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A hybrid continuum-particle solver for unsteady locally rarefied gas flows implemented in OpenFOAM®

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The simulation of unsteady rarefied gas flows remains a challenging task. Such problems have received more attention recently [1-3]. Even though significant progress has been made in this field, insurmountable difficulties may occur when the density levels are mixed throughout the domain, which is often the case in practice in the field of vacuum technology [4]. Structures like strong shocks as well as regions of stagnant gas may be found in the same flow domain. The conditions may be such that the Knudsen number spans in its whole range throughout the flow domain, from the hydrodynamic (viscous) up to the free molecular regime, and with large variations in time. Significant modelling errors as well as numerical difficulties may occur when the Navier-Stokes equations are used due to the inherent hypothesis of the gas as continuum. Even though the applicability of continuum-based methods may be consistently extended up to Kn=0.1 to include non-equilibrium phenomena [5], this may be insufficient for some problems. On the other hand, the computational cost of methods based on the Kinetic Theory of Gases, such as the Direct Simulation Monte-Carlo (DSMC) method [6], increases significantly as the Knudsen number decreases and/or the flow velocity drops. As a result, it may be unrealistic to apply them in the complete flow field for some applications. These limitations are significantly stricter for phenomena of unsteady nature in comparison with steady state flows.
In this presentation, we present a hybrid particle-continuum method implemented using the computational software library OpenFOAM®. This hybrid simulation algorithm uses the compressible Navier-Stokes equations and the DSMC method only in those spatial regions where they apply. The Navier-Stokes and DSMC regions are identified and then computationally connected through a Schwarz-type technique involving buffer cells. The mass conservative coupling of the two methods at their common interface is achieved by the generation of particles according to the local Maxwellian distribution in the buffer cells and the imposition of macroscopic mass fluxes obtained from DSMC in the continuum solver. Dynamic characteristics of the continuum-particle decomposition scheme allow a flexible and fully configurable determination of the two regions. Two different parellisation strategies (using MPI) have been examined. For the validation of the code, two unsteady problems, namely a shock tube and the unsteady flow through an opening orifice, have been considered and validation has been performed through a comparison with analytical and reference DSMC results.

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