Tethered Aerothermodynamic Research Needs

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It is widely recognized that there exist significant gaps in our understanding of the aerothermodynamics of flow in regimes that are both hypersonic and rarefied. We refer here principally to flows of orbital velocity at altitudes of 90 km and above. In this paper, we identify and discuss needs for new information essential to progress on problems of design and computation for flight in these regimes. Measurement requirements implied by research needs are discussed in the context of a tethered research satellite. This vehicle is of the approximate mass and general sophistication of the proposed TSS-2. Recent estimates of drag, and tether and vehicle temperature, provide background materials for the discussion.

Nomenclature

d = orifice diameter
E_i = energy incident on wall due to incident molecules
E_r = energy re-emitted from wall by scattered molecules
E_w = energy re-emitted from wall by scattered molecules following full adjustment to wall enthalpy
Kn = Knudsen number, λ/l
l = characteristic dimension
Pi = pressure, measured within orifice
Pw = surface pressure at wall adjacent to orifice
$\dot{q}$ = heat transfer rate
R = radius of body or nose
S = molecular speed ratio
T = thermodynamic temperature
U = macroscopic gas speed
α_e = thermal energy accommodation coefficient, $(E_i - E_r)/(E_i - E_w)$
λ = mean free path
ρ = gas density
θ = angular location of orifice (see Fig. 10)

Subscripts

w = wall values
1,2,3 = identification of probe location
∞ = freestream values

Introduction

THE tethered satellite is increasingly recognized as a vehicle of significant promise for new aerothermodynamic study. The possibility for sustained observation at orbital speed in the lower thermosphere would seem at this time to provide an unmatched potential for such investigation, and the features of retrievability and reuse add additional attraction.

We focus on measurement opportunities that are realistic within the current context of launch and deployment practice and that will yield critically needed new information. We consider such opportunities as would be available to a vehicle of the general size and mass of the projected Tethered Satellite System-2 (TSS-2),[1] which is proposed for launch in the spring of 1996. The TSS-2 is jointly sponsored by NASA and the Italian Space Agency (ASI), and would become the second tethered research system to be launched by shuttle. The first of these, the TSS-1, will be launched upward from the shuttle in the early spring of 1991 to study tether electrodynamic interaction in the Earth's magnetic field. As a result, our understanding of the logistics and mechanics of tether deployment will become greatly enlarged.

We must remember that the TSS-2, shown in Fig. 1, is presently in the early stages of definition; and thus, details of experiments and instrumentation are not established. Still, it is useful to consider the general features of size, mass, power, and configuration of the TSS-2 and of the vehicle environment that, together, establish our context. The vehicle is envisioned as a sphere 1.6 m in diameter. It is proposed for downward deployment to a minimum elevation of 130 km, at which location temperature rise and atmospheric drag would be easily managed. The total mass of the vehicle is 500 kg, of which 44 kg are proposed for experimental systems. It is planned to incorporate a stored energy power supply of 2000 watt-hours capacity. Proposed deployment duration is 36 h.

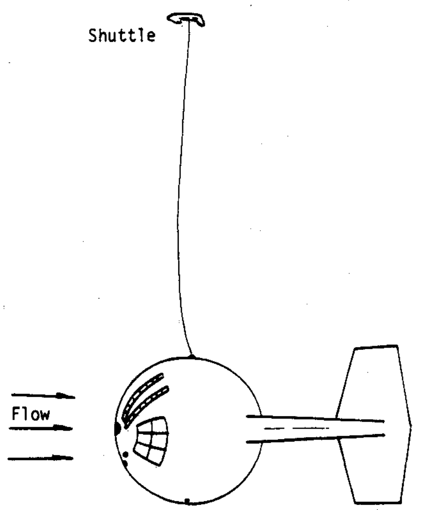

Fig. 1 Conceptual view of tethered satellite.

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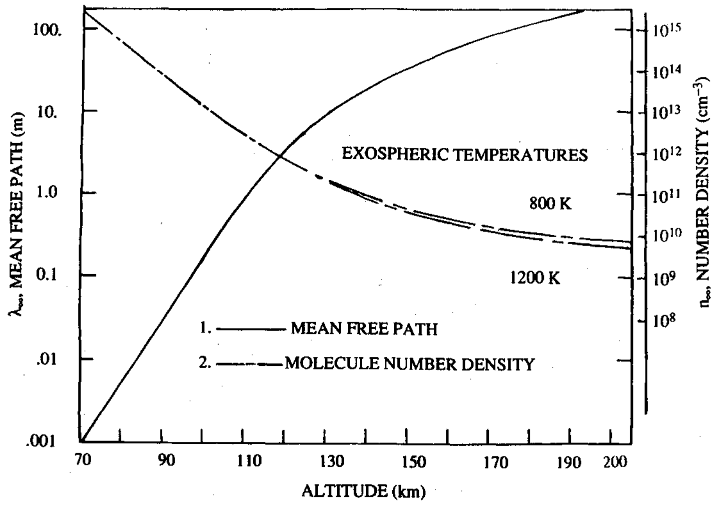


Fig. 2 Number densities for exospheric temperatures of 800 and 1200 K (n/cm^3).

The authors have worked independently on separate but strongly related aspects of flight environment and aerothermodynamic behavior. The work has been fully coordinated through the office of Dr. George Wood at Langley Research Center and through our joint participation in workshops, frequent communication, and exchange and review of materials. There have been two general sorts of outcome. First, a general sophistication of views relating to research requirements and programs for the TSS-2 or similar satellite has taken place, so that the definition of experiments and of instrumentation will be more concisely achieved. The substance of these views will be related in paragraphs to follow. Second, we have examined associated aerothermodynamic and environmental factors. This work includes new calculations of free-molecule lift, drag, and surface temperatures for cylinders and flat plates at angle of attack,[2] continued examination of thermomolecular effects on orifice probes,[3] and a preliminary examination of the effect of lift on tether configuration. Reference will also be made to new preliminary studies by Direct Simulation Monte Carlo (DSMC) of density and velocity fields about a wedge in high-velocity rarefied flow. Results will be reviewed and discussed.

Aerothermodynamic Background

At the minimum altitude, 130 km, the free-molecule drag on a sphere of 1.6 m diameter is about 1.06 N, assuming a velocity of 7890 m/s and atmospheric properties, as given by Jacchia Table 11.[4] The atmospheric density is about 2×10^{17} particles per cubic meter at 130 km, the mean molecular weight is 25.46, and the atmospheric temperature is 500 K. The model atmosphere in this instance is based on an exospheric temperature of 1200 K. It has been suggested recently[5] that the Jacchia Table, based upon an exospheric temperature of 800 K, provides a more accurate time-averaged value. Both values are well within the common range of exospheric temperatures. A plot of densities from both tables is found in Fig. 2.

At 90 km altitude, the atmospheric composition is scarcely changed from that at sea level. Above that level, however, the composition alters rapidly and in a very important way. We refer here to the dissociation of oxygen molecules, due to effects of solar radiation. Between 190 and 200 km elevation oxygen atoms become the most numerous single species and, remarkably, the number density drops only a decade for the next 100 km. These points are illustrated in Fig. 3.

Although the molecular number density at 130 km is quite small and the mean distance between molecular collisions is about 10 m, a sphere of 1.6 m diameter is not in fully developed free-molecular flow. The Knudsen number Kn serves as the chief measure of the degree of rarefaction. Kn is defined as

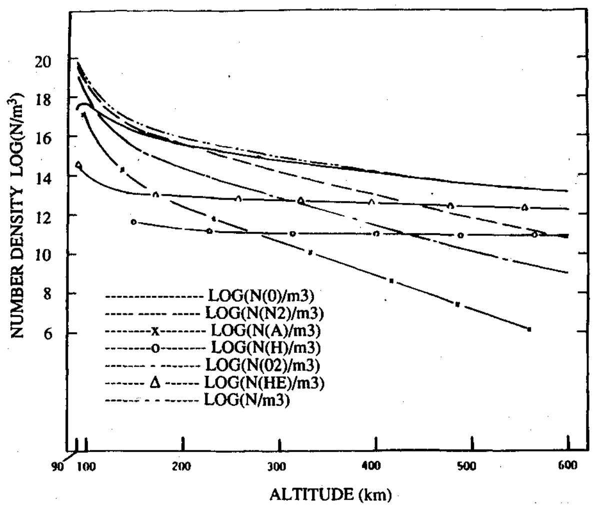


Fig. 3 Concentration vs altitude for atmospheric species.

the ratio of the molecule mean-free-path to a characteristic dimension, such as the nose radius of our spherical body, giving for the TSS-2 a value of Kn approximately equal to 12.5. A correction to account for the effects of molecular collisions by methods discussed in Ref. 6 would lower the drag force to about 0.98 N. On the other hand, the tether itself, having a radius of perhaps 1.0 mm, would clearly be in free-molecular flow. However, total tether drag is several times that of the tethered vehicle itself because of the great length of tether. A rough integration accounting for the density and compositional change with altitude yields an estimate of about 20 N of total drag on a tether 100 km long. The total tether tension, it should be noted, is a little more than 300 N, a value owed in large part to the gravitational gradient.

At 130 km, the tether temperature is somewhat lower than the ambient temperature. We calculate values of approximately 335 K in the Earth's shadow and about 410 K in sunlight, assuming a thermally conducting cylinder and a surface emissivity, appropriate for polymers, of 0.8. As density decreases with altitude, the gas kinetic heat input diminishes so that the tether temperature reaches low values in the Earth's shadow. In sunlight, however, the temperature above 130 km is largely controlled by solar radiant influx, giving steady-state values that remain essentially constant to high elevations. These points are illustrated in Fig. 4. We also may see from this figure that steady-state temperature values depend strongly upon the surface emissivity. It is evident that surface emissivity on the physical vehicle must be controlled carefully to avoid localized high temperatures.

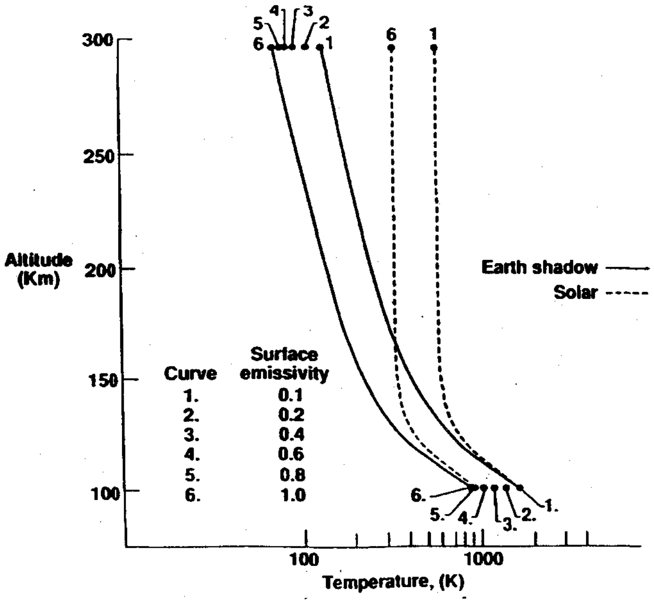


Fig. 4 Tether temperature vs altitude, surface emissivities from 0.1 to 1.0, tether 90 deg to incident flow.

Values of drag and temperature cited in the foregoing have been taken from Ref. 2. In this work, all calculations were made assuming free molecule flow and diffuse molecular scattering at the surface with full thermal and momentum accommodation. In calculations of drag and lift, appropriate components of the net momentum transfers were found for each species by numerical integration over body surface elements. These were then summed over the total number of species. In finding the momentum of the scattered molecules, it was first necessary to find surface temperatures. This was done by summing energy residues left after scattering by molecules of each species, then iterating to take account of the radiant energy balance. Results were obtained at each sample altitude for six values of surface emissivity at nine angles of attack. All cases were calculated for full solar radiation (1400 W per meter squared) and again for total shadow.

Atmospheric drag on the sphere itself under conditions of rarefied flow, that is, in transitional flow regimes that are neither continuum nor free-molecule, may be calculated correctly in principle by DSMC. However, certain approximate methods that are outlined elsewhere in this paper and discussed in Ref. 6 can provide accurate results with much less computational effort. At values of Kn greater than about 0.01, it is ordinarily agreed that the flow is transitional. Aerodynamic behavior is no longer fully defined by continuum fluid theory. At values of Kn of perhaps 100 and larger, the flow may be characterized as free-molecule and calculated by the methods of collisionless flow kinetic theory. In a recent paper, Dogra and Moss[7] give results of DSMC calculation demonstrating transitional rarefaction effects on the shuttle at surprisingly high altitudes, i.e., 160 km and somewhat higher. They argue correctly that it is a mistake to rely entirely on free-molecule calculation. However, the assumption of free-molecule flow for the tethered satellite at 130 km is satisfactory in first approximation. It should be pointed out that our calculations for drag, lift, and thermal transfers are not better than our assumption concerning the wall/gas interactions, and these may be substantially in error. It is a major objective of the tethered satellite mission to provide experimental data in this important area. Experimentation in this and in other areas will be discussed in the following sections.

Research Requirements

It is useful to consider the nature of experimental problems that may be addressed on an early flight and will greatly, perhaps critically, advance our understanding of aerothermodynamic processes. Certain measurements may be considered to be primary, as, for example, the observation of the transfer of momentum or thermal energy to particular elements of surface. Others may be termed "housekeeping" in the sense that they provide essential support for the primary studies. We refer, for example, to the measurements of the local atmospheric composition or of the incident momentum flux. Both sorts of measurement of local environmental properties would be of equal interest to the atmospheric scientist. The opportunity for an extended sequence of observations, the stability of the tethered vehicle, the knowledge of altitude and position, the availability of other concurrent observations—all would provide a unique basis for significant measurement.

These supporting observations, or determinations from signals received, are in essence requirements for tethered satellite aerothermodynamic research. Included are the satellite geocentered velocity, the freestream dynamic pressure, static pressure and temperature, the satellite attitude with respect to the freestream, the tether tension and vector direction, the freestream composition, the gas density, and the magnitude and direction of local accelerations. These data also support aerodynamics studies and other primary experimental studies discussed in following sections. On every flight, the vehicle internal temperature and pressure, and the temperature of certain critical areas of surface, also should be monitored. A list of supporting measurements is given in Table 1.

As we have noted, the planned minimum elevation on the first of the downward deployed flights is about 130 km. Below this level, the value of the Knudsen number quickly decreases, becoming about 0.08 at an elevation of 100 km. Temperatures will rise to about 1000 K at this level, a value, however, within the operating range of several alternative tether materials. Here there would be a rich field for aerothermodynamic study that would include direct measurement of density profiles using electron beams with optical scanners, boundary-layer species analysis, spectrometric observations of local luminous fields, fore and after body skin temperatures and heat flux measurements, and the direct determinations of stability parameters using controllable airfoils. Significant modifications of the TSS-2 configuration would be required.

Principal Areas of Study

We consider now certain areas of study that can be addressed within the constraints of an early launch and that will provide unique and important new aerothermodynamic data. In the first, we are concerned with the direct transfers of energy and momentum through the impingement of atmospheric gases on the vehicle surface. In the second, we would study the thermomolecular and dynamic factors governing pressure observations made through probes. In the third, we would study effects of surface reactive processes, for the most part resulting from the influx of atomic oxygen.

Molecule/Surface Energy and Momentum Transfers

At elevations where rarefaction effects become pronounced, the methods of DSMC offer, apparently, the only computa-

Table 1 Research requirements: experiment environment measurements

Atmospheric composition and density
Geo-centered satellite velocity
Freestream dynamic pressure
Static pressure and temperature
Satellite altitude
Tether tension and vector direction
Vehicle accelerations
Vehicle interior and surface temperatures
Internal pressure
Solar radiation flux

tional approach to the prediction of aerodynamic forces and heat transfer at the surface. The need for detailed experimental information is critical since DSMC employs the direct collisional outcomes between gas molecules and surfaces as integral components of the calculation. At the moment the basis for such information applicable to speeds in the orbital range is highly inadequate. In consequence, most DSMC predictions rely upon idealized global models, the "accommodation" coefficients. DSMC calculations for high-velocity transition and free-molecule flows will remain subject to errors of unacceptable magnitude until direct measurements in the correct environment are made.

The greatest part of needed information would be given by measurements of incident and scattered molecular velocity distributions. These might then be used in tabular form or converted to suitable analytic representations, in either case for direct insertion into DSMC computation. Both the deposition of energy as a function of the angular parameters and the transfers of momenta would be made available. For the present, experimental equipment yielding data of this sort are more suited to the laboratory than to an early tethered satellite.

In the absence of such detailed information, we may use direct measurements of averaged heat flux as a function of attack angle and, in analogous fashion, the direct measurement of transferred normal and tangential momenta. In Fig. 5, we illustrate certain features of the measurements. Results would contain much more information than global momentum and thermal accommodation coefficients (even if correct values were known), and would greatly strengthen the credibility of DSMC as a design tool.

Instrumentation for heat flux measurement could be organized in a number of ways. For example, sensors could well be located on a series of active elements positioned on an arc beginning at or near the stagnation point. Each active element would meet the oncoming freestream at a particular incident angle. Three or four arrays would be used to provide a suitable

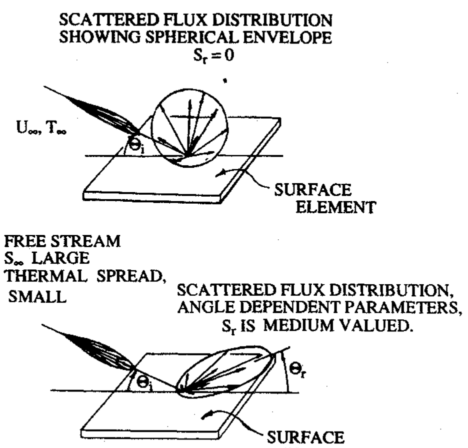


Fig. 5 Schematic representation of scattered flux distribution.

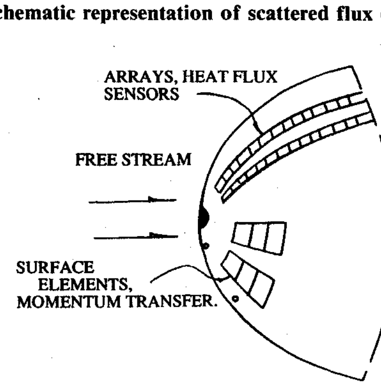
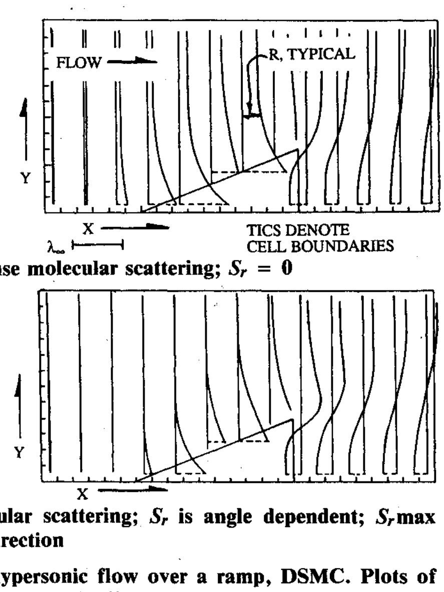


Fig. 6 Tethered satellite nose with heat flux sensors and surface elements for force measurements.

mix of surface materials, as suggested in Fig. 6. An analogous arrangement of balance systems could be used to measure momentum transfers, although it would seem preferable to mount a few balance systems on a rotatable pylon. This option is discussed in Ref. 8.

A recent DSMC study of rarefied hypersonic flow over a flat plate reveals a remarkable dependence of the field parameters on the form of the scattered molecular velocity distribution (Ref. 9). In this analysis, distributions were defined by the Nocilla model, which permits the specification of exit distributions through parameters giving the exit speed ratio and the energy lost to the surface. The governing parameters are themselves functions of the incident angle. The background for this approach and the mode of application to DSMC are discussed in the reference. We shall describe briefly here preliminary results from similar studies, now in progress, of flow over a ramp with a backward facing step. Helium at Mach 10, having a Knudsen number of about 0.3 based upon ramp length, originates from a room temperature reservoir. In Figs. 7a and 7b, we show field plots of the ratio of local particle number density to that of the entering freestream for two representative sorts of scattering. Fig. 7a illustrates the result for diffuse molecular scattering. The incident translational energy has been fully transferred to the surface in this instance; the issuing velocities are representative of the surface temperature. In the second of this pair, Fig. 7b, we see the results of a scattering process in which the molecules retain a significant fraction of their translational momentum. The exit speed ratios of the scattered molecules depend upon the incident angle, and in the simulation results here, have ranged from 0.0 at normal incidence to 3.0 at tangential incidence. The thermal accommodation coefficient takes on values from 1.0 to 0.4 over the same range of angles. We would expect Fig. 7a to be representative of rarefied gas flows involving low-energy molecular impacts at the surface. On the other hand, molecules at orbital velocity might, for some surfaces, produce results resembling Fig. 7b. Evidence for the requisite molecular scattering behavior at surfaces is discussed in Ref. 9. We see, for example, a weakening of the viscous interaction above the ramp in Fig. 7b, as compared with that in Fig. 7a, and a greater reduction in density near the backward step is apparent in Fig. 7b. Thus, the form of the scattering distribution profoundly affects the ongoing flow while determining transfers of energy and momentum to the surface.

Conjectures concerning the nature of scattering at orbital velocities are primarily derived from and supported by laboratory observations.[10] Unfortunately, the total amount of work in this area has been small, and experimental conditions have



a) Diffuse molecular scattering; $S_r = 0$

b) Lobular scattering; S_r is angle dependent; $S_r$max = 3.0 for tangent direction

Fig. 7 Hypersonic flow over a ramp, DSMC. Plots of Y vs R = (local number density/freestream number density). R = 1.0 on station lines.

not been well matched to flight aerothermodynamic requirements. Although much more effort should be directed to laboratory investigation, such work must be accompanied by in-flight experiment. The tethered satellite provides an experimental platform that offers an unparalleled opportunity for direct experiment on energy and momentum transfers to surface elements and for concurrent observations of the integrated effects on vehicle aerothermodynamics. Our ability to design and our confidence in the use of DSMC as a design tool will be greatly enhanced. Results of these direct studies will also substantially advance our understanding of flight and pressure instrumentation, as will be considered more carefully in the next section.

Molecular Flow at Orifices

A generally obscure phenomenon often encountered in experiments involving orifices in surfaces in low-density gases may cause the pressure p_i measured inside of an orifice to be much different than the force per unit area p_w on the surface outside of the orifice. Owing to the obvious interest in pressure measurements and other data from instrumentation requiring inlets in the satellite surface, such as a mass spectrometer, it is of utmost importance to recognize, apply, and refine the correction methodology that predicts the difference in p_i and p_w.

At the Fourth International Symposium on Rarefied Gas Dynamics (1964), one of the present authors and colleagues first discussed the problem of estimating corrections to pressures measured within cavities in surfaces when energy exchange, such as aerodynamic shear and/or heat transfer, exists at the surface.[11] It was shown theoretically and confirmed experimentally that finite-energy transfer causes pressures measured within orifices to be different, in general, from the force per unit area on the surface at the orifice. This phenomenon was analyzed on the basis that the aerodynamic shear could be neglected so long as the shear stress is not comparable to the local pressure. An expression for the pressure in the cavity was derived for the case where orifice diameter is much less than a local mean-free path, i.e., for free-molecular flow. Experimental laboratory data were presented for the transitional flow regime, and the combined theory and experiment enabled the construction of a semiempirical method for correcting measured pressures to account for the "orifice effect" in the entire flow regime of free-molecular to continuum flow.

In 1967, Kinslow and Arney[12] extended the experimental investigation by collecting and analyzing a large number of new direct measurements of orifice effect under laboratory conditions. They also discussed and reported new data on the role of thermal accommodation coefficient in this problem.

When applied to the data available prior to 1968, this earlier method seemed quite satisfactory. In the earlier analysis the authors had chosen to use wall temperature as a characteristic temperature in calculating and correlating orifice effect. However, it was always suspected that gas temperatures external to the orifice should have a more prominent role in correlating the data. In 1970, Kinslow and Potter[3] presented a re-evaluation of the orifice effect phenomenon, starting on the basis of Ref. 11, but including consideration of shear stress and using a correlating parameter for the transitional flow regime based on a reference gas temperature adjacent to the orifice. That work provided the basis for the present discussion.

The analytical approach of the method for relating p_i and p_w involves use of two-sided Maxwellian velocity distributions for free-molecular flows incoming and outgoing at an orifice. Diffuse reflection of molecules from the solid surface is assumed. Figure 8 illustrates the problem. Free-molecular flow is considered first to establish the limiting relationship of p_w and p_i. Guided by the analysis of free-molecular flow, extensive experiments, performed under laboratory conditions, provided the data for the transitional flow regime. Thus, the method may be applied for all conditions between collisionless and continuum flow. Required data at the locations of the pressure orifice are as follows: gas molecular weight, ratio of specific heats, heat transfer rate, shear stress, surface temperature, orifice diameter, and energy accommodation coefficient. Given p_i, then p_w is calculated, or vice versa.

Although it is evident that several parameters must be either computed or measured for the relation between p_i and p_w to be solved, it will be noted that the energy accommodation coefficient is likely to be the most troublesome because of the lack of information on that parameter under actual space conditions.

However, heat transfer rate is defined as

$$\dot{q} = -\alpha_e(E_i - E_w)$$

where α_e = energy accommodation coefficient, E_i = incident energy, and E_w = re-emitted energy for full accommodation to wall enthalpy (the negative sign indicates heat transferred to the surface).

Thus, if $\dot{q}$ is measured, where ρ_∞, U_∞, T_w, and the local angle of incidence are known, E_i and E_w may be calculated and a value for α_e may be inferred. That will also require an assumption regarding the equilibrium of translational and internal energy modes.

To illustrate the significance of the orifice effect, the results are presented in Fig. 9, giving the predicted ratio of p_w/p_i at the stagnation point of the TSS-2 at 130 km altitude. The several heat transfer rates correspond to different assumptions for α_e. Clearly, the magnitude of the differences between wall surface and internal orifice pressures warrants experiments on the TSS-2 to refine the predictive procedure that will have numerous applications in tethered satellite and other flight experiments in rarefied flow. As a point of interest, it may be added that this phenomenon affects measurements made on the windward surface of the STS Orbiter at altitudes as low as 80 km, so it is by no means only a spaceflight or free-molecular flow problem.

Experiments in this area obviously are closely related to the gas/surface experiments outlined previously. This would entail obtaining p_w from direct measurement of normal force on a small element of surface area, measurement of tangential or shear force on the same or a nearby surface element, measurement of heating rate, measurement of surface temperature, and measurement of p_i in the same location. Temperature at the transducer measuring p_i, as well as orifice and tubing diameters, would have to be known, and any lag-time effects on the pressure p_i would have to be assessed. Knowledge of the

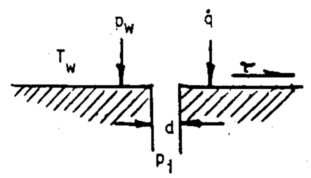


Fig. 8 Pressure orifice.

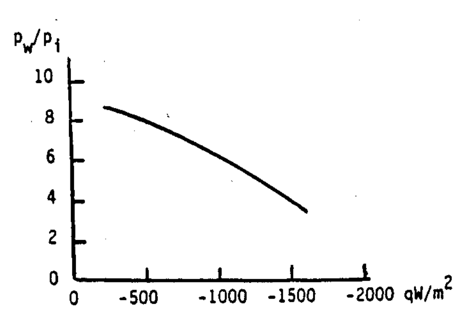


Fig. 9 Predicted effect of heating rate on ratio of pressures (outside-to-inside) at TSS-2 stagnation point orifice at 130 km.

gas constituents, mass fractions, and related characteristics would be desirable, but reasonable approximations for those properties could be used until later more sophisticated experiments are possible.

Feasibility of Free-Molecular Pressure Probes

The measurement of freestream atmospheric pressure and temperature under the low-density hypervelocity conditions of tethered satellite operations presents a more difficult problem than may be apparent at first. Yet, these properties of the atmosphere are of major concern to both atmospheric scientists and aerothermodynamicists. Therefore, it is suggested that the technique outlined here be given consideration as a key element in the planning of research with tethered satellites.

With reference to Fig. 10, it has been shown by theoretical analysis (cf. Ref. 13) that, if $S_\infty \cos\theta \gg 1$ and free-molecular flow exists throughout region 1, then

$$(p_1/T_1^{0.5})(T_\infty^{0.5}/p_\infty) = 2\pi^{0.5} S_\infty \cos\theta \qquad (1)$$

This equation has been derived on the basis of the classical model of free-molecular flow with diffuse reflection assumed. The theory has been extended to include the effects of a length of tube connecting the surface orifice and the pressure transducer cavity, but present purposes are served by merely considering the simple orifice configuration sketched.

It is seen in Eq. (1) that if S_∞, p_1, and T_1 are measured, then $p_\infty/\sqrt{T_\infty}$ is determined. By also measuring p_2 and T_2 at a second orifice located as shown, two equations for $p_\infty/\sqrt{T_\infty}$ are made available, and both p_∞ and T_∞ can be found. These are the ambient air properties of interest to atmospheric scientists.

When a location for the off-axis orifice is chosen, it must be remembered that $S_\infty \cos\theta \gg 1$ has been assumed. However, the case where that condition is not met is also covered by the theory of Ref. 13, and so no obstacle is created if higher θ and lower $S_\infty \cos\theta$ values are selected.

It can be shown that, for $\theta = 90$ deg and corresponding conditions denoted by subscript 3,

$$p_3 = p_\infty (T_3/T_\infty)^{0.5} \qquad (2)$$

Combining Eqs. (1) and (2) leads to an equation for S_∞ when $S_\infty \gg 1$, viz.,

$$S_\infty = \left[1/\left(2\sqrt{\pi}\cos\theta\right)\right](p_1/p_3)\sqrt{T_3/T_1} \qquad (3)$$

If p_1 is at the stagnation point, $\cos\theta = 1$. If the third orifice were installed, an independent check for agreement with S_∞ furnished by satellite tracking techniques would be possible.

Equations (1–3) are based on collisionless or free-molecular flow in the orifice, as well as in the external region of the probe. It seems appropriate to take orifice diameter as the critical physical dimension for the orifice flow. If Knudsen numbers are calculated on the basis of mean free paths based on an estimated probe wall temperature of 350 K and calculated pressures on the wall outside of the orifice, assuming an operating altitude of 130 km and orifice diameters of 0.0015 m, it is found that

$$Kn_w = \lambda_w/d = 12.5 \text{ at } \theta = 0 \text{ deg}$$

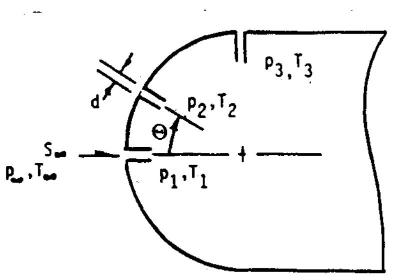


Fig. 10 Pressure probe.

Higher values of Knudsen number would be computed for locations of $\theta = 30$ and 90 deg. These values are marginally high enough to justify the assumption of free-molecular flow. We recall that the Knudsen number for a spherical 1.6-m-diam satellite at 130 km is $Kn_\infty = \lambda_\infty/R = 12.5$. This also is too low to allow an assumption of collisionless flow, but it would be easy to install a pitot-static probe of smaller diameter to provide a free-molecular pressure measurement device at 130 km. A probe nose of small diameter will encounter free-molecular conditions if it is extended from a 1.6-m-diam spherical satellite at 130 km, but the pressure and temperature there will not be the ambient or freestream quantities because of the spherical satellite's flowfield. If the probe nose is to be positioned where "freestream" conditions exist, it will have to extend a considerable distance upstream or a somewhat lesser distance to the side. However, even if the probe is within the satellite's flowfield, it could serve a useful purpose by mapping that field if it were traversed along a radial path. These applications deserve further study and planning of an experiment on the TSS-2 to explore the feasibility of obtaining ambient air data by this means.

Surface Reactive Events

We have noted that the composition of the atmosphere above 90 km is radically altered by the effects of solar radiation. From Fig. 3 we observe that the influx of oxygen atoms to the surface of a tethered satellite becomes a maximum at about 100 km. At 130 km, this flux is approximately 15 times larger than that at 220 km, although the relative concentration of atomic oxygen has continued to increase. In consequence, experimental observation times for reactive events associated with the impact of atomic oxygen will be materially shortened at the lower altitude.

Impact energies of the several atmospheric constituents are shown in Fig. 11. We see that oxygen atoms from the stationary atmosphere possess a kinetic energy relative to the satellite of about 5 eV, whereas the energy of the oxygen molecule is twice that. These high energies are of the order of chemical bonding and are sufficient to produce the dissociation of surface compounds and the impact dissociation of incoming oxygen molecules. The scattering of gas molecules will, in general, be inelastic and will normally involve changes in rotational, vibrational, and electronic states. The impact energy is too low for the direct dissociation of molecular nitrogen but large enough to permit its participation in surface reactive events, including those resulting in the production of NO. It can be visualized that there are a great many possible processes, many having strong implications for energy and momentum transfers to the surface. Exit molecules of numerous species having various configuration of internal energy will move into and influence the ongoing stream.

Under favorable circumstances, scattered molecules may produce visible radiation through the decay of excited species.

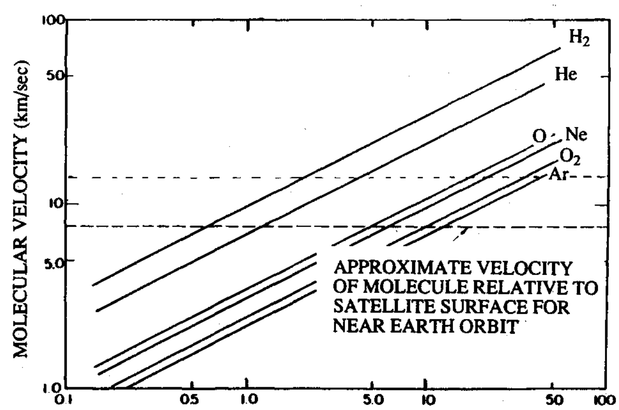


Fig. 11 Velocity vs kinetic energy for six atmospheric species.

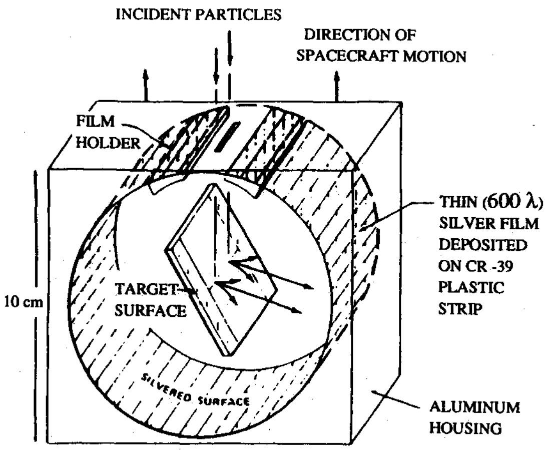


Fig. 12 The oxygen atom reflectometer flown on Shuttle STS-8 (from Ref. 15).

Table 2 Research requirements: experiment measurements

Net transfer of atmospheric gas internal and kinetic energies to surfaces as function of attack angle
Transfers of tangential and normal momenta from atmospheric gases to surfaces as functions of attack angle
Total incident momentum flux and total incident heat flux
Orifice probe pressure measurements
Free-molecule probe pressure measurements
Spectrophotometric observations
Mass spectrometric determinations of atmospheric composition
Atomic oxygen: surface reactivity studies
Atomic oxygen: scattered flux distributions

Photometric measurements aboard the Atmospheric/Explorer-C satellite revealed appreciable radiant intensities over a large altitude range. In this instance, as discussed by Torr,[14] glows were observed at the vehicle nose in directions near the incoming velocity vector over a range of altitudes from 140 to 500 km. Highest intensities were observed at the lowest altitudes. Above 160 km, the radiant intensity correlated with atomic oxygen concentration, below that level, more closely with the concentration of molecular oxygen. Several mechanisms were suggested as possible contributors. It is believed that the glow observed on the shuttle originates from similar effects.

Spectrometric observations can be made from the tethered vehicle using well-explored methods. Because such observations would provide the basis for much new insight concerning reactive processes at the surface and in the gas phase, we consider study of locally generated radiation to be a primary research requirement. The tethered satellite is admirably suited to the support of such work.

Concurrent observations of species concentrations using mass spectrometric methods would develop new and detailed support for atmospheric models and would give direct support to the interpretation of optical data. Such information would also assist the interpretation of surface heat flux gauges and total energy traps, and would be essential in the support of thermomolecular probe studies.

One sort of reactive process—the removal of atomic oxygen by chemical combination at a surface or by catalytic recombination at the surface—can be studied easily using a form of scattering gauge (Fig. 12) introduced by Gregory and Peters.[15] Freestream atoms enter the gauge through a slit and scatter from an active surface. Only the scattered atomic oxygen is recorded by the sensitive silver film lining the rim. The relative reactivity of various surfaces, such as quartz, carbon-carbon, and nickel-steel, could easily be studied. A gauge of a slightly different design using the same detection method is proposed here to measure the scattered flux distribution reaching a sensitized hemisphere rather than a two-dimensional rim. Atomic oxygen from the freestream would impinge upon a small nonreactive scattering surface such as quartz and would pass from there to the sensitized hemisphere. These gauges would be entirely passive, light in weight, and physically uncomplicated. On the other hand, they could be used only once during the flight and would give information on the behavior of only one species, atomic oxygen. In the balance and for the near term, it seems very worthwhile to include such studies among the primary requirements. In the long term, more sophisticated studies will be required.

Discussion

It is our view, and the view of many active contributors to aerospace programs, that we lack critical elements of technological background in high-speed rarefied flight regimes required for effective design or for the creation of effective calculational models. In this paper, we assert that the most promising opportunity in the near term for advancing our understanding of the aerothermodynamics of these flight regimes is offered by the tethered satellite. We have directed our attention to two general sorts of measurement, the first of these being, in essence, the requirements that provide concurrent background and support for satellite research. These are measurements that would be performed on every mission and that are essential to the support of other research efforts. They include measurement of local environmental properties, total incident heat and momentum fluxes, various surface and interior temperatures, tether tension, and vector direction and local acceleration. Velocity and locational information would be transmitted from the vehicle.

We have termed the second sort of measurement "primary" to suggest these would be undertaken to satisfy research requirements of a more general nature. But the language is a bit artificial, since we must recognize that each increment of well-measured data is of enormous value.

Three major areas have been identified within which there are critical requirements for new knowledge. We have suggested approaches that would yield significant information yet fit within the technological requirements imposed by an early launch date. In the first of these areas, we would examine energy and momentum transfers between the freestream and the surface. These examinations would be sufficiently detailed to provide information on surface response as a function of attack angle. Such information would greatly enhance the utility of DSMC computation.

In the second of these areas, we would study factors controlling the response of pressure instrumentation for which the surface orifice is impacted by the freestream. Improved understanding of relevant processes would feature importantly in the design and interpretation of vehicle instrumentation. A useful approach to the determination of freestream Mach number and temperature is discussed.

As a third area, we have proposed the investigation of reactive gas effects using optical and mass spectrometry and surface gauges. The results of study here would also enhance the utility of DSMC and enlarge our understanding of high-energy molecular processes at the surface and in the gas phase.

In each of these areas, the measurements would involve sound and conservative instrumentation, some of which has been suggested in the foregoing. A list of measurements to be made in the three primary areas is given in Table 2.

In closing, we offer the following view: experimental observations in the three primary areas together with supporting measurements, conducted in the near term using a tethered satellite, would result in a profound enhancement of our knowledge of aerothermodynamics in the lower thermosphere.

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