Direct Numerical Simulations of hypersonic turbulent boundary layers with thermochemical non-equilibrium effects

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High-temperature effects arising in hypersonic flights have a major impact on aerodynamic performance of a vehicle. In addition, transition from a laminar to a turbulent regime may occur in real flight conditions and represents a major concern. All these phenomena take place in the boundary layer developing on the vehicle fuselage. The accurate prediction of the two-way coupling of wall-bounded compressible turbulence and thermochemical processes triggered by the high temperature at stake is a subject partially unexplored.
In this work, the behavior of spatially evolving flat-plate boundary layers in hypersonic conditions is inspected by means of Direct Numerical Simulations (DNS), ensuring no uncertainties deriving from deficiencies of turbulence closure models. Adiabatic and wall-cooled configurations are investigated, from the laminar up to the fully turbulent regime. A five-species air mixture model is considered, with the final aim of studying the effect of finite-rate chemistry and vibrational relaxation on high compressible turbulent flows. It is found that chemical activity has an impact on transport properties, thermal fields and turbulent fluctuations, when the temperature is high enough to trigger significant molecular oxygen dissociation. In the case of slight decoupling between characteristic times of flow and thermochemistry, classical correlations of turbulent quantities are found to be in accordance with the results obtained for low-Mach gases. Turbulent transport is found to redistribute chemical species and to sustain thermal non-equilibrium. Velocity fluctuations have indeed a major role in the mixing of hot and cold gases, which lead to the excitation of all energetic modes and lags in the vibrational energy with respect to its equilibrium value; accordingly, thermal mean and fluctuating quantities are affected by this mechanism.

Keywords: hypersonic flows, boundary layers, compressible turbulence, high-temperature effects, thermochemical non-equilibrium.