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Numerical Investigation of Shock Wave Interference Heating in Chemical Nonequilibrium

Birgit U. Reinartz*, **Jörn van Keuk,** and **Josef Ballmann**

Lehr- und Forschungsgebiet für Mechanik, RWTH Aachen, Templergraben 64, D-52062 Aachen

A Navier-Stokes solver is extended by a nonequlibrium gas model to investigate heat transfer rates in hypersonic flow. The nonequlibrium model is shortly discussed and results for a type IV interaction on a cylinder are presented and compared to experimental measurements.

1 Chemical Nonequilibrium

The flowfield around vehicles in hypersonic flight is characterized by high temperature and low density conditions that give rise to chemical nonequilibrium effects. In real gas flow, transport properties may change drastically depending on the properties of the present species and on their mixture. This affects the transport processes close to the surface and, thus, the surface loads. Furthermore, chemical reactions change the overall flow pattern and the position of shock waves, which in turn influence the surface heat flux of a hypersonic vehicle. Accurate predictions of the wall heat flux on such vehicles is of particular interest because the thermal load may be very severe. Especially, shock interactions cause peak heating that can be many times that of the stagnation point maximum. In the present paper, an Edney type IV shock interaction is studied numerically with a well validated Navier-Stokes solver for perfect gas flow, which has been extended by a nonequilibrium gas model.

2 Computational Method

The DLR FLOWer code [1] is applied, which solves the Navier–Stokes equations for compressible fluid flow using a cell–centered finite volume method on block–structured grids. The convective and diffusive fluxes are discretized with an AUSM upwind scheme and by centered approximations, respectively. Time integration is performed by a five-step Runge–Kutta method. Both, time and space discretization are second order accurate [2]. Within the frame of the present investigations, gas models for pure nitrogen as well as for five-species air flow are implemented into the code [3]. This requires four new transport equations for the mass concentration of the different species. The reaction rates contained in the source terms of those equations are modeled by an Arrhenius ansatz as described by Klomfass et al. [4]. The laminar viscosities and the thermal conductivities of the different species are computed by Blottner's model [5] and Gupta's curve–fits [6], respectively. Subsequently, Wilke's semi-empirical mixing rule [7] is used for computing the total transport properties of the flow. Furthermore, to avoid restrictions due to small chemical reaction time scales, a semi point–implicit scheme, a so–called Strang splitting, is used for time integration where every time step is divided in two. During the first step an inert fluid is transported and during the second step chemical reactions are allowed to take place. With the newly extended flow solver, shock interaction test cases with relevance to hypersonic flight are investigated [3].

3 Results

The interferogram of an Edney type IV shock interaction [8] is shown in Fig. 1 where a weak shock impinges close to the stagnation point of a blunt body. This interaction type produces a supersonic jet that hits the body and causes intensive surface heating. The test conditions of the experiment, which has been conducted at the CalTech T4 Shock Tunnel [8], are $M_\infty = 5.28,\ \rho_\infty = 0.0157\ kg/m^3,\ and\ T_\infty = 2326.5\ K$. The experiment was used as nonequilibrium testcase for the numerical simulation assuming an isothermal, non-catalytic wall. The computed density contours are also shown in Fig. 1. The applied resolution is 129 nodes in the circumferential direction and 119 nodes in the normal direction. In Fig. 2, the measured and computed heat flux distributions are shown. The Stanton number is normalized by the stagnation point Stanton number as approximated by Fay and Riddell and depicts the factor of intensification due to the shock interaction. The numerical distribution reflects the measurements and the overall agreement is satisfying; however, there is still a discrepancy between experiment and numerics in the area of peak heating. This might be due to neglection of turbulent and unsteady effects in the computation as well as measurement uncertainties. Future work contains the investigation of turbulent effects on shock interaction heating.

* Corresponding author: e-mail: birgit@lufmech.rwth-aachen.de, Phone: +49 241 80 94632, Fax: +49 241 80 92126

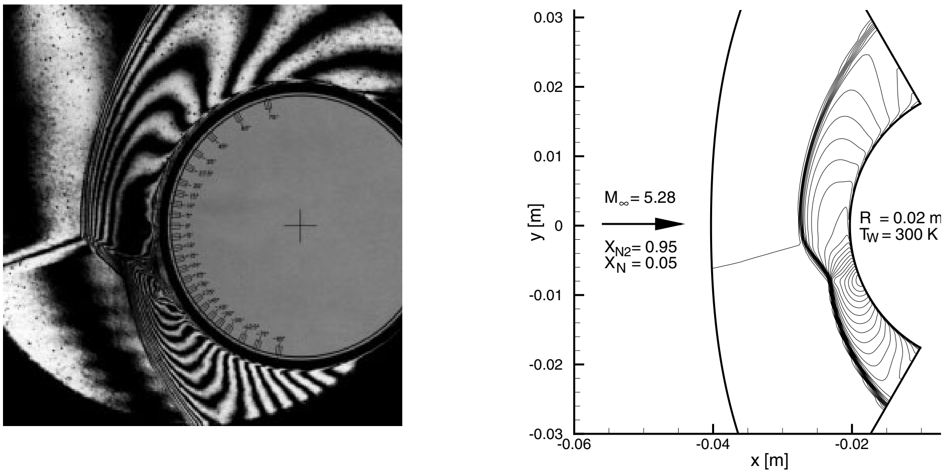

Fig. 1 Interferogram (left,taken from [8]) and corresponding computed density distribution (right) for a type IV shock interaction.

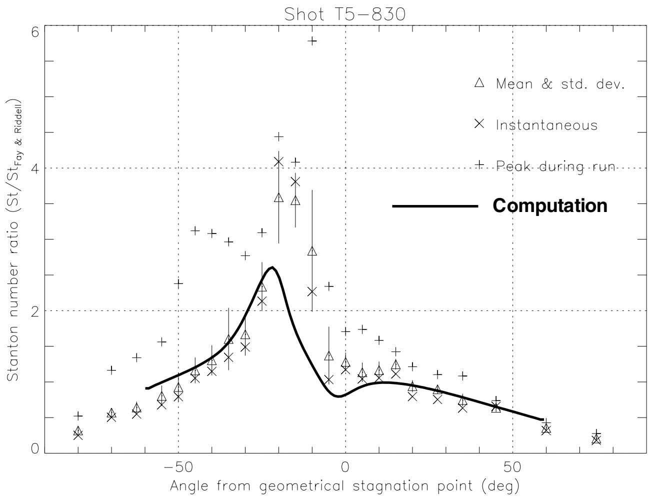

Fig. 2 Comparison of non-dimensionalized measured and computed Stanton number for type IV interaction flow (measurements taken from [8]).

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