

Supersonic and hypersonic boundary layer flows

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ABSTRACT

Supersonic and hypersonic numerical research activities of the “Lehrstuhl für Aerodynamik” at the Technische Universität München are presented in this paper.

Based on the ADM (Approximate Deconvolution Method), LES simulations of a turbulent ramp flow with a subsequent decompression corner at $M=2.95$ are conducted. The results excellently compare with the experimental findings and show the feasibility of such large-scale simulation albeit their large computer resource requirements. These simulations predict flow phenomena which can not be captured with RANS simulations.

For the hypersonic research, flat-plate boundary layers are investigated to examine the influence of chemical and thermal non-equilibrium on laminar-turbulent transition with direct numerical simulations. This encompasses the modelling of the chemical reactions of dissociating gas and the variable thermodynamic properties which depend on species concentrations. A second temperature describing the vibrational degrees of freedom of the molecules involved is used to model the thermal non-equilibrium.

INTRODUCTION AND METHOD

Large-scale simulations for the investigation of complex flows at supersonic and hypersonic Mach numbers are still a challenge for the method employed and the computers used. Complex flow phenomena like shock/boundary-layer interactions and the simulation of reacting flows require careful attention to the numerical method and require fine enough resolution to calculate all necessary physical effects properly.

For the simulation of turbulent supersonic flows, early simulations with DNS by Adams [1–3] showed the development of the shock-turbulence interaction at a supersonic ramp flow. The *Approximate Deconvolution Method* (ADM) was developed for incompressible flows by Stolz, Adams & Kleiser [19] and subsequently adapted

to compressible flows [20,4]. The ADM improved the quality of the modeling of the subgrid stresses at the expense of a somewhat higher computational cost due to the increased number of filtering operations on the same grid size. The method was used by Loginov to compare with experimental results and gain insight into detailed features of the specific flow. Surpassing the confirmation of experimental results, the LES discovered large-scale structures (Görtler-type vortices) and low-frequency shock motion.

The hypersonic investigations have been conducted with Direct Numerical Simulations with the numerical method developed by Adams [1] and extended by Stemmer [16–18] for thermal and chemical non-equilibrium effects. The chemical source terms have been modeled according to Park [14] and the thermodynamical properties have been calculated on the base of [9,15]. An in-

production to non-equilibrium DNS is also given in Candler [8]. As Schneider [21] points out, dependable experimental data on transition in hypersonic flows is not available which underlines the importance of numerical investigations of flows that are not reproducible in wind tunnels in all the similarity numbers like Re , Ma and Da . Bertin & Cummings [7] consider the difficulties and uncertainties in hypersonic research. Comparisons of equilibrium calculations with Linear Stability [12,18] have shown the applicability of the developed method. An experiment at very high Mach numbers by Mironov & Maslov [13] is available for comparative purposes.

RESULTS

Supersonic Ramp flow

The confirmation of experimental results can be comprehended at hand of the comparison of the numerical density gradient (Fig. 1) with experimental Schlieren images (Fig. 2). The features visible in the experimental Schlieren image are excellently reproduced in the numerical picture of the density gradient averaged in spanwise direction exceeding the clarity of the Schlieren image. The shock, the turbulent separated flow and the compression waves underneath the shock are clearly to be identified.

Table 1

Fow parameters for the supersonic ramp flow

M_∞	2.95
Re_{δ_0}	63,560
ramp angle	25°

The experiments found a low-frequency oscillation of the shock which could be confirmed by the numerical simulations. As the experimental Reynolds number was somewhat larger ($Re_{\delta_0} =$

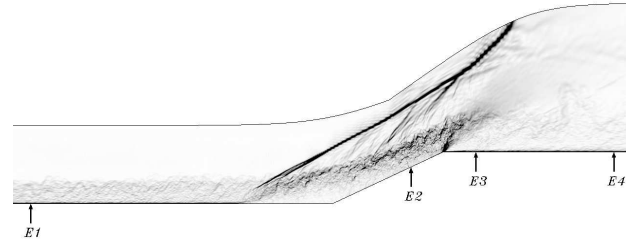


Fig. 1. Instantaneous Schlieren-type image (density gradient averaged in spanwise direction) from the LES

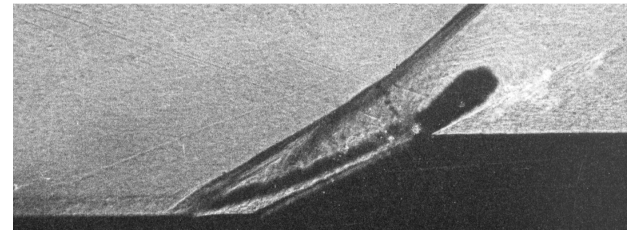


Fig. 2. Schlieren image from the corresponding experiment

144,000, which was out of reach for the present simulations), the frequencies do not match as can be expected [11].

The mean-flow structure over the compression ramp is shown in Fig. 3. where 10 streamlines from the inflow boundary can be traced downstream through the shock (light shaded). Görtler-like vortical structures can be seen on the upward surface of the ramp.

Hypersonic reacting flat-plate boundary-layer flow

The simulations presented were conducted at free stream $Ma=20$ at an altitude of $H=50$ Km, which corresponds to a point on the flight return path of a LEO-vehicle. The atmospheric properties can be taken from Table 2. A steady two-dimensional base flow is calculated. Periodic three-dimensional blowing and suction at the wall is prescribed to introduce the disturbances.

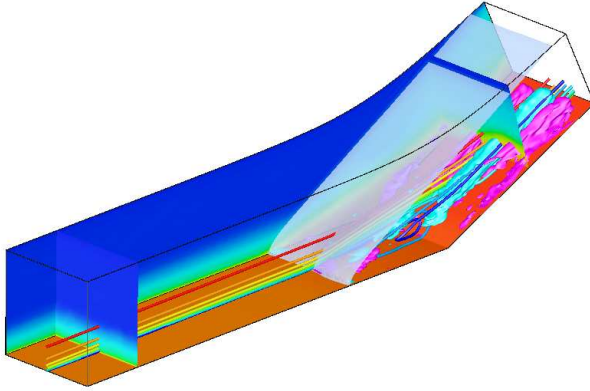


Fig. 3. Time-averaged flow with stream lines and vortical structures

Table 2

Atmospheric and flow parameters for hypersonic simulations

M_∞	20.0	p_∞	79.78 Pa
Re_{δ_1}	34,951	U_∞	6596 m/s
T_∞	270.65 K	x_0	1.609 m
T_{Wall}	811.95 K		

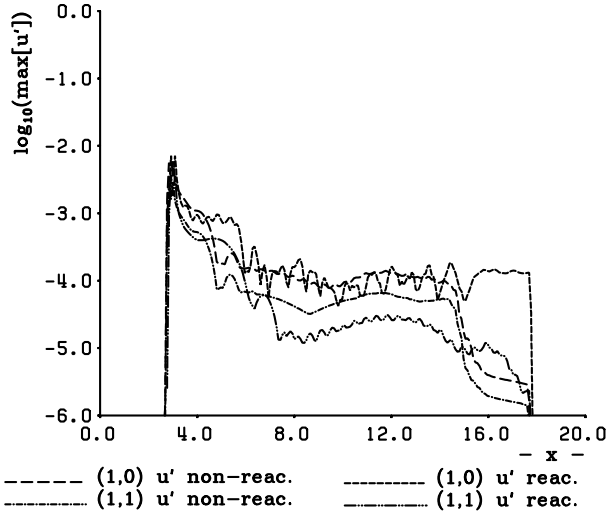


Fig. 4. Disturbance development as the wall-normal maximum for non-reacting and reacting flow

The differences between ideal gas and chemically reacting flow in the disturbance development is presented in Fig. 4. The linear disturbance amplitude for the three-dimensional disturbance is

diminished by a factor of 2-3 at the presence of chemically reacting flow. For the simulation of non-equilibrium chemically reacting flow, a stronger influence on the disturbances for higher amplitude levels are to be expected.

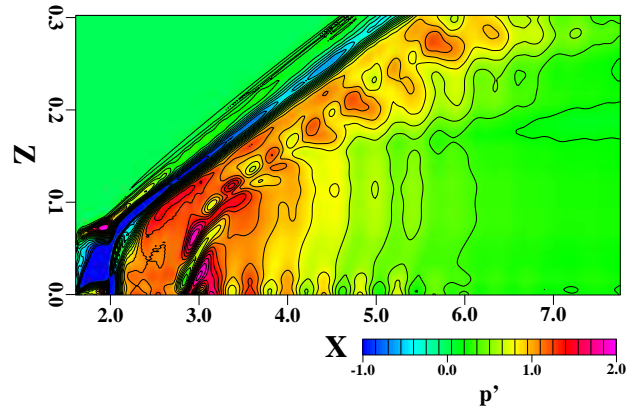


Fig. 5. Disturbance development in the vicinity of the disturbance location ($x = 2.1$) as disturbance pressure contours

The vicinity of the disturbance strip is shown in Fig. 5. The contours correspond to the disturbance pressure levels. The disturbances are bound in the wall-normal direction by a characteristic in the angle of the local Mach number ($\alpha \approx 3^\circ$). This contradicts the prerequisites of the Linear Stability Theory (exponential decay in wall-normal direction of the disturbance modes) and leads to a decrease in disturbance amplitude up to the point where the characteristic is far enough away to justify the assumption.

CONCLUSIONS

LES of supersonic ramp flow and DNS of hypersonic reacting flow have been presented. The current research activities will continue at the “Lehrstuhl für Aerodynamik” to investigate supersonic and hypersonic transitional flows with state of the art, high-performance numerical methods to gain detailed insight into these flows which are important for future generation aircraft and re-entry vehicles.

BIBLIOGRAPHY

- [1] N.A. Adams, K. Shariff, “A High-Resolution Hybrid Compact-ENO Scheme for Shock-Turbulence Interaction Problems”. *J. Comp. Phys.* **127**, 27–51, 1996.
- [2] N.A. Adams, “Direct Numerical Simulation of Turbulent Compression Ramp Flow”. *Theor. and Comp. Fl. Dynamics.* **12**, 109–129, 1998.
- [3] N.A. Adams, “Direct Simulation of the Turbulent Boundary Layer Along a Compression Ramp at $M=3$ and $Re_\theta=1685$ ”. *J. Fluid Mech.* **420**, 47-83, 2000.
- [4] N.A. Adams and S. Stolz, “A Deconvolution Approach for Shock-Capturing”, *J. Comp. Phys.* **178**, 391–426, 2002.
- [5] J.D. Anderson, *Hypersonic and High Temperature Gas Dynamics*. AIAA publication, 1989.
- [6] F.P. Bertolotti, “The influence of rotational and vibrational energy relaxation on boundary-layer flow”. *J. Fluid Mech.*, **372**, 93-118, 1998.
- [7] J.J. Bertin and R.M. Cummings, “Critical Hypersonic Aerothermodynamic Phenomena”. *Ann. Rev Fluid Mech.*, **38**, 129-157, 2006
- [8] G. Candler, “Chemistry of external flows”. *Aerothermochemistry for Hypersonic Technology*, VKI-LS 1995-04, 1995.
- [9] R.N. Gupta, M.J. Yos, R.A. Thompson & K.-P. Lee, *A Review of Reaction Rates and Thermodynamic and Transport Properties for an 11-Species Air Model for Chemical and Thermal Nonequilibrium Calculations to 30,000K*. NASA RP-1232, 1990.
- [10] S.K. Lele, “Compact Finite-Difference Schemes With Spectral-Like Resolution”. *J. Comp. Phys.*, **103**, 16–42, Academic Press, San Diego, 1992.
- [11] M.S. Loginov, N.A. Adams & A.A. Zheltovodov, “Large-eddy simulation of shock-wave/turbulent boundary-layer interaction”. *J. Fluid Mech.*, accepted for publication, 2006.
- [12] L.M. Mack, “Boundary-Layer Stability Theory”, *JPL Report 900-277 Rev. A*, Jet Propulsion Laboratory, Pasadena, USA, 1969.
- [13] S.G. Mironov and A.A. Maslov, “Experimental study of secondary stability in a hypersonic shock layer on a flat plate”. *J. Fluid Mech.* **412**, 259-277, 2000
- [14] C. Park, “A Review of Reaction Rates in High Temperature Air”. *AIAA Paper 89-1740*, 1989.
- [15] G.S.R. Sarma, “Physico-chemical modeling in hypersonic flow simulation”. *Progress in Aerospace Science* **36**, 281-349, 2000.
- [16] C. Stemmer and N.N. Mansour, “DNS of transition in hypersonic boundary-layer flows including high-temperature gas effects”. *Annual Research Briefs 2001* Center for Turbulence Research, Stanford University, NASA Ames, 143–150, 2001.
- [17] C. Stemmer, “Transition investigations on hypersonic flat-plate boundary layers flows with chemical and thermal non-equilibrium”, In: *Sixth IUTAM Symposium on Laminar-Turbulent Transition*, Ed.: Govindarajan, Rama, IUTAM-Symposium, 13.-18. December 2004, Bangalore, India, 363-368, Springer Verlag, 2006.
- [18] C. Stemmer, “Hypersonic Transition Investigations In A Flat-Plate Boundary-Layer Flow at $M=20$ ”, *AIAA Paper 2005-5136*, 2005.
- [19] S. Stolz, N.A. Adams and L. Kleiser, “An approximate deconvolution model for large-eddy simulation with application to incompressible wall-bounded flows”, *Phys. Fluids* **13**, 997–1015, 2001.
- [20] S. Stolz, N.A. Adams and L. Kleiser, “The approximate deconvolution model for large-eddy simulation of compressible flows and its application to shock-turbulent-boundary-layer interaction”. *Phys. Fluids* **13**, 2985–3001, 2001.
- [21] S.P. Schneider, “Flight data for boundary-layer transition at hypersonic and supersonic speeds”. *J. of Spacecraft and Rockets* **36**, 8-20, 1999.