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Book Review

Advances in Hypersonics, Vol. 1: Defining the Hypersonic Environment
J. J. BERTIN, J. PERIAUX, and J. BALLMAN (eds.), Birkhauser Boston, Cambridge, MA, 1992, 438 pp., $129.00.

This is the first of a three-volume series entitled *Advances in Hypersonics* that reproduces material presented at the Second and Third Joint U.S.-Europe Short Course in Hypersonics, held at the U.S. Air Force Academy and the Technical University of Aachen in 1989 and 1990. Volumes 2 and 3 in the series are *Modeling Hypersonic Flows* and *Computing Hypersonic Flows*, respectively. The main idea of these short courses was to present the state of the art of mathematical modeling, computation, and experimental methods needed to define the aerothermodynamic environments encountered by space vehicles during atmospheric hypersonic flight, with an aim to broaden perspectives on problems of integrated system design. The present volume consists of eight papers, led by two articles on aerothermodynamic phenomena and hypersonic vehicle design, which provide a perspective for the more specific studies that follow. Many features and issues brought out in the book are noteworthy and are commented on following the title and author of each article.

1) "Aerothermodynamic Phenomena and the Design of Atmospheric Hypersonic Airplane," E. H. Hirschel. The author discusses design approach and methodology as affected by heating and other hypersonic phenomena encountered in sustained flight. The scope of the discussion is limited mainly to the flight Mach-number range below 12, for which high-temperature real-gas effects are far less important than at higher speed. It is mentioned that extended cruise at speeds greater than Mach 10 may be forbidden, owing to insufficient cooling potential of the onboard cryogenic hydrogen fuel, and that the turbulence-transition location may affect the take-off weight (of the X-30 design) by a factor of two or more. Because of the complexity and expense entailed in a full-scale validation, the author advocates the introduction of an experimental flight vehicle (such as the FRG Mach 5.5 Hypersonic Technology Experimental Vehicle) as the capstone of a technology and validation effort. The author also believes that the altitude range of the ozone layer, 10-20 km, to be "vulnerable" and should be avoided. Problems of simulation of hypersonic flight by numerical and wind-tunnel means are noted with specific references to the need of duplicating flight Reynolds number and to the uncertainty in modeling and controlling laminar-turbulence transition. Problems caused by incomplete experimental simulation of inlet and nozzle flows, surface roughness, and aerothermoelasticity are noted.

2) "Concept of Hypersonic Aircraft," P. Perrier. Attention is again paid to the problems of heating, propulsion integration, and other aspects considered in the preceding article, but the concepts are more clearly brought out in the form of several design constraints: total program cost, aerothermal heating, propulsion system, and control and guidance requirements. Entropy production is introduced as an index of the vehicle's aerothermal efficiency. Several design issues on the air-intake integration are raised with examples from the Concorde, the Mirage, the SR71, the Hotol, and the Dassault Star-H. Owing to inadequate estimates on aerodynamic coefficients common in preliminary design practice, the feasibility of different concepts is often determined by the ability to achieve robust control. The author remarks that a progressive analysis of many relevant problems is needed to support the concept selection, and this may be viewed as progressive freezing of the design in several iterative loops.

3) "Hypersonic Wind Tunnel Testing," R. K. Mathews. The author observes that wind-tunnel experiments in the 1960s and 1970s were often motivated by the desire to verify an empirical or theoretically inexact correlation; this appears to be quite different from corresponding activities today which are concerned more with the substantiation of a CFD code. As the first of four articles on hypersonic ground testing facilities and techniques (articles 3-6), this paper provides an overview of test and measurement techniques, based mostly on experience with continuous-operation tunnels. The measurement techniques are examined in three groups: i) force and moment, ii) pressure, and iii) flow-field diagnostics. Forces and moments on models are measured with strain-gauge balances; water jackets are used, when space permits, to stabilize temperature and reduce balance zero shifts. Pitot, total-temperature, Mach-number and flow angularity probes as well as boundary-layer transition detectors, laser-particle monitors, laser Doppler velocimetry, and laser-induced fluorescence are described, and their merits are discussed under the classifications of intrusive and nonintrusive diagnostic techniques. Since aerothermal heating is central to the test objective, the test methodology must give due consideration to structure-component survivability. Thermal mapping techniques using phase-change paint, infrared scanning and thermographic phosphor paint are described. Discussed in some detail are discrete measurement techniques utilizing a calorimeter

heat balance, the coaxial (thermocouple) gauge, Schmitt-Boelter gauges, Gardon gauges, and the more standard thin-film type.

4) "Wind-Tunnel Based Definition of the AFE Aerothermodynamic Environment," C. G. Miller and W. I. Wells. Aeroassisted orbital transfer vehicles (AOTV) have been a focus of NASA space-vehicle research since the early 1980s. In view of design uncertainties associated with the limitations of both ground facilities and CFD codes, the aeroassist flight experiment (AFE) was initiated by NASA as a subscale precursor of the AOTV to provide needed aerothermodynamic information for the design of the final, manned version. The present article provides a combined computational and wind-tunnel study in support of the AFE's preliminary design. Valuable synopses of two papers by J. J. Jones and G. D. Walberg et al. on the rationale and design of the AFE are included in appendices.

A scaled-down version of the 14-ft diameter configuration is used for wind-tunnel studies, even though Mach and Reynolds numbers, as well as other parameters of the test, are far different from those pertaining to the full-scale flight environment. Descriptions of the test models and instrumentation for force, surface pressure, and heat transfer measurements are presented rather thoroughly. Over 700 wind tunnel tests, with more than 23,000 data points, have been performed. Comparing the Euler calculations with wind-tunnel data for shock shape and pressure distributions on the fore and after bodies indicates: i) the Reynolds numbers in the test sections are sufficiently high that an inviscid-flow model, allowing very thin boundary layers, may be adequate; ii) even the rather simple "modified Newtonian formula" can give excellent prediction of forebody pressure; and iii) although the shock-wave location predicted by the Euler calculation (HALIS code) for equilibrium air at Mach 31 fails to closely match the measured shape in air and in CF_4, the predicted and measured shapes, together with surface pressure distributions, suggest a local flow symmetry in the nose cap, allowing the stagnation point to be approximately identified with the point of maximum entropy. The measured data and the Navier-Stokes (LAURA code) prediction of heat transfer distribution also appears to be adequate, except for discrepancies of 20% about the maximum, which was believed to have resulted from the CFD truncation error due to a grid singularity. Since the objective is to provide an adequate data base for the preliminary design, and the inviscid code proves to be excellent for pressure prediction, one might ask why a corresponding calculation using a boundary-layer code was not made.

5) "High-Enthalpy Testing in Hypersonic Shock Tunnels," B. Esser, H. Gronig, and H. Oliver. This article reviews different high-enthalpy hypersonic ground-test facilities and describes the development of a relatively recent shock-tunnel research program at the Technical University of Aachen. The major program objective has been to provide an aerothermodynamic data base to support the current European space shuttle program Hermes and future projects such as Sanger II or Hotol. Briefly discussed are the characteristics of four types of high-enthalpy flow devices; shock tunnel, free piston shock tunnel, gun tunnel, and long shot. The presentation of the Aachen shock tunnel design, measurement techniques, and preliminary calibration results are thorough and includes assessment of the boundary-layer and van der Waals effects on the driver gas. Although an analysis with 34 elementary reactions behind a bow shock was undertaken, the possibility of thermal and chemical freezing in the nozzle was not examined. Detailed estimates of Mach and Reynolds numbers and other pertinent parameters in the tunnel operating ranges do suggest that the tunnel is capable of simulating the Hermes re-entry environment, at least in the continuum regime.

6) "Low Density Facilities," G. Koppenwaller. This article surveys low-density hypersonic facilities that allow virtually continuous operation. The review focuses mainly on the design principles and issues, and simulation and measurement techniques of several types of facilities, capitalizing on the author's extensive experience with the continuous wind tunnels and free-jet facilities at Princeton and Göttingen. However, the potential of experiments in this tunnel type for diagnostic study of nonequilibrium gas dynamic states is not brought out too clearly. Various nonequilibrium flow regimes of rarefied hypersonic flows and their simulation requirements are first examined. Criteria for strong viscous laminar interaction and limits of continuum, slip, near free-molecular, and free-molecular flows are given.

The author is concerned also with the simulation of heterogeneous chemical reaction on the (model) surface associated with familiar catalytic-wall effects as a special form of gas-surface interaction. There is another type considered by the author, which occurs in the surface vicinity in a sufficiently rarefied flow (first-collision regime), wherein the free-stream molecule can collide with one of the slowly moving molecules from a cold surface. Owing to the high relative speed of the encounter in this case, more inelastic collisions leading to dissociation will be expected in the wall vicinity. However, the notion of a "chemical reaction in the Knudsen layer" used by the author to denote this type of reaction could lead to confusion, since "Knudsen layer" has been normally used to refer specifically to the sublayer across which the wall slip occurs in a near-continuum flow. Freezing of flow chemistry as well as the molecular internal state in an expanding, low-density nozzle flow are well documented. To what degree they may affect the simulation capability of these and other facilities is not thoroughly discussed.

7) "Hypersonic Boundary-Layer Transition," K. F. Stetson. This and the next article provide state-of-the-art reviews on two aspects of viscous flows deemed most essential to practical air-breathing vehicle designs; namely, turbulence transition and viscous interactions at high Mach numbers. This article includes not only current data, but also valuable comments by an outstanding experimental worker in the field.

Owing to the high cruising altitude of a hypersonic vehicle, boundary-layer transition becomes a much stronger driver in overall vehicle design strategy. Yet a relevant data base does not exist, as the author notes. This adds to design uncertainties due to unverified codes, incomplete modeling, and an unproven propulsion system. The discussion is in five parts: boundary-layer instability (theory and experiment); control of transition experiments through Mach-number variation, nosetip bluntness, and crossflow; general comments on transition mechanisms suggested by the linear theory and the "bypass mechanism", and on flow-field calculations; commentary on Transition prediction methods; and advice on the proper use of prediction methods.

A number of features and issues, such as the significance of the generalized inflection point, higher instability modes, dominance of the second mode, adverse wall-cooling effect on instability, tip bluntness and the entropy layer swallowing, etc., emerge as recurrent themes in these five parts. The extensive comparison of the theory and experiment constitutes a good part of the text and figures. An issue discussed at some length is the influence of nosetip bluntness on the stability of the hypersonic boundary layer on a slender cone (7-deg half angle in the experiment). Remarks and observations are made on the notions of crossflow and unit Reynolds numbers, "environmental effects," effect of wall cooling and roughness, local pressure gradient, mass transfer, and other factors. A discussion is presented on current practice in transition prediction methods, including the e^N method and the importance of using more accurate viscous calculation methods to provide the initial data for instability analysis.

8) "Viscous Interactions Affecting the Design of Hypersonic Intakes and Nozzles," I. L. Stollery. This article discusses viscous interactions on four specific topics critical to scramjet engine design: i) two-dimensional (2D) inviscid-viscous interaction in compression corners, applicable to intakes and combustion chambers; ii) glancing interaction, a three-dimensional (3D) interaction caused by an oblique/curved shock from a ramp/strut intersecting on a side wall; iii) shock-shock interaction of an Edney type near cowl lip and strut; and iv) displacement-type, global viscous interaction that modifies the effective intake/exhaust-nozzle contour. Considerations are given to both laminar and turbulent boundary layers.

For laminar boundary layers, the 2D interaction problem of the compression ramp corresponds to the laminar triple-deck theory of a sharp-corner ramp. The experimental measurements of induced pressure and surface heat-transfer rate in this case, with and without separation at $M_\infty = 9.7$, appear to be in accord with the existing triple-deck analysis, although direct comparison with the latter is not made.

An important example of the glancing interaction is provided by a scramjet intake with side walls that are at right angles to the compression ramp. Experiments show that a turbulent boundary layer on the side wall is more susceptible to separation due to this type of interaction than to the more familiar quasi-two-dimensional type discussed before. For a laminar side-wall boundary layer, separation due to this kind of interaction occurs more readily, as expected, although the reattachment usually will accompany separation in this case, making the effects strictly local, causing only a minor blockage problem. Interestingly, the experimentally recorded ramp angle causing incipient side-wall separation in this case can be correlated by a surprisingly simple criterion discovered by Korkegi, i.e. $M_\infty \alpha_i = 17$ deg.

Blunting of a strut adds another complexity to interaction scenarios, because the oblique shock from the ramp intersects the strong bow shock around the leading edge. This, in fact, belongs to the same category of shock-shock interaction familiar from the scramjet cowl-lip problem. This type-IV shock-shock interaction from Edney's early definitive work is known to give rise to a jetlike high velocity stream directed toward the blunt surface, causing abnormally high local heat transfer, 10–30 times higher than the normal rate. Since turbulent boundary layers are far more resistant to separation, the author advocates ensuring such a condition when the first compression corner is reached in a ramp design. In the conclusion, it is indicated that the effects of sweeping the strut "forward" is harmful, although the reasons are not elaborated.

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