NASH CR-176,747

NASA-CR-176747
19860014093

COMMENTARY ON THE 1985 NASA/VANDERBILT SYMPOSIUM ON FUTURE HYPERVELOCITY FLIGHT REQUIREMENTS

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(NASA-CR-176747) COMMENTARY ON THE 1985 NASA/VANDERBILT SYMPOSIUM ON FUTURE HYPERVELOCITY FLIGHT REQUIREMENTS Semiannual Status Report, 1 Sep. 1985 - 28 Feb. 1986 (Vanderbilt Univ.) 16 p HC#A02/MF#A01 N86-23564 Unclas G3/02 06018

NASA Research Grant NAG-1-549

Semiannual Status Report No. 2

Period Covered: September 1, 1985 - February 28, 1986

1969

March 1, 1986

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SEMIANNUAL STATUS REPORT

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SUMMARY

This report continues the discussion, started in Semiannual Status Report Number 1, on aerothermal problems of hypervelocity flight and experiments that may lead to significant improvements in analytical/computational predictive methods. The commentary given herein is based upon presentations made by speakers at a symposium on this subject held in December 1985.

Symposium participants focused on the serious deficiencies that exist in knowledge of real-gas, nonequilibrium thermochemical-kinetic processes, catalytic processes, surface and shock slip, gas/surface interaction, boundary layer transition, and vortical leeside flows under hypervelocity conditions. Programs of laboratory research and computations leading toward in-flight experiments were recommended. Feasibility of appropriate measurement techniques for the flight environment was assessed and problems for study in that area were identified. A synopsis of the oral presentations is given in this report. A compilation of the visual aids used by the speakers has been distributed to all attendees.

INTRODUCTION

Reference 1 presents a general review of aerothermodynamic issues that are unresolved obstacles to the design of more efficient, higher performance maneuvering re-entry aerospace vehicles. Because of the inadequate simulation of hypervelocity flight conditions in laboratory facilities (Refs. 1,2) the possibility of in-flight experiments was a principal theme. Needs for deeper study and the enlistment of experts in several areas of research were recommended.

In order to obtain the benefits of criticism and extended discussion of Ref. 1, as well as to uncover any new ideas on the subject, a symposium of selected attendees, persons with established credentials and current involvement, was organized as quickly as possible. This report supplements Ref. 1 with information from the symposium. Uniformity in coverage is not attempted; the following remarks are mainly chosen to emphasize points and reflect the sense of the symposium participants. It is emphasized that this commentary presents the views of the writer. It draws upon the symposium and is believed to be in general accord with presentations made by the participants.

THE SYMPOSIUM

Overview

On 9-10 December 1985 a symposium was sponsored under a NASA research grant at Vanderbilt University. The subject of discussion was Future Hypervelocity Flight Requirements, with specific concern for aerothermodynamics as opposed to structural and propulsion problems.

The objectives of the Symposium were to identify major uncertainties in predictive methods for aerothermodynamic quantities relevant to future lifting vehicles in the Earth's atmosphere at velocities above 5 km/sec and altitudes above 50 km, to suggest laboratory or flight experiments, or computations that may lead to improved accuracy of predictions, and to discuss measurement techniques by which needed data may be obtained. Del C. Freeman and James N. Moss of NASA LaRC and this writer were the organizers. A list of presentations appears in Appendix A.

Sixteen invited presentations, plus two (combined) by this writer were given. Approximately fifty attended, including the speakers, and an extended discussion followed each presentation. The invitations were planned so that a range of general aerothermo topics and related flow-diagnostic measurement techniques were covered. All viewgraphs or slides were copied and a compilation (nearly 500 pages) of these (Ref. 3) was mailed to each attendee after the Symposium. Owing to the short period between announcement and meeting of the Symposium it was not thought reasonable to ask the speakers for this material ahead of that time. Although the number of attendees was larger than expected, and the discussion lengthier than usual at most technical meetings, it was possible to close the meeting in the early afternoon of the second day so that anyone wishing to do so could reach the airport in time for departures to the east or west on 10 December.

The Symposium was not the occasion of dramatic new revelations but its great value was the expert and timely testimony on aerothermodynamic problems and the way in which experiments may help solve them. This supported and extended Ref. 1 and similar discussions within NASA and the Air Force, it identified researchers with specific concepts regarding experiments and techniques of measurement in the subject area, and it revived interest in hypersonic gas dynamics.

Recommend Research Areas

For present purposes, it is convenient to treat this report as an addendum to Ref. 1, thereby avoiding the need to repeat anything included therein. Proceeding on this basis, the following comments are offered.

CFD and Thermochemical-Kinetic Data. Computational fluid dynamics (CFD) obviously will be a major tool in the design of new hypervelocity vehicles. For instance, it is the best means for extending perfect-gas hypersonic wind tunnel results to real-gas full-scale flight conditions. To do so with confidence, however, it is essential that the real-gas modeling be correct. At present, this cannot be safely assumed. There are little data on individual thermochemical-kinetic processes under realistic nonequilibrium conditions. The relative importance of the various gas processes is not clear in many cases of interest. Nonequilibrium real-gas processes can be produced in laboratory apparatus, most notably in aeroballistic ranges and shock tubes, but the reactions occur over finite time and distance, making it virtually impossible to obtain the desired measurements under the size and observation time constraints of those facilities. Not only the forward-going processes at the strong bow shock wave but also the deexcitation and recombination in the downstream flow field and at the vehicle surface are of concern. Quantities of prime interest in an experiment are (1) shock stand-off distance, (2) vibrational and rotational temperatures of O_2 and N_2 across the shock layer at various distances from the nose, and (3) density of NO, N, and O at the same locations.

The best capabilities in facility design and measurement techniques should be directed toward the goal of state-of-the-art laboratory research programs to extend the information about real-gas nonequilibrium processes, surface- and shock-slip phenomena, and to develop and demonstrate flow-diagnostic equipment for future flight experiments. At the same time, the best capabilities in CFD should be applied to standard test problems on simple blunt-nosed configurations, first in perfect-gas flow for which hypersonic wind tunnel data of high quality are also obtained, and then to the same configurations in real-gas equilibrium and nonequlibrium flows. Once it is proven that a particular CFD method reliably matches experimental data on simple configurations in perfect-gas flows, it would become eligible for extension, first to three-dimensional perfect-gas flows for which tunnel data are obtainable, secondly to aeroballistic range real-gas test cases, and finally to predict flight results that could be measured using STS Orbiters. It may seem that numerous computer codes are already available, but no code known to the writer has passed all of the tests enumerated above.

It is not meant to imply that all of the needed thermochemical-kinetic gas process data can be obtained and incorporated in CFD codes without flight experiments. The laboratory facilities fall short of meeting these requirements, as already observed, but they are important for the development of measurement techniques to be later used in flight, and they can provide data for the testing of CFD codes for the specific conditions of those facilities.

The necessity to provide computed results for the transitional rarefied flow regime should not be overlooked. It now appears that the direct simulation Monte Carlo (DSMC) approach is most suitable for this function, but more information on gas/surface interaction and real-gas nonequilibrium thermochemical-kinetic processes is required for input to the DSMC method.

Transition and Separation. Boundary layer transition and separation are important features of high-altitude hypervelocity flight. Analytic methods for predicting separation, which depends primarily on pressure distribution, have been developed in simple forms for two-dimensional flow. CFD codes for two-and three-dimensional flows can be used to predict separation as well as other viscous flow quantities such as skin friction. However, the laminar or turbulent state of the boundary layer has to be known or assumed in applying any of these methods.

The process by which boundary layer transition occurs, the roles of the factors influencing it, and generally improved methods for predicting it on highly swept, highly cooled lifting bodies in hypersonic flow are topics of practical interest. Transition location at different times during reentry influences thermal protection design and vehicle performance, and allowable surface roughness is planned with consideration of its predicted influence on transition.

There are serious questions about theoretical prediction of transition by stability theory and assumed amplification to transition. It is unclear how the boundary layer responds to freestream disturbances, how to define those distrubances in flight, and how to deal with the magnitude of disturbance represented by turbulence. There are arguments about the correctness of different calculations, and it is now more widely appreciated that many different factors enter into the transition process. When, as often happens, transition occurs without the process being restricted to the features described by stability theory, there are said to be "bypasses". This term, coined by Mark Morkovin, is very fitting. There nearly always will be a variety of factors present in any experiment, and they may be viewed as offering bypass routes to transition that compete with or enhance the process of amplification of Tollmein-Schlichting waves.

Leading edge sweep and radius of curvature, surface roughness, vibration and temperature, Mach and Reynolds numbers, angle of attack, vehicle motion, and, under some conditions, noise may be involved in determining free-flight transition. Other factors, or other ranking in strength of these factors may be found in wind tunnels.

The process by which transition may occur on inclined or swept bodies has been categorized in the following ways:

(1) Laminar separation followed by transition in the free shear layer with possible reattachment of the turbulent boundary layer or separation extending to the trailing edge.

(2) contamination by disturbances entering the flow along an attachment line such as exists on a swept leading edge or inclined, elongated body. Examples of common sources of contaminating disturbance are surface roughness and wing-body intersection.

(3) cross-flow destabilization arising in 3-dimensional boundary layer flows.

(4) Streamwise-flow transition by the process of amplifying waves of unstable frequencies. This is the process most often discussed and it is the model upon which linear stability theory has been based. Most systematic experimental investigations

have been carried out with flat plates, hollow cylinders, cones, or wedges in 2-dimensional or axisymmetric flow with the intent to produce this category of transition. As a result, there has been far more attention to this mode that to the others listed.

Features of compressible-flow transition, in addition to those characterizing low-speed flow, include (1) density as well as velocity fluctuations, (2) "inviscid" entropy layers superimposed upon boundary layers downstream of blunt noses; (3) shock waves from sharp or slightly blunted noses laying almost upon the boundary layer; (4) critical height of maximum instability in boundary layers at δ/y well removed from the surface; (5) ratios of wall temperature to adiabatic recovery temperature much less than 1.0, with important, incompletely understood effect on transition; and diminished effectiveness of boundary layer trips, making it difficult to simulate higher Reynolds numbers in wind tunnel experiments, but easing the requirements on surface smoothness of full-scale hypersonic vehicles.

The puzzling effect of the unit Reynolds number upon transitional Reynolds number is a source of difficulty. It cannot be assumed to be absent in flight, yet wind tunnel data are apparently unreliable because of the influence of noise radiated from nozzle wall boundary layers.

Even though there are well known limitations on wind tunnels preventing measurements of transition Reynolds numbers that directly equal those to be experienced in flight, it would be very interesting to undertake verification of Poll's analysis (Ref. 4) of Shuttle transition by experiments in a hypersonic wind tunnel and thereafter in flight. At the present time, such a project seems to be the most likely to bring about early improvement to methods for prediction of transition on hypervelocity, lifting bodies similar to the STS.

It appears that leeside pressure distributions in high-altitude, high-speed flight cannot, in general, be duplicated in existing wind tunnels because of nonequilibrium real-gas processes. The latter would be expected to be particularly important when strongly shocked air is expanded into the lee of a body, and it is suggesed that this could affect aerodynamic loading enough to produce unexpected moment coefficients. Therefore, computational studies of pressure distributions in lee flows with perfect -, equilibrium -, and nonequilibrium-gas processes are suggested as a first step, to be followed by appropriately located pressure measurements on a flight vehicle to check on the computed pressures. Even if the computations are not highly accurate, or if simplified geometry has to be assumed, the qualitative effect of non-equilibrium in the lee areas may be illuminated. It would be highly desirable to obtain perfect-gas hypersonic wind tunnel data for the chosen shape at correct Mach and Reynolds numbers in order to assess the validity of the perfect-gas computations.

Gas/Surface Interaction and Slip. There is some tendency to discount the importance of rarefied flow in connection with re-entry vehicles because aerodynamic heating and forces are reduced at low densities. However, heating and forces at low orbital and aero-assisted orbital transfer conditions are of interest, and very useful data could be obtained from flight experiments at upper altitudes. Several presentations at the Symposium dealt with this possibility. In particular, the widely recognized criticality of gas/surface interaction justifies a flight experiment. The higher altitude environment, in some respects, is the least difficult for conducting experiments, and action toward that end could be started immediately. More details are given in Ref. 4 by Hurlbut and by Fisher.

Knowledge of thermal accommodation and the tangential and normal momentum transfer on vehicle surfaces at real flight conditions would not only enable better estimates of performance in rarefied flow, but it would also provide firm anchoring for bridging formulas which are widely used to predict aerodynamic properties throughout the transitional flow regime. It is also possible that better understanding of gas/surface interaction in rarefied flow will lead to better modeling of slip at surfaces in continuum flow. There is mutual interface of these gas dynamic phenomena, and there is general concern that neither is adequately understood or modeled at the present time.

The suggested experimental approach to improved knowledge in this area entails the same combination of laboratory and in-flight research recommended in the real-gas nonequilibrium and the boundary layer transition/separation areas discussed earlier. The laboratory would serve for development of the measurement techniques and systems, as well as measurements of the best data obtainable under ground-based conditions. Flight experiments would be necessary in order to obtain the flow and surface interaction conditions of ultimate interest. Actions directed toward the goal of improved gas/surface interaction and slip data could begin immediately.

Measurement Systems. The Symposium included several presentations on this topic by persons closely identified with aerothermodynamic research as well as advanced flow diagnostic expertise. It was argued by Muntz that the electron beam fluorescence technique could be used for in-flight flow field studies at altitudes of 50 to 120 km, but further laboratory development and in-flight measurement of spectrally resolved flow field emission intensities should precede a full-blown flight experiment.

Miles, et al. (Ref. 5) earlier concluded that Rayleigh scattering is the most promising technique for density, velocity, and temperature measurements at altitudes of 40-80 km. At the Symposium, Miles reiterated this and added that more recent events suggest that a KrF excimer laser of narrow line width could be sucessfully used for these measurements.

Cattolica proposed a combination of electron beam and laser induced fluorescence techniques for the desired flow diagnostics. Both he and J.W.L. Lewis showed results of experiments in low-density wind tunnels using electron beam fluorescence, illustrating the fairly long history of electron beam use. Lewis discussed beam spreading, collisional quenching, multiple excitation paths, and high-temperature excitation cross sections. Cattolica reviewed work in combustion diagnostics using laser induced fluorescence. Species studied in the latter program include H, O, OH, CH, NO, CO, O_2, C_2, I_2, NO_2, and H_2CO.

McKenzie briefed the group on planning for a STS Orbiter flight experiment involving Rayleigh scattering from a pulsed ultraviolet laser beam. It is the objective of this effort to resolve 1% variations in ambient density along the flight path from approximately 80 to 40 km. This may be the first in-flight demonstration of laser photo-diagnostics. The description also gave an insight into the practical difficulties of such an experiment.

REFERENCES

1. Potter, J. L., "Discussion of Flight Experiments with an Entry Research Vehicle", Semiannual Status Report No. 1, NASA Research Grant NAG-1-549, Vanderbilt University, Nashville, TN 37235, June 30, 1985.

2. Potter, J. L., "Transitional Hypervelocity Aerodynamic Simulation and Scaling in Light of Recent Flight Data", AIAA Paper 85-1028, June, 1985.

3. Collected Presentations of the NASA/Vanderbilt Symposium on Future Hypervelocity Flight Requirements, 9-10 Dec. 1985 (compiled by J. L. Potter, Vanderbilt Univ., Mechanical and Materials Engineering Dept.) Nashville, TN 37235.

4. Poll, D.T.A., "Boundary Layer Transition on the Windward Face of Space Shuttle During Re-Entry", AIAA Paper 85-0899, June 1985.

APPENDIX A

NASA/VANDERBILT SYMPOSIUM

ON FUTURE HYPERVELOCITY FLIGHT REQUIREMENTS

December 9-10

Vanderbilt University
Nashville, Tennessee

Opening Remarks

Session I.

1. Del Freeman, NASA LaRC.
2. R. L. Jaffee, NASA ARC, "Physical and Chemical Processes in High Temperature Nonequilibrium Flows: How comprehensive is the data base and how computational studies can fill in the gaps."
3. C. D. Scott, NASA JSFC, "Nonequilibrium Flow and Catalysis in Hypersonic Flight."

Session II.

4. F. C. Hurlbut, UC Berkeley, "Remarks on Shuttle Based, Surface Interaction Experiments."
5. C. H. Lewis, VRA, Blacksburg, "Comments on Continuum Aerothermodynamics and a Suggestion for a Near-Term Computational Olympiad."
6. J. T. Chrusciel, Lockheed, Sunnyvale, "Proposed Research/Experiments for High Altitude Aerodynamic Phenomena."

Session III.

7. F. G. Blottner, Sandia, Albuquerque, "Review of Modelling and Computational Approaches for Hypersonic Vehicles at High Altitudes."
8. F. R. DeJarnette, NC State, Raleigh, "Data from Flight Experiments At High Speeds and Altitudes for Comparison with Computational Results."
9. W. Grabowsky, TRW, San Bernardino, "High Altitude On-Board Instrumentation."

Session IV.

10. M. S. Holden, Arvin/Calspan, Buffalo, "Aerothermal Problems Associated With Viscous Interaction in Hypervelocity Flight."
11. J. L. Potter, Vanderbilt U., Nashville, "Status of Understanding of Boundary Layer Transition on Hypervelocity Vehicles."
12. J. G. Mitchell, USAF/AECD, Tullahoma, "Ground Test Facilities."

Session V.

13. D. J. Peake, NASA ARC, "Separated, Vortical Leeside Flows." (To be presented by J. L. Potter)
14. S. S. Fisher, UV, Charlottesville, "Recommended Rarefied Flow On-Board Measurements."
15. E. P. Muntz, USC, Los Angeles, "Electron Beam Flow Field Diagnostics System for High Speed Flight Experiments Between 120 and 50 km."

Session VI.

16. R. B. Miles, Princeton U., "Rayleigh Scattering Measurements of Temperature, Velocity, and Density Surrounding a Re-entry Vehicle."
17. R. J. Cattolica, Sandia, Livermore, "Role of Advanced Optical Diagnostics in Trans-Atmospheric Aerothermophysics."
18. J. W. L. Lewis, UTSI, Tullahoma, "Electron Beam Diagnostics."
19. R. L. McKenzie, NASA ARC, "Applications of Laser Spectroscopy to Aerothermodynamic Research."

Session VII. - Concluding Discussion

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