State-to-State investigation of hypersonic high-enthalpy nitrogen flows

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Summary
This work presents the investigation of hypersonic nitrogen flows past a sphere by employing a State-to-State model for weakly ionized plasma. The research extends previous results obtained for neutral air mixtures showing a better agreement with experiments in terms of shock stand-off distance compared to predictions provided by multi-temperature approaches.

1 Background of the study

Nowadays, reusable vehicles to access space are very attractive for cost reduction. Many reusable spacecrafts, such as Space Shuttle, have been conceived for both orbital and suborbital services [1]. These vehicles must withstand very high temperatures when they fly at hypersonic speeds in the continuum regime, and an adequate Thermal Protection System (TPS) is needed.

Modeling high enthalpy flows is a challenge requiring an efficient CFD solver coupled with an accurate chemical-physical scheme capable to describe non-equilibrium conditions. The multi-temperature (mT) approach has the advantage to implement a minimal kinetic scheme, describing the vibrational energy of molecules with a temperature Tv, but its accuracy is limited. Many assumptions are needed to extend the rate given for thermal equilibrium system to mT and to determine the effects of chemical reaction on the internal energy. As an alternative, the State-to-State (StS) kinetics, describing the evolution of each internal level as an independent chemical species, obtains this information directly from the distributions. However, the computational load is much larger than mT, limiting the diffusion of StS models.

Over the last few years, these authors have developed a CFD solver of the Navier-Stokes equations, accelerated by GPUs, implementing a vibrationally resolved StS kinetics for the neutral air mixture. They demonstrated [2,3] that this approach to thermochemical non-equilibrium provides better results than the classical mT model [4] due to non-equilibrium vibrational distributions that, departing from the Boltzmann one, affect the global dissociation rates. In general, the shock stand-off distance predicted by the StS model is larger than the one provided by the mT model. This study was limited to freestream conditions with total enthalpy not large enough to generate plasma flows.

Recently, Guo et al. [5] showed analogous results by comparing the shock stand-off distance predicted by the StS and the mT models with values measured in nitrogen hypersonic flows past spheres [6]. Nevertheless, they employed a neutral kinetic model even if the translational temperature downstream of the bow shock was larger than 10000 K and ionization phenomena could be not negligible.

2 Methodology

In this scenario, an effort is ongoing to extend the StS model for neutral air mixture to the ionization regime. A first step in this direction has been made by implementing a kinetic model for weakly ionized nitrogen in order to study a titanium plume produced by a ns-pulsed laser in a nitrogen environment [7].
The model includes the nitrogen StS vibrational kinetics, i.e., vibration-vibration, vibration-translation by molecules and by atoms, and dissociation/recombination by molecules and by atoms.
For charged species the following processes have been considered: vibrationally induced ionization, associative ionization and resonant charge exchange.
Finally, electron impact causes atomic nitrogen ionization, N_2 dissociation, ionization and internal transitions.

This kinetic scheme is integrated in a cell-centered finite-volume solver of the Navier-Stokes equations. The solver employs an operator-splitting approach thus solving the frozen fluid dynamic equations first and then updating the solution by integrating the chemical source terms. Convective fluxes are discretized by using the Steger and Warming flux vector splitting with second order accuracy obtained by a MUSCL reconstruction of primitive variables. As regards diffusive terms, the Gauss theorem is employed to compute derivatives at face centers. Finally, a multi-step Runge-Kutta approach is employed for time integration. On the other hand, the stiffness of source terms is managed by a Gauss-Seidel iterative scheme.

3 Results

In this work the in-house solver is employed to investigate hypersonic nitrogen flows past spheres at enthalpies that could induce ionization by considering the experimental setup of Ref. [6]. The results in terms of shock stand-off distance, flow and wall quantities are compared to those provided by experiments [6] and numerical simulations [5].

4 Conclusion

The results represent a first application of a vibrationally-resolved model to nitrogen flows including charged species, to test the StS performances in ionization regimes. This study can be regarded as a first attempt to extend the CFD code capabilities to high-enthalpy Earth atmosphere re-entry in conditions of moon return.

Acknowledgements

G. Pascazio, F. Bonelli and D. Ninni were partially supported by the Italian Ministry of University and Research under the Programme “Department of Excellence” Legge 232/2016 (Grant No. CUP - D93C23000100001).
This work is part of the project NODES which has received funding from the MUR –M4C2 1.5 of PNRR funded by the European Union - NextGenerationEU (Grant agreement no. ECS00000036).
F. Bonelli, G. Pascazio, G. Colonna, A. Laricchiuta were funded by the European Union – Next Generation EU – Piano Nazionale Resistenza e Resilienza (PNRR), Missione 4 Componente C2 Investimento 1.1 – Decreto Direttoriale n. 1409 del 14/09/2022, Bando PRIN 2022 PNRR, CUP Master - D53D23018520001, CUP Politecnico di Bari - D53D23018520001, CUP CNR - B53D23027270001, Hypersonic Entry flow simulator for Access To Space – HEATS.

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