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PARTICLE KINETIC SIMULATION OF HIGH ALTITUDE HYPERVELOCITY FLIGHT

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NASA

Rarefield flows about hypersonic vehicles entering the upper atmosphere or through nozzles expanding into a near vacuum may only be simulated accurately with a direct simulation Monte Carlo (DSMC) method. Under this Cooperative Agreement, the models employed in the DSMC method were enhanced, and simulations in support of existing NASA projects and missions were performed.

DSMC models were developed and validated for simulating rotational, vibrational, and chemical relaxation in high-temperature flows, including effects of quantized anharmonic oscillators and temperature dependent relaxation rates. State-of-the-art advancements were made in simulating coupled vibration/dissociation/recombination for post-shock flows.

Models were also developed to compute vehicle surface temperatures directly in the code rather than requiring isothermal estimates. These codes were instrumental in simulating aerobraking of NASA's Magellan spacecraft during orbital maneuvers to assess heat transfer and aerodynamic properties of the delicate satellite.

NASA also depended on simulations of entry of the Galileo probe into the atmosphere of Jupiter to provide drag and flow field information essential for accurate interpretation of an on-board experiment.

Finally, the codes have been used extensively to simulate expanding nozzle flows in low-power thrusters in support of propulsion activities at NASA Lewis Research Center. Detailed comparisons between continuum calculations and DSMC results helped to quantify the limitations of continuum CFD codes in rarefied applications.

During the first four years of this research program, the work was performed under the direction of Dr. Iain Boyd. Dr. Brian Haas joined the team in January, 1991, and became sole investigator in January, 1993. The results obtained during the phase when Dr. Boyd was Principal Investigator were presented in *periodic research reports* dated 11/2/89, 5/15/90, 11/28/90, 4/5/91, 3/6/92, and 1/4/93 as summary report. The scientific papers published in the open literature resulting from this phase of the program are included in the listing below.

The first periodic report with Dr. Haas as Principal Investigator was submitted on 12 October, 1993. His research from 1/1/93 through 1/31/94 included a detailed study of the rates of rotational and vibrational relaxation in the DSMC method to resolve numerous inconsistencies and differing interpretations appearing in the literature. This study developed a consensus among many researchers in the field and was reported in Ref.(15).

A second research area of Dr. Haas concerned modeling of gas-surface interactions. Rather than require prescribed temperature estimates for spacecraft surfaces, as is typically done in DSMC methods, a new technique was developed which couples the dynamic surface heat transfer characteristics into the DSMC flow simulation code to compute surface temperatures directly. This model, as applied to thin planar bodies such as solar panels, was described in Ref.(13).

Application of the DSMC method to problems of practical interest requires a trade-off between solution accuracy and computational expense and limitations. A parametric study was performed to assess the accuracy penalties associated with simulations of varying grid resolution and flow domain size, and was reported in Ref.(16).

The DSMC code was applied to two different spacecraft entry studies. First, the pitch, yaw, and roll aerodynamics of the Magellan spacecraft during entry into the Venus atmosphere at off-design attitudes was studied and reported in Ref.(14). Secondly, a study of entry of the Galileo probe into the atmosphere of Jupiter was conducted to assess vehicle drag in support of the on-board Atmosphere Structure Experiment during the most rarefied portion of the trajectory. This material was submitted in the form of an abstract for the AIAA Thermophysics Conference slated for June, 1994 (Ref.(17) -- see Appendix).

The following papers and publications resulted from the research activities conducted under Cooperative Agreement NCC2-582:

(1) I.D. Boyd, "*Assessment of Chemical Nonequilibrium in Rarefied Hypersonic Flow,*" AIAA-paper 90-0145.

(2) I.D. Boyd, P.F. Penko and L.M. Carney, "*Efficient Monte Carlo Simulation of Rarefied Flow in a Small Nozzle,*" AIAA-paper 90-1693.

(3) B.L. Haas and I.D. Boyd, "*Vibrationally-Favored Dissociation Applicable to a Particle Simulation,*" AIAA-paper 91-0774.

(4) B.L. Haas and J.D. McDonald, "*Validation of Chemistry Models Employed in a Particle Simulation Method,*"

AIAA-paper 91-1367.

(5) I.D. Boyd and T. Gökcen, *"Evaluation of Thermochemical Models for Particle and Continuum Simulations of Hypersonic Flow,"* AIAA 27th Thermophysics Conf., Nashville, TN, 1992, AIAA-paper 92-2971.

(6) I.D. Boyd and E.E. Whiting, *"Decoupled Predictions of Radiative Heating in Air Using a Particle Simulation Method,"* AIAA 23rd Plasmadynamics & Lasers Conf., Nashville, TN, 1992, AIAA-Paper 92-2954.

(7) I.D. Boyd, *"Analysis of Vibration-Dissociation-Recombination Processes Behind Strong Shock Waves of Nitrogen,"* Phys. Fluids A 4 (1), 1992, 178.

(8) B.L. Haas and D.Schmitt, *"Simulated Pitch, Yaw, and Roll Torques on the Magellan Spacecraft During Aerobraking,"* Atmospheric Flight Mechanics Conf., 1993.

(9) B.L. Haas, *"Particle Simulation of Satellite Aerobraking with Coupled Surface Heat Transfer,"* 18th Rarefield Gas Dynamics Symposium, 1993.

(10) B.L. Haas, *"Flow Resolution and Domain of Influence in Rarefield Hypersonic Blunt-Body-Flows,"* AIAA 28th Thermophysics Conf., Orlando, FL, 1993; AIAA Paper 93-2806.

(11) I.D. Boyd and E.E. Whiting, *"Decoupled Predictions of Radiative Heating in Air Using Particle Simulation Method,"* AIAA Paper 92-2971, Presented at the AIAA 23rd Plasmadynamics & Lasers Conference in 6/92.

(12) B.L. Haas, D. Hash, G.A. Bird, F.E. Lumpkin, III, and H.A. Hassan, *"Rates of Borgnakke-Larsen Thermal Relaxation in Direct Simulation Monte Carlo Methods,"* Phys. of Fluids A, submitted.

(13) B.L. Haas, *"Models for Dynamic Surface Temperatures During Rarified Aeropass Maneuvers,"* AIAA 28th Thermophys. Conference, Orlando, FL, 1993; AIAA-Paper 93-2765; presented at the AIAA Thermophysics Conference in 7/93.

(14) B.L. Haas and D.A. Schmitt, *"Simulated Rerefield Aerodynamics of the Magellan Spacecraft During Aerobraking,"* AIAA Paper 93-3676; presented at the Atmospheric Flight

Mechanics Conference in August, 1993, and submitted to J. of Spacecraft and Rockets.

(15) B.L. Haas, D.B. Hash, G.A. Bird, F.E. Lumpkin, and H.A. Hassan, "*Rates of Thermal Relaxation in Direct Simulation Monte Carlo Methods,*" Phys. of Fluids A, 1994 (in print); presented at the Fluid Dynamics meeting of the APS, 11/93.

(16) B.L. Haas M.A. Fallavollita, "*Flow Resolution and Domain of Influence in Rarefied Hypersonic Blunt-body Flows,*" AIAA-paper 93-2806; presented at the Thermophysics Conf. in 7/93 and submitted to J. Thermophysics and Heat Transfer.

(17) B.L. Haas and F.S. Milos, "*Simulated Rarefied Entry of the Galileo Probe into the Atmosphere of Jupiter,*" AIAA Thermophysics Conference, 6/94, submitted.

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15. Supplementary Notes

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16. Abstract

Rarefied flows about hypersonic vehicles entering the upper atmosphere or through nozzles expanding into a near vacuum may only be simulated accurately with a direct simulation Monte Carlo (DSMC) method. Under this grant, researchers enhanced the models employed in the DSMC method and performed simulations in support of existing NASA projects or missions. DSMC models were developed and validated for simulating rotational, vibrational, and chemical relaxation in high-temperature flows, including effects of quantized anharmonic oscillators and temperature-dependent relaxation rates. State-of-the-art advancements were made in simulating coupled vibration-dissociation-recombination for post-shock flows. Models were also developed to compute vehicle surface temperatures directly in the code rather than requiring isothermal estimates. These codes were instrumental in simulating aerobraking of NASA's Magellan spacecraft during orbital maneuvers to assess heat transfer and aerodynamic properties of the delicate satellite. NASA also depended upon simulations of entry of the Galileo probe into the atmosphere of Jupiter to provide drag and flow field information essential for accurate interpretation of an onboard experiment. Finally, the codes have been used extensively to simulate expanding nozzle flows in low-power thrusters in support of propulsion activities at NASA-Lewis. Detailed comparisons between continuum calculations and DSMC results helped to quantify the limitations of continuum CFD codes in rarefied applications.

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