Shock Waves Manuscript-Nr.
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Calculation of stagnation streamline quantities in hypersonic blunt body flows

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Received

Abstract. An approximate method for the efficient calculation of stagnation-streamline quantities in hypersonic flows about spheres or cylinders is suggested. Based on the local similarity of the flow field the two-dimensional Navier-Stokes equations are simplified to a one-dimensional approximation for the stagnation streamline. These equations are solved with an implicit finite-volume scheme. Comparisons with fully two–dimensional Euler and Navier–Stokes calculations for flows about spheres are presented, that include perfect gas flows and flows in chemical non-equilibrium. Comparisons with a number of experiments conclude this report.

Key words: Non-equilibrium, Stagnation Streamline, Local Similarity, Navier-Stokes equations, Chemically reacting flows

Nomenclature

a_f	frozen speed of sound [m/s]
γ_f	ratio of frozen specific heats [-]
ρ_α	partial density of component α [kg/m^3]
$\underset{\sim}{v}$	velocity vector [m/s]
$\underset{\sim}{j}_\alpha$	diffusion flux vector [kg/m^2 s]
$\underset{\sim}{q}$	molecular heat flux vector [W/m^2]
ω_α	chemical production rate [kg/m^3 s]
$\underset{\approx}{\tau}$	shear stress tensor [N/m^2]
p	hydrostatic pressure [N/m^2]
E	total energy [J/kg]
H	total enthalpy [J/kg]
e_α	specific energy of component α [J/kg]
h_α	specific enthalpy of component α [J/kg]
T	temperature [K]
x_α	mass fraction of component α [-]
y_α	mole fraction of component α [-]
D	diffusion coefficient $[kg/m^3 s]$
μ	viscosity coefficient $[kg/ms]$
λ	heat-conduction coefficient $[W/mK]$

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1 Introduction

The hypersonic flow about a spacecraft entering the atmosphere at orbital velocity is characterized by two main features: the high kinetic energy of the flow that leads to strong molecular collisions, and the low density of the atmosphere that results in small molecular collision rates. Molecular collisions with sufficient energy lead to the excitation of higher molecular modes and to changes in the gas composition as molecules dissociate. Due to small collision rates local non-equilibrium may be relevant. This is the case if the respective equilibration times of the chemical composition and the molecular energy distribution are comparable to the mean resident time of the gas in the flow field. In the following only local chemical non-equilibrium is taken into account, i.e. local thermal equilibrium is assumed.

The non-equilibrium flow is then described mathematically by the conservation equations for the mass, the momentum and the total energy of the gas mixture and additional balance equations for the partial densities of the components. The physical model enters these equations via the expressions for the chemical production rates and the molecular fluxes.

The calculation of stagnation-streamline quantities in hypersonic flows about spheres and cylinders requires the solution of the governing equations with two independent spatial variables. The computational domain has to be extended at least beyond the boundaries of the subsonic region of the shock layer, cf. Fig. 1. The computation is thus rather time consuming and not suitable for parametric studies or a fast analysis of a specific flow situation.

In the approach suggested in the present work the governing equations are simplified by reducing the number of independent spatial variables. This leads to a quasi one-dimensional approximation for the stagnation streamline in the considered flows. The simplified set of equations, in the following called dimensionally reduced Navier-Stokes equations (DRNSE), can be solved numerically within some minutes on a standard workstation or PC, even with very high spatial resolution. This makes the approach useful e.g. for evaluating the effects of