An OpenFOAM-based open source multiphysics framework for modelling low temperature plasmas: Application to pin-to-plate and plasma jet discharges at atmospheric pressure

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We present the development and validation of an open source multiphysics framework for the simulation of non-equilibrium low temperature plasmas, implemented as an extension of the OpenFOAM finite volume library. The presented framework currently provides two plasma fluid solvers: (i) a detailed chemistry model that resolves multi-species plasma kinetics including electrons, ions, metastables, and excited species, and (ii) a reduced three-species model where all species are grouped into electrons, positive and negative ions.

The framework is fully integrated within the OpenFOAM environment, enabling the direct coupling of the plasma equations with the existing fluid dynamics and heat transport solvers. Charged species continuity equations are solved under the drift-diffusion approximation and are self-consistently coupled with Poisson's equation for the electric potential [1]. Electron transport and reaction rate coefficients are evaluated under either the Local Field Approximation (LFA) or the Local Mean Energy Approximation (LMEA) [2], allowing transport data to be expressed as functions of reduced electric field or mean electron energy, respectively. The transport and the reaction rate coefficients are provided to the model by a dedicated python-based interface that enables automated coupling with BOLSIG+ [3] Boltzmann equation solver. This utility retrieves or accepts user-defined cross-section datasets from the LXCat [4] database, downloads and executes BOLSIG+, parses the results, and generates OpenFOAM-compatible lookup tables. This workflow guarantees consistency between kinetic data and the plasma fluid model's coefficients and eliminates manual preprocessing steps.

The adoption of the OpenFOAM infrastructure enables the treatment of complex geometries, out of the box parallel execution on High Performance Computing (HPC) systems, flexible implementation of advanced plasma models by the user and direct communication with external plasma chemistry databases and dedicated plasma tools as plug-ins (see above). Its open source C++ architecture provides a modular and transparent environment where governing equations, chemistry models, boundary conditions, and discretization schemes can be implemented or extended according to the specific application. With regards to its use in HPC, parallel tests show near-linear strong scaling up to 300 cores, with efficiency above 80% up to 500 cores and a maximum speed-up of 8.8× relative to 50 cores.

In this current work, we benchmarked our code using two atmospheric pressure configurations: (i) a pin-to-plate discharge and (ii) a helium plasma jet (see figures). In the first case, we used a pin electrode with spherical tip powered by 3kV of DC voltage in atmospheric air, while the grounded plate was placed 3 mm away from pin. The results have been obtained using both the detailed chemistry and three-species solver, provided by the current framework. In the second case, the plasma jet reactor consists of a wire electrode, operated under pulsed applied voltage, with diameter of 0.125 mm, placed inside a quartz dielectric tube with inner and outer diameter of 1.2 and 2.5 mm, respectively. A dielectric target is placed at distance 30 mm from the tube's exit. The device operates using helium gas at 1 and 3 slm volumetric flow rates, corresponding to a laminar and turbulent jet flow, respectively. In this case, a detailed He/N_2/O_2 chemistry was implemented, consisting of 32 reactions with 16 species [5]. In both cases, stable discharge structures and physically consistent electric field distributions are obtained under the LFA closure. Overall, the proposed framework provides the plasma community with a transparent, extensible, and high-performance open source platform suitable for both fundamental studies and industrial applications.

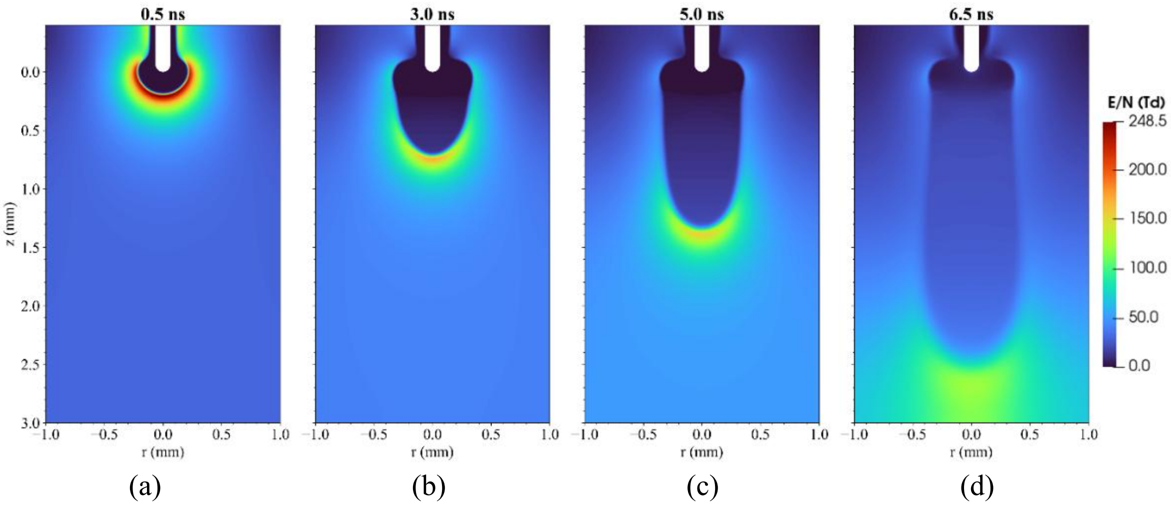

Fig. 1: Evolution of the reduced electric field E/N (Td) for a pin-to-plate configuration discharge at various time instants, at constant applied voltage of 3 kV.

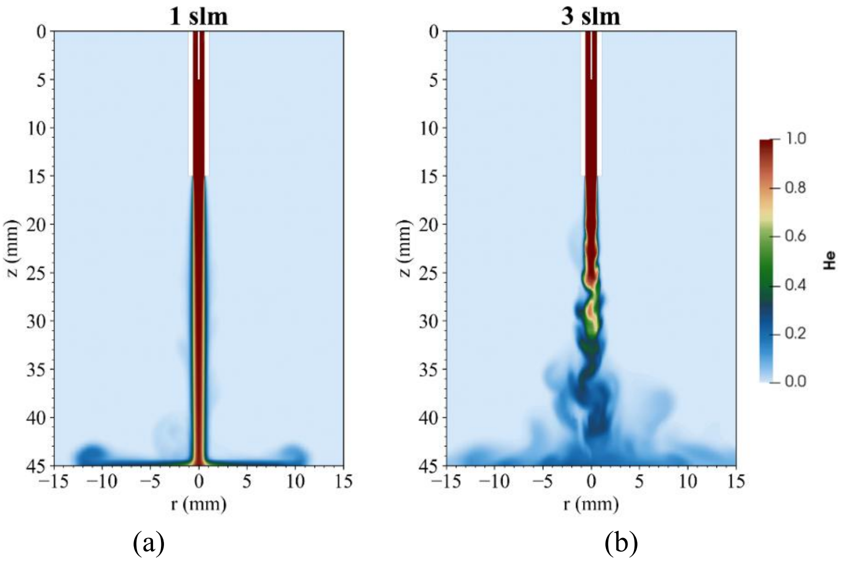

Fig. 2: Helium mass fraction of a helium plasma jet (APPJ) interacting with a dielectric target for volumetric flow rates (a) $\dot{Q}_{He} = 1$ slm and (b) $\dot{Q}_{He} = 3$ slm that correspond to a laminar and turbulent flow, respectively.

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