to a second generation of STARFAC. In the absence of more detailed information, we may find a net equivalent momentum vector (NEMV) for each angle of incidence to represent the behavior of the scattered molecules. Such information would be used directly in the determination of free-molecule drag and lift on convex bodies and could be applied with acceptable accuracy to shapes where first-order effects would be only slightly modified by one or two interreflections. In application to studies by DSMC, the NEMV would provide the experimental ground underlying the selection of re-emitted molecular velocities. Additional assumptions would, of course, be needed.

In general, freestream molecules leave a fraction of their kinetic and internal energies with the surface. Although it is not possible to know from momentum exchanges what the energy left with the surface may have been, the difference between reflected and incident momenta establishes a maximum value for energy transferred.

Momentum traps have been used in free-molecule flow experimentation over many years. In the proposed application, one of the normal force balances would be fitted with a trap surface, as noted earlier. The determination of total incident momentum flux provides a direct measure of local density since the velocity is known and the gas composition is known to good approximation through independent local mass-spectrometric determination. The momentum trap is seen to serve as a valuable aid to the atmospheric science program.

Transition Flow Studies

In light of wide ranging opportunities for the acquisition of aerodynamic and ancillary information, several kinds of experiments are proposed for the transition flow regimes. As the satellite is deployed downward, certain experiments would be undertaken at high elevation under free-molecule conditions and would be continued to the lowest practicable altitude. If this should prove to be about 90 km, the Knudsen number at that altitude, based upon vehicle width, would have fallen to approximately 0.02, a value signifying flows of slight rarefaction. Other experiments would be initiated and conducted only within the transition regime.

These proposals are perceived as consistent with general STARFAC constraints on size and power consumption and are presented as supportable by a single tethered research vehicle. Four general categories of experiments are proposed. The first incorporates the measurements of lift, drag, and pitching moment for the vehicle as a whole in its various forms, at several altitudes, and over a suitable range of angles of attack. Measurements would be made first in free-molecule flow and then throughout the transition regime.

The second category comprises a number of housekeeping experiments that, as has been noted, are essential to the aerodynamics studies and also will be of substantial benefit to the atmospheric science program. Measurements such as total momentum flux, species composition, total pressure, charged particle flux, total energy flux, surface pressure, and surface temperature are included. The third category is very closely related to the second. In this group, we are interested in careful determinations of the probe-entry flows and surface-pressure tap flows associated with instrumentation. Fundamental information and system calibrations derived from the tethered satellite at its several altitudes would prove to be of significant value in the development of instrumentation for aerospace flight vehicles.

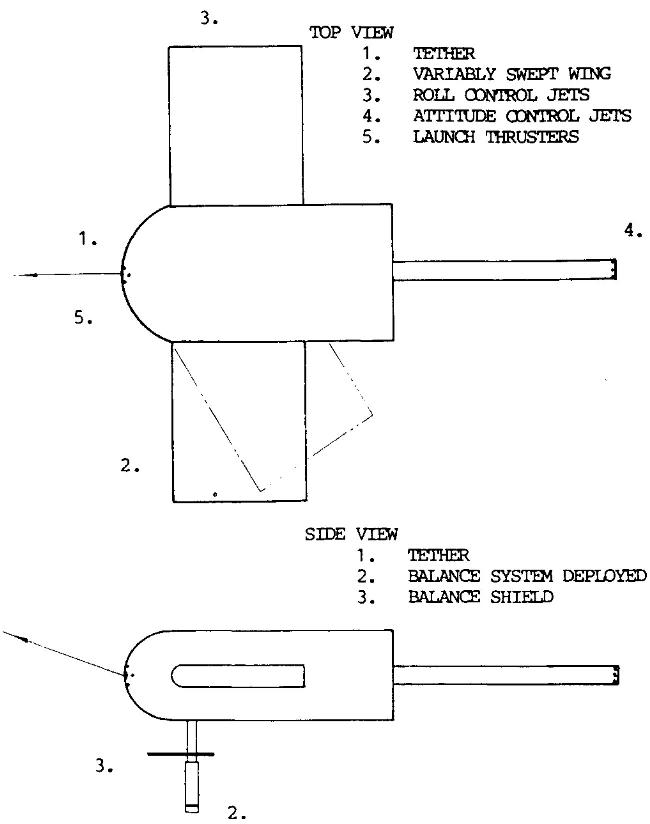

Fig. 7 Schematic of a tethered satellite for aerodynamic research.

The fourth category includes measurements of density, velocity, and temperature fields in the stagnation region and over windward and leeward surfaces. This work would employ electron-beam fluorescence instrumentation, free-molecule flow probes, total pressure probes, and thermal probes. The list of these experiments could be long, and very clearly, a close prioritization will be required.

Vehicle Aerodynamics and Support Studies

To provide a conceptual base for the discussion that follows, it is appropriate to suggest a configuration for the research vehicle. Schematic views are shown in Fig. 7. Overall, the vehicle is a flattened cylinder with a spheroidal nose and variably swept wing. More specifically, the nose cap, a portion of an oblate spheroid, has a major radius of 0.8 m and is faired into a round-edged parallelepiped body 1.5×1.0 m in cross section. The total length of the vehicle is 3.0 m. Wings pivot into the body, collapsing by segment, thus allowing arbitrary sweep for the leading edge. Fully extended, the wingspan is 5.0 m. The attitude of the tethered satellite must be precisely controlled, and it is also essential that residual oscillations in pitch and yaw, possibly continuing for some time after launch, be eliminated. To this end, an extensible boom will be deployed from an aft section of the vehicle to a length of about 3.0 m, carrying at its tip a set of micro jets. Micro jets are also placed at the wing tips to dampen roll and to ensure that the transverse plane is normal to the plane of incidence. This plane is defined by the tether and the freestream velocity vector. Wings are flat with cylindrical leading edges and vertical trailing surfaces. Thruster jets surround the tether attachment placed on the axial center at the nose. The body and wings carry instrument packages internally which deploy as appropriate.

Measurements of vehicle lift, drag, and pitching moment are performed as the logical follow-on to surface-force measurements since empirical momentum-transfer data would now be in hand. Vehicle flight-performance data under free-molecule flow conditions would provide a useful data set with which to test predicted values. At lower altitudes, transitional flow data would provide the basis for the calibration of neutral and reactive molecular-collision models and molecular-flow simulation methods.

The velocity of the tethered vehicle, flying as it does at altitudes lower than the shuttle orbiter, will be slightly smaller than orbital, resulting in a net downward gravitational force. At finite angles of attack, aerodynamic forces will in general result in pitching moments that must be counteracted by the attitude-control jets. Accordingly, several factors must be known for the calculation of aerodynamic forces and moments. These are tether tension, attack angle, tether angle with the freestream velocity vector, thrust of attitude-control jets, satellite altitude, and ambient gas density and composition. Although both negative and positive attack angles will be employed, most of the data probably will be taken at negative values of attack angle since positive lift may add to the complication of tether control.

A number of experiments in the second category have been discussed recently by Siemers et al.[3] and by Wood,[10] and are included in Table 1 as essential to the aerodynamics mission. I shall add a few words about two of these. The variety of ambient conditions encountered in the course of the tether experimental period provides an opportunity to obtain a thorough sampling of surface heating. Temperature measurements of specimen surfaces located at the nose cap, wing leading edge, and on the wing and body surfaces will assist in the assessment of aerodynamic heat-transfer coeffi-

Table 1 Tether satellite aerothermodynamic measurements

In free-molecule flow
Total momentum flux
Tangential and normal forces on flat plate at angle of attack
Total pressure using probes and surface taps
Surface pressures and temperatures
Tether tension, tether angles, accelerations, and related parameters
Satellite attitude and moments applied for attitude control
Satellite altitude
Atmospheric gas composition
Internal temperatures and pressures
In rarefied transition flow
As above, where atmospheric density permits
Additional flight-performance evaluation
Density field surveys in stagnation region and wing boundary layer using electron beam
Velocity field surveys using free-molecule probe

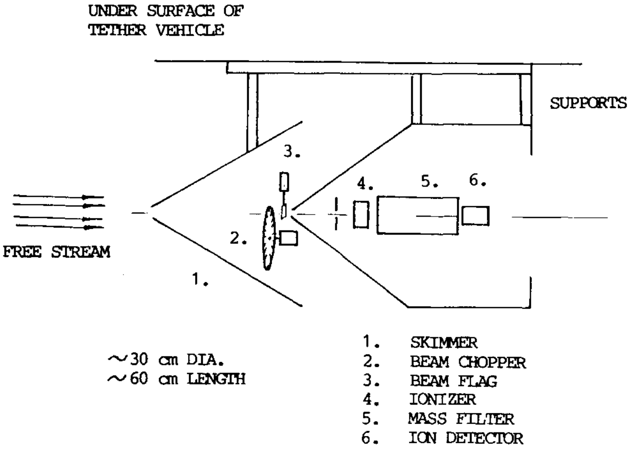

Fig. 8 Schematic of open molecular beam mass spectrometer.

cients and of surface thermal accommodation and catalyticity. Such measurements will also support the interpretation of the normal- and tangential-force measurements.

The second remark concerns quite a different sort of measurement. The deployment of the satellite through a large altitude range provides a remarkable opportunity to determine species composition. It should be noted that accurate species concentrations can be determined using the open molecular beam mass-spectrometric technique illustrated in Fig. 8. Advantage is taken of the high molecular speed ratio and low ambient pressure to provide the necessary high vacuum conditions. Freestream molecules collimated by skimmers pass into the mass spectrometer ionizer without encountering a surface. The oriented tether satellite, as compared with other, proposed research satellites, has a unique potential for the determination of species concentrations of the unaltered freestream using the foregoing method.

Flow behavior at wall taps and probes has been the subject of investigation over many years. In the most recent and perhaps most sophisticated of such studies, Moss and Bird[11] have employed DSMC in support of the Shuttle Upper Atmosphere Mass Spectrometer program. External high-enthalpy flows transform to thermally equilibrated internal flows in a complex of chemical and dynamical processes. Key factors needed for system design are missing at present; additional understanding of wall/gas scattering and catalyticity are seen by the authors as essential. In the absence of such detailed information, direct aid to flight instrumentation and science experiments can be given by the results of empirical calibration studies conducted aboard the tethered satellite. These studies should include total and static pressure-measurement systems and systems for mass-spectrometric observations.

Flowfield Studies

In work cited earlier,[4] the author has examined details of the flowfield above a flat plate in hypersonic low-density flow using the approach to DSMC developed by Bird.[12] Effects of the commonly used diffuse/specular models, separately or in combination, were compared with those for the baseline model employing fully accommodated diffuse scattering. These results also were compared with the lobular scattering model developed by Hurlbut and Sherman following a suggestion by Nocilla (HSN). The HSN model brings together empirical information drawn from molecular beam studies in a form easily applied to computation. Distributions of scattered molecular density having lobular form, and speed distributions also consistent in form with observation, are given through certain parameters as discussed in Ref. 8. Other equally satisfactory parameterizations built on the available data might well be found.

Simulated flow conditions were chosen to match those of wind-tunnel experiments performed at Berkeley by Becker et al.[13] The method of electron-beam fluorescence was used to determine density, temperature, and velocity fields above the sharp-edged plate in a Mach 10 flow of helium. The mean free path of the gas at the leading edge was 1.3 mm giving a Knudsen number based on the plate length of about 0.02. This value is about twice the value of the Knudsen number at 90 km based on the wing chord suggested for the tether satellite. In Fig. 9, calculated gas temperatures are shown at 1.25 mm above the surface for several axial locations downstream of the leading edge and are compared with wind-tunnel results at the same elevation. Where diffuse scattering has been assumed the agreement is excellent, particularly at locations very close to the leading edge. This is a fully anticipated result for the flows of low thermal order that are available to Earth-based wind tunnels. Agreement is even closer in simulations also completed in 1987 by Hermina[14] using the same background materials.

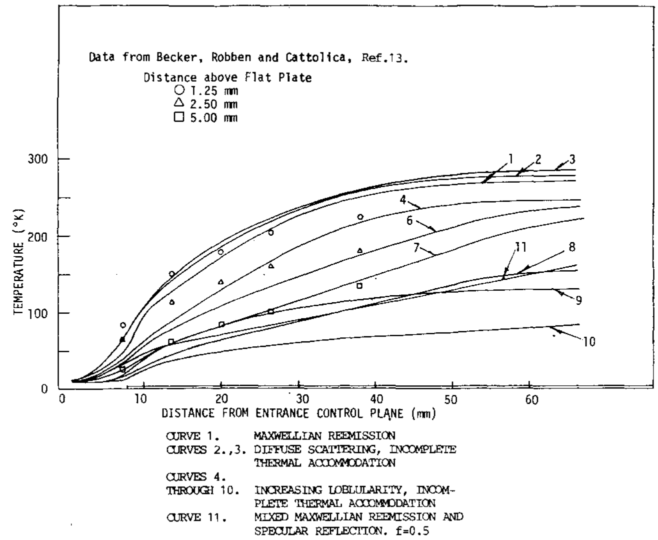

Fig. 9 Axial dependence of gas temperatures at one mean free path above surface of flat plate in hypersonic flow.

For assumptions of lobularity that differ only moderately but increasingly from the baseline assumption of Maxwellian re-emission, we see an increasing and substantial departure from the original distributions. In Fig. 10, gas-density ratios are plotted vs distance above the surface at two stations along the plate using the same set of wall/gas interactions. The effect of increasing lobularity on the magnitude and location of the maximum density is profound. The density ratio

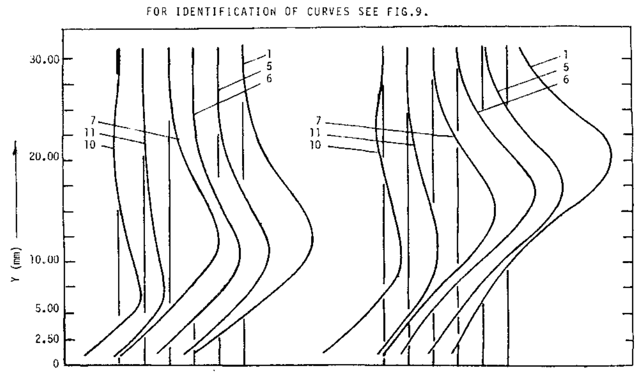

Fig. 10 Density ratio. Distance above flat plate at axial location $x/\lambda_\infty \simeq 28$ and $x/\lambda_\infty \simeq 44$.

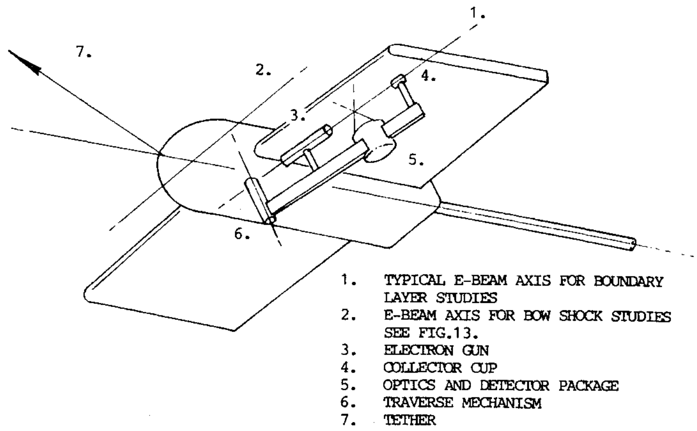

Fig. 12 Electron beam positioned beneath tether vehicle wing.

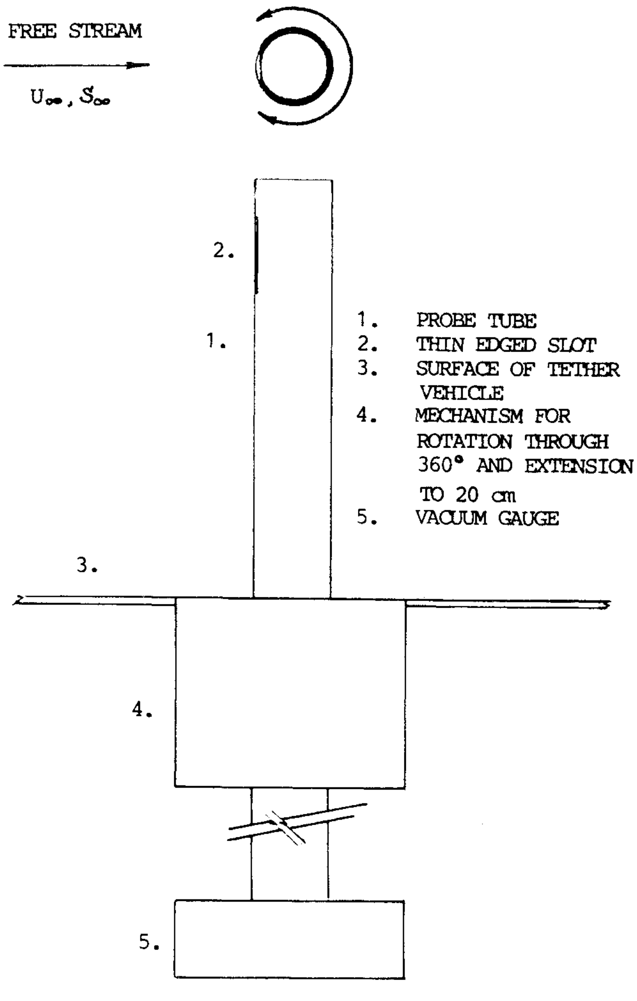

Fig. 11 Schematic diagram of free-molecule orifice probe.

diminishes and the position of the maximum moves closer to the surface as the lobularity is increased.

The foregoing results strongly suggest that LDH flows, over slender shapes of all kinds moving at re-entry velocities, will be altered significantly from those predicted using diffuse scattering. Such alteration, however, is not only a matter of wall/gas behavior but also of the physical outcome of intermolecular collisions. Measurements of flowfield characteristics, the fourth category of experiment proposed here, will provide a solid basis for the comparison of calculational methods and physical assumptions.

It should be emphasized at this point that the tether satellite must be placed at an altitude where the vehicle is in transitional flow; that is, where the Knudsen number, based on a major dimension such as the wing chord, is not less than about 0.01 and not greater than about 100. We find from Fig. 3 that the appropriate range of altitudes extends from about 90 to perhaps 120 km.

Two major sorts of instrumentation for flowfield studies are proposed. The first of these, the free-molecule orifice probe, is well understood and has been used successfully over many years by a number of investigators.[15,16] Briefly, a rotatable cylinder of free-molecular size placed in the flow perpendicular to the flow velocity, as shown in Fig. 11, is connected with a vacuum pressure cell. An orifice or slot penetrates the cylinder wall. The pressure, measured as a function of angle as the cylinder is rotated through 360 deg, can be interpreted to give the macroscopic velocity, freestream temperature, and density. In high Mach-number flows, it is probable that the precision of temperature measurements would be poor. In light of the large particle flux and large mean free path, the probe can be of convenient size and response time can be short. Probes would be rotated or extended into position, then moved to scan the desired region of flowfield.

The method of electron-beam fluorescence is proposed for use in a second and complementary set of flowfield studies. This method also is well understood and in combination with the scanning Fabry-Perot interferometer has, through the work of several investigators, contributed significantly to our understanding of gas dynamic processes.[17-19] A collimated electron beam of perhaps 50-kV energy is directed through the region of interest. Beyond this is a collection cup that serves in the control of direction and current. A short segment of the luminescence generated along the beam path lies at the focal point of a lens that transmits the light through narrow-band spectral filters. It then goes either directly to a photocell for density measurement only or to a scanning Fabry Perot interferometer for velocity determination and temperature measurement by Doppler shift.

Laboratory investigation would be required to establish the feasibility of temperature and velocity determinations for the diatomic species. At the moment, the prospects for such measurements are not bright. On the other hand, helium and argon are present and have been the gases most frequently used in laboratory studies. In all probability, atomic oxygen would serve nicely but the point would need verification through laboratory spectrographic study.

However, in connection with either the measurement of velocity or temperature, critical consideration must be given to the question of fluorescence intensity since ambient densities are considerably below those customary in this work. Further-

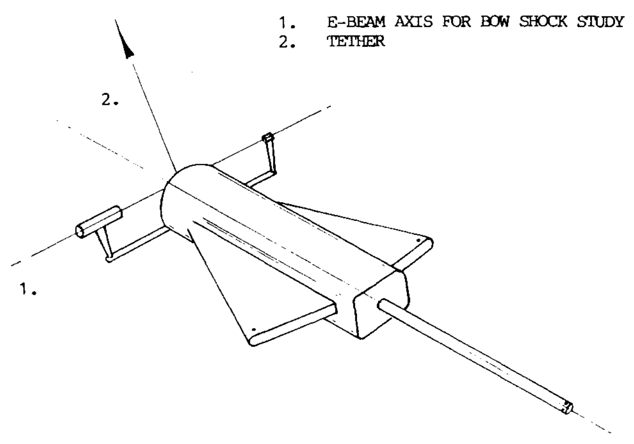

Fig. 13 Electron beam positioned for bow shock density measurement.

more, although the measurements would be done in the Earth's shadow, some sources of background illumination would be present. In contrast, the measurement of density requires far less spectral resolution, even when done on a species-specific basis, and so can be conducted at much lower light levels.

Two promising regions in which to measure densities are indicated in Fig. 12. One of these lies below the wing surface that, as you will remember, can be either the windward or the leeward side. The other is at the nose near or on the stagnation line. To avoid direct interference by the tether and its attachment, the satellite would be placed at a suitable angle of attack. The general arrangement of system elements for the wing-flow measurements is suggested in Fig. 12. The electron gun, collection cup, and optics would be fixed to an optical bench that would be rotated to any suitable angle from its housing in the body. This assembly also would be translatable toward or away from the wing surface and would, through these movements, provide useful areas of observation at arbitrary settings of the leading edge. The assembly would be rotated forward to permit calibration in the freestream. Mechanical and electronic elements of the experiment required no new technology. For example, the electron-beam system can be made in small size and have been used in space experiments.

The second electron-beam assembly also deploys from the body as shown in Fig. 13, positioning itself outside the bow shock and transverse to the vehicle axis. Within the shock layer, the gas density may be up to about a hundred times that of the freestream. However, at altitudes available to the tether satellite, electron-beam penetration of this region will be entirely sufficient. It should be possible and extremely useful to obtain density ratios for the parent and dissociated species. Since the tether satellite permits the time for delicate observations and the choice of times within which to conduct them, it seems in the foregoing application, too, to have distinct advantages over alternatives.

Concluding Remarks

In this paper I have examined the potential of the tether satellite for aerodynamic research under conditions of low-density hypervelocity flow and have suggested a number of experiments that are consistent with the objectives of the STARFAC proposal. Except where noted, the technology is mature and has been applied to successful laboratory experimentation and, in some instances, flight instrumentation. This is not to minimize the requirement for the intensive development of each instrument system. Such development would include various sorts of validating testing, including wind-tunnel testing under partially simulated flight conditions.

An order of experimentation is proposed in which the most generally applicable of the experiments would be undertaken first. These involve the direct measurement of normal and tangential stresses on representative aerospace surfaces at altitudes from about 160 km down to 110 km. Interpretation of experiments undertaken during the same mission but at lower altitudes would draw upon those results. The satellite is envisioned as a spheroidal nose, slab-sided cylinder with variably swept wing. Suggested experiments include measurements of vehicle lift, drag and pitching moment, ambient gas density and composition, surface temperatures, wall tap and impact probe behavior, and, using electron-beam fluorescence methods, measurements of gas densities above the wing surfaces and on and near the stagnation line. It would seem, on the basis of a number of considerations relating to the successful acquisition of new aerodynamic understanding of this regime of flows, that the tether satellite offers distinct advantages over alternatives.

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