Atmospheric re-entry flow simulations in ionization regime

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The present work is aimed at supporting the design of space reusable vehicles, in line with new trends for a virtuous reduction of wasted materials, related to inexpensive access to space and its economical exploitation. Indeed, during atmospheric entry, a shock wave forms around the vehicle. The gas temperature jumps to very large values (> 10000 K) activating thermochemical processes that make the air a non-equilibrium weakly-ionized plasma. Although the gas temperature decreases as the flow approaches the vehicle, its value at the surface is still very high and a thermal protection system (TPS) is necessary to reduce the heat absorbed by the vehicles. Hence, a predictive code is a very desirable tool to reduce the costs of demanding experimental campaigns (ground test facilities or flight tests) and to optimize the TPS characteristics, such as its thickness and chemical nature, through fully virtual simulations of the heat load. Moreover, ground test facilities do not reproduce exactly the entry conditions because the high-speed flow is generated by initially heating the gas, which is already excited in the free flow. In this scenario, an accurate and efficient numerical software able to predict the thermo-fluid dynamic conditions around a vehicle traveling at hypersonic speed in the continuum regime has been developed[1]. The software, widely validated for the case of a neutral air mixture[2,3,4], is accurately extended to consider very high-energy re-entry, such as super-orbital or return from Moon exploration (e.g., Artemis I and II missions). The software employs an accurate State-to-State (StS) approach, considering 68 and 47 levels for the N_2 and the O_2 molecules, respectively, and only the ground state for the NO molecule and atomic species (N, O). The source terms of N_2 and O_2 vibrational level populations are computed according to vibrational-translational (VT) and vibrational-vibrational (VV) energy exchanges and dissociation/recombination (DR) or ladder-climbing (LC) processes due to collisions with atoms and molecules[1]. In the ionization regime, the extension includes processes like vibrationally induced ionization[5], associative ionization[6], resonant charge exchange[6], and nitrogen/oxygen radiative recombination[6], atomic nitrogen/oxygen ionization[7], N_2 and O_2 dissociation[8,9], ionization[10,11] and internal transitions[12]. Because the accuracy of the StS model requires a huge computational cost, a multi-GPU platform is employed utilizing an operator-splitting procedure to separate the Navier-Stokes fluid dynamic equations from the stiff chemical source terms[1], thus optimizing GPU performance. Consequently, in this work, we will evaluate the accuracy of the new model by comparing 2D simulation results with reference data, ensuring its reliability and effectiveness in predicting complex hypersonic entry conditions.

Acknowledgements

This work was funded by the European Union – Next Generation EU - Piano Nazionale Resistenza e Resilienza (PNRR), CUP - D53D23018520001, Hypersonic Entry flow simulator for Access To Space - HEATS and by the Italian Ministry of Education, University and Research under the Program Department of Excellence Legge 232/2016 (Grant No. CUP - D93C23000100001).

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