Turbulent Effects in Type4 Shock Interactions

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Type4 shock interactions in hypervelocity flows are investigated numerically using two different codes: The well-known DLR FLOWer-code as well as the QUADFLOW-code developed at the RWTH Aachen. Main focus of the paper is the correct prediction of the high heat loads for the contour caused by these interactions.

The Navier–Stokes equations represent the appropriate model for the simulations. The two–dimensional Navier–Stokes equations for flows in chemical nonequilibrium in a simply connected domain V with boundary ∂V can be written as

$$\int_V \frac{\partial \mathbf{U}}{\partial t} dV + \oint_{\partial V} \left\{ (\mathbf{F} - \mathbf{F}_v)\, e_{n_x} + (\mathbf{G} - \mathbf{G}_v)\, e_{n_y} \right\} dA = \int_V \mathbf{Q} dV \quad (1)$$

where

$$\mathbf{U} = (\rho, \rho u, \rho v, \rho e, \rho X_1, ..., \rho X_{N-1})^T \quad (2)$$

is the vector of conserved quantities with the total density ρ, the cartesian components of velocity u, v, the total energy e and the mass fractions X_i of the corresponding ith species of altogether N species being considered.

$$\mathbf{Q} = (0, 0, 0, 0, \dot{\omega}_1, ..., \dot{\omega}_{N-1}) \quad (3)$$

is the source term as a consequence of the non–equilibrium chemistry, where $\dot{\omega}_i$ are the mass production rates, respectively. Finally $\mathbf{F}$ and $\mathbf{G}$ are the physical flux functions of the convective part of Eq.(1) in the x and y direction, respectively, whereas $\mathbf{F}_v$ and $\mathbf{G}_v$ are the physical flux functions of the diffusive part.

The first numerical algorithm used to calculate approximate solutions of the two–dimensional Navier–Stokes equations is based on the DLR FLOWer–Code (Version 116.x (DLR 2001)). This code was originally developed for the simulation of subsonic and transonic flows and has been extended to supersonic and hypersonic flow computations (van Keuk, Ballmann 1998, Reinartz et al. 2002). In this context several flux–vector– and flux–difference–splitting techniques like AUSM (Liou et al. 1993), AUSMDV (Wada et al. 1994), LDS (Edwards 1997) or the well known scheme of Roe (Roe 1981) have been implemented. Second order in space accuracy is reached by means of MUSCL–Extrapolation where different limiter functions are used to guarantee the TVD property of the schemes. For the discretization of the diffusive part of Eq.(1) central discretization is used. Time integration is performed by an explicit 5–stage Runge–Kutta scheme and for steady state solutions several techniques for convergence acceleration like multigrid, local time stepping and implicit residual smoothing are used. In the framework of a postdoctoral fellowship from the Deutsche Forschungsgemeinschaft the FLOWer–Code is extended to real gas flow simulations with both chemical reactions in local equilibrium and chemical nonequilibrium (van Keuk et al. (2003)). Further modifications concern the calculation of the mixture transport properties. The species viscosities are calculated using Blottner's curve fits (Blottner et al. 1971) whereas Gupta's curve fits are applied for thermal conductivity (Gupta et al. 1990). The mixture properties are calculated following Wilke's mixing rule (Wilke 1950). In the case of chemical nonequilibrium the forward and backward reaction rates in the source term of Eq.(1) are calculated as discussed by Gupta et al. (Gupta et al. 1990).

The QUADFLOW program system is an integrated framework for solving the Euler- and Reynolds-averaged Navier-Stokes equations for compressible fluid flow. Its central objective is to realize adaptively generated discretizations. Preference is given to curvilinear meshes, which are embedded into a multiblock concept. A key idea is to represent such meshes by a parametric mapping from the computational domain into the physical domain by means of B-spline techniques. The mesh is locally adapted to the solution according to the concept of h-adaptation. Adaptation criteria are based on multiresolution techniques. The spatial discretization is based on a finite volume scheme for two- and three-dimensional flow problems. Thereby, the grid is considered as a fully unstructured mesh, composed of simply connected elements with otherwise arbitrary topology. The method is of second order accuracy in space and time. The convective fluxes are discretized with upwind schemes, while diffusive fluxes are handled in a quasi-central fashion. Time integration is based on a fully implicit Newton-Krylov type approach.

At the Graduate Aeronautical Laboratories (California Institute of Technology) hypervelocity flows around blunt bodies with and without impinging oblique shock have been investigated in detail both theoretically and experimentally (e.g. Wen, Hornung 1995, Sanderson 1995). The freestream conditions are for example $\rho_\infty = 0.0155 kg/m^3$, $T_\infty = 1190.60K$, $M_\infty = 6.29$, $Re_\infty/m = 1.63 \cdot 10^6$ and $X_{N_2} = 0.99$. Depending on the impinging point of the oblique shock with the detached bow shock different complex shock interactions arise, that - particularly in the case of the so-called Type4 interaction - lead to very strong thermal loads for the contour. Numerical computations for such flows are carried out with the modified FLOWer–Code. Fig. 1-2 show exemplary measured and calculated results for the density distribution and the wall

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heat flux. The density distribution is qualitatively well captured, but the numerically predicted heat flux is lower than experimentally observed. So in this paper the influence of turbulent effects on the heat flux is investigated. Furthermore, the improvements using the adaptive flow solver on the one hand and considering the non-equilibrium chemistry on the other hand of the quality of the results is assessed.

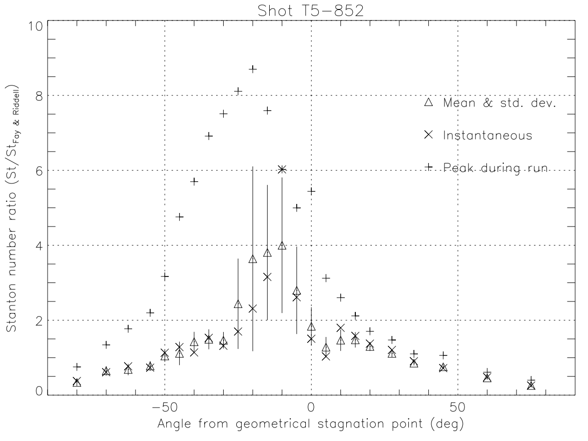

Figure 1. Measured Wall Heat Flux for Type4 Shock-Interaction at $Ma_\infty = 6.29$ (Sanderson 1995).

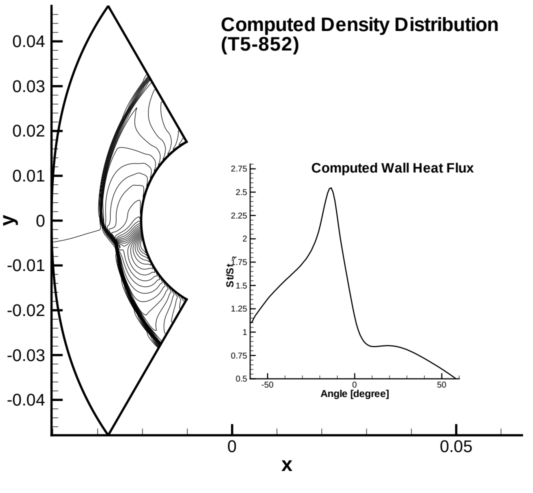

Figure 2. Calculated Density Distribution and Wall Heat Flux for Type4 Shock Interaction at $Ma_\infty = 6.29$ (van Keuk et al. (2003)).

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