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# COMPARISON OF KINETIC MODELS WITH ROTATIONAL DEGRRES OF FREEDOM FOR HYBRID METHODS

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Flow fields where localised rarefaction phenomena are relevant, occur in various engineering application such as supersonic/hypersonic and micro-flows. The methods that are commonly employed to simulate rarefied flows, i.e. DSMC and discrete-velocity methods for the Boltzmann equation, require high computational cost compared to continuum methods. This has motivated the development of hybrid techniques which restrict the use of the expensive non-continuum approaches to regions where significant non-equilibrium effects occur. Usually an hybrid technique couples two different simulation methods by means of an exchange of information between the parts of the domain where they are employed. This can be achieved using an overlap region where flow state variables or numerical fluxes are exchanged between the two models or employing a buffer region where the two models are blended at equation level. Recent works on multi-physics methods focused on rarefied high Mach flow can be found in [1, 2, 3]. All these works follow the principle defined above, while an alternative approach is presented in [4]. Indeed, the latter employs a finite-volume method where the numerical fluxes are based on the solution of the Shakhov model [5].
In the present work, a computational framework which includes methods for the kinetic Boltzmann equations, and has been successfully employed for different monoatomic cases [6], is improved and used to predict rarefied high speed flows applying both state-based and flux coupling. A novel aspect of the method is the concept behind the parallelisation of the computational load. Indeed, while in the literature, a split of either the physical space or the phase space among the processors is employed, the current framework allows both level of parallelisation at the same time.
For rarefied gas flows at high velocities it is necessary to take into account the excitation of the internal degrees of freedom; indeed, in these regime flows are characterised by large non-equilibrium regions with multiple temperatures (translational, rotational and vibrational temperature). For this reason, the framework has been recently developed with the addition of kinetic models for diatomic gases, presented in [4, 7, 8], which are based on the assumption that the fraction of collisions involving the excitation of the rotational degrees

of freedom is a given constant or a function of the flow temperatures. As first stage only the rotational degree of freedom has been taken into account and the present work will evaluate and compare these models for a number of different test of practical aerospace applications; i.e. normal shocks, single/double-cones, hollow flares, single/double-wedges and cylinders. Also the possibility of refining these approaches will be considered. Furthermore, kinetic models for diatomic gases are not yet well established in the context of the hybrid approaches and the coupling between a diatomic kinetic model and a Navier-Stokes solver still presents a number of challenging tasks. Among them, the evaluation of the different way of coupling and the need to ensure that the kinetic model recovers the correct transport properties in the continuum limit, where the coupling takes place, are also part of the present work.

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