HYPERSONIC VISCOUS FLOW

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RESEARCH AND DOCUMENTED WORKS ON VISCOUS HYPERSONIC FLOW THEORY AT THE UNIVERSITY OF SOUTHERN CALIFORNIA SUPPORTED BY AFOSR CONTRACT (88-0146) ARE SUMMARIZED AND REPORTED. ~~TWO~~ TOPIC AREAS WHERE THE RESEARCH HAS BEEN FOCUSED ARE: A FULLY VISCOUS VERSION OF THE SHOCK LAYER (FVSL) AND ITS EXTENSION BEYOND THE NAVIER-STOKES (NS) LEVEL BASED ON GRAD'S THIRTEEN ~~(13)~~ -MOMENT EQUATIONS. (2) INVISCID-VISCOUS INTERACTION IN HYPERSONIC FLOWS. THE DEVELOPMENT IN AREA 1 HAS LED TO A PRINCIPLE WHICH ALLOWS CORRELATION OF A SHOCK LAYER FLOW FAR FROM TRANSLATIONAL EQUILIBRIUM WITH A CORRESPONDING FLOW BASED ON THE NS EQUATIONS, AS SUBTANTIATED BY EXTENSIVE COMPARISON OF DIRECT SIMULATION MONTE CARLO AND NS-BASED CALCULATIONS. THE DEVELOPMENT IN AREA 2 RESULTED IN A TRIPLE-DECK THEORY OF HYPERSONIC BOUNDARY LAYER UNDER STRONG WALL COOLING WHICH EXHIBITS DRASTICALLY DIFFERENT STRUCTURE AND PROPERTIES OF THE TRIPLE-DECK. (EDC)

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I. INTRODUCTION

The prediction of rarefied hypersonic flow fields encountered at high altitude requires flow physics modeling capabilities not found in most continuum methods/codes. The studies performed under the AFOSR (88-0146) contract at USC during the past two years enables a fruitful research development on viscous hypersonic flows, jointly supported by the NASA/DOD Grant (NAGW-1061), to a stage where useful applications become evident in the key problem areas of high-altitude hypersonic aerothermodynamics. The research program has focused on two topic areas:

1. A fully viscous version of the shock layer (FVSL) theory and its extension beyond the Navier-Stokes (NS) level based on Grad's thirteen-moment equations.

2. Inviscid-viscous interaction in hypersonic flows.

The following will summarize the key developments and publication/documentation in each of the two areas.

II. KEY RESEARCH DEVELOPMENTS AND PUBLICATIONS/DOCUMENTS

The 13-Moment Based Viscous Shock Layer

The research in topic area 1 has made concrete a conclusion previously made by the P.I. that, under a strong wall cooling. wall-slip are far less important than the "shock slip" in a FVSL. This was documented in an AIAA paper 88-2731 by Cheng and Wong, superseded by USCAE Report 147[1].

At high enough altitudes or Knudsen Numbers, not only will the shock layer become fully viscous, but the NS equations of the continuum model loses its physical basis from the gas-kinetic theory. The FVSL theory was thus reformulated from Grad's 13-moment theory of the gas kinetics. The new formalism leads to a system of nonlinear stress and strain-rate relations which nevertheless permit reduction of the thin-layer 13-moment system to one based on a NS model. The development thus leads to a principle which allows correlation of the shock layer flow in translational nonequilibrium with a corresponding NS flow. The theory has been demonstrated by the consistently good correlations of the FVSL analysis with DSMC calculations in skin-friction, surface heat-transfer, normal wall stress of a flat plate at finite attack angle, as well as the corresponding lift-to-drag ratio, (at 90-100 km altitude with speed 7.5 km/sec). This was documented in AIAA paper 89-1663 by Cheng, Lee, Wong and Yang[2], and also in a paper in the Proceedings of the International Conference on Hypersonic Aerodynamics[3].

The foregoing comparison and conclusion is further confirmed in a more recent study based on Maxwell gas. A part of this study was reported in a paper by Cheng, Wong, Hoover and Dogra, to be presented at the First International Hypersonic Waverider Symposium this Fall,[4] in which a strip theory is also shown to be completely consistent with the 3-D FVSL equations, including inner and outer boundary conditions, and thus a valid (leading) approximation. An example of a model waverider, with a (nearly) planar lower surface and a planform and dimensions similar to those of the Space Shuttles, is studied. The study suggests a bridging formula for the Shuttle's L/D ratio in the transition range for altitudes up to 110 km.

Apart from furnishing a theoretical (rational) basis for the strip theory, the 3-D development has also completed a formulation in terms of the Dorodnitsyn variables, using a pair of conjugate stream functions as dependent variables. A generalization to a FVSL flow with binary, finite-rate relaxation and chemical kinetics shows that reduction to a corresponding NS system is possible, but each rate in the reduced system in this case must be augmented by an amount proportional to p/P_{22} (where p is the thermodynamic pressure and P_{22} the normal stress in the transverse direction).

Inviscid-Viscous Interactions of a Hypersonic Boundary Layer: Critical Wall-Cooling Effects

Upstream influence and separation can occur in a laminar boundary layer on a triple-deck scale which is much smaller than the (global) streamwise length scale assumed in the classical theory of hypersonic boundary-layer interaction. Research under partial AFOSR support reveals that there exists a critical range of wall-to-stagnation temperature ratio, T_w/T_o, in and below which the scale describing the triple-deck interaction theory and the displacement-pressure law become significantly different from the classical triple theory. The paper by Brown, Cheng and Lee presenting this theory has been accepted for publication in the *J. Fluid Mechanics*[5].

III. CONCLUSION

Research on Viscous Hypersonic Flow supported by AFOSR during the period 02/01/88 - 01/31/89 has resulted in a development in the theories on rarefied hypersonic flows and on inviscid-viscous interaction. Works with encouraging results have been and are being documented in AIAA papers,[1,2] conference proceedings[3,4] and journal publication[5]. Subsequent journal publication of more extensive and definitive works is planned in the near future. Research on a modification of Grad's method to overcome its difficulty in the shock-structure analysis and to furnish a uniformly valid flow field description for rarefied hypersonic flows is being continued.

IV. REFERENCES: DOCUMENTED WORKS GENERATED UNDER THE PRESENT PROGRAM

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4. Cheng, H. K., Wong, E. Y., Hoover, L. N. and Dogra, V. K., "Flat Plate at Incidence as a Waverider in Rarefied Hypersonic Flow," Proc. First International Hypersonic Waverider Symposium, Univ. Manchester, England, Oct. 18-19, 1990 (1990).

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