A high-order scheme for the numerical simulation of high-enthalpy hypersonic flows

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Abstract: A high-order shock-capturing finite-difference scheme for the numerical simulation of hypersonic high-enthalpy flows is presented. The suitability of the numerical strategy and the capabilities of the shock-capturing sensor are assessed by analysing different thermochemical non-equilibrium configurations.

Keywords: Compressible flows, shocks, thermochemical non-equilibrium, high-order methods

1 Introduction

High-speed turbulent flows are encountered in most space-related applications (including exploration, tourism and defense fields) and represent a subject of growing interest in the last decades. At such conditions, the shock waves generated produce a large increase of the fluid temperature, possibly leading to vibrational excitation and gas dissociation, resulting in a thermochemical non-equilibrium state. A major challenge in performing high-fidelity simulations of such flows resides in the stringent requirements for the numerical schemes to be used. These must be robust enough to handle strong, unsteady discontinuities, while ensuring low amounts of intrinsic dissipation in smooth flow regions.
Recently, Sciacovelli *et al.* [1] presented a central-difference scheme with nonlinear artificial dissipation conceived to perform high-fidelity simulations of hypersonic flows in chemical non-equilibrium conditions. Such a scheme has been successfully applied to the DNS of high-enthalpy turbulent boundary layers in chemical [2] and, only recently, in thermochemical non-equilibrium. However, its capability of accurately and robustly simulating more severe high-enthalpy flow configurations, such as flows in thermochemical non-equilibrium with strong shock waves, has yet to be demonstrated in full. On this basis, the goal of the present study is to demonstrate the suitability of such a scheme in faithfully capturing the dynamics of hypersonic flows undergoing both thermal and chemical non-equilibrium.

2 Preliminary results and work in progress

The present numerical scheme uses a blend of a ninth-order-accurate dissipation term based on tenth-order derivatives of the conservative variables (used to damp grid-to-grid oscillations) along with a low-order shock-capturing term. A highly-selective sensor is used to turn on shock capturing and smooth out flow discontinuities and/or strong thermal, dynamic or mass gradients [1]. This solver has been recently extended to account for thermal non-equilibrium following the two-temperature model of Park [3], which has been validated by means of a 0D heath bath of a single species [4] (see figure 1(a)). The extension of the scheme to handle strong vibrational energy gradients relies on the use of a vibrational-temperature-based shock sensor that will be presented in detail at the conference. The approach will be studied for configurations of increasing complexity. First, the capabilities of the shock-capturing technique will be tested against a vibrationally-excited one-dimensional shock tube. Afterwards, the results of spatially-developing laminar boundary layers in thermochemical non-equilibrium will be compared with those obtained by means of the locally self-similar theory, as in figure 1(b) for a Mach number of approximately 12; a case of laminar shock-wave/boundary-layer interaction will also be presented. Lastly, we consider the thermochemical extension of the classical 2D viscous shock tube of Daru & Tenaud [5], which will confirm the shock capturing capabilities in the context of complex unsteady behavior.

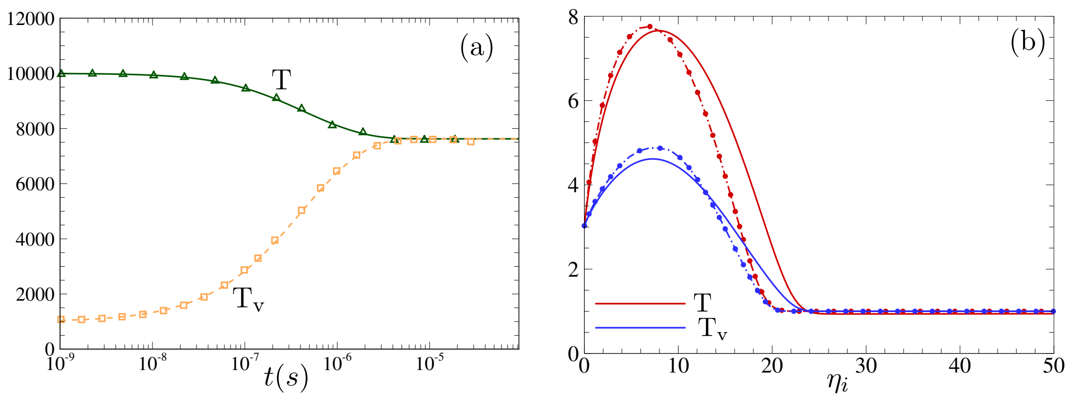

Figure 1: Left: Vibrational-Translational relaxation towards equilibrium of N_2 heath bath; symbols from Casseau *et al.* [4]. Right: wall-normal profiles of normalized temperatures at a distance x=0.3 m from the leading edge of a boundary layer in thermochemical non-equilibrium; lines: Navier-Stokes solution, symbols: locally-self-similar solution.

References

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