EsgeeTechnologies Inc.
Analysis and Design through High-Fidelity Simulations

# VizGlow Application Note

## Simulation of Coupled Plasma, Electromagnetic Wave and Gas Flow Physics in an Inductively Coupled Discharge

This note discusses the modeling of a flow-through Inductively Coupled Plasma (ICP) reactor with the *VizGlow Plasma Modeling Software Package* and provides an example of tightly coupled multi-physics simulations with the software. Discharge physics including multi-temperature, multi-species transport, and finite-rate plasma chemistry effects are coupled to electromagnetic wave phenomena driven by inductive coils, and a bulk fluid flow through an inlet/outlet configuration.

The geometry and mesh for theplasma discharge simulation are shown in Figure 1. The axisymmetric discharge comprises a dielectric tube of 10 cm inner diameter that is closed on the left with flow inlet along the axis (inlet diameter 1 cm) and an open inlet on the right. The axial length of the discharge is 20 cm. The dielectric tube thickness is 5 mm. Four coils are place just outside the dielectric window and are driven by radio-frequency (RF) currents to generate non-equilibrium plasma within the tube. The RF coil frequency is 13.56 MHz and the coils deliver a total of 300 W into the plasma. The first set of two coils on the left indicated by "coil1" are driven at a current phase lag of 180$^{o}$compared to the second set of coils "coil2". Furthermore the "coil2" is driven with 50% greater current than "coil1", i.e. at any instance $J_{coil2}$ = -1.5 $J_{coil1}$, where $J$ is the coil current. The radiation from the coils is confined on the outside by caging the discharge within a conductive boundary. A 100 sccm pure argon gas flow enters through the inlet boundary and exits from the outflow boundary where a 100 mTorr pressure is imposed.

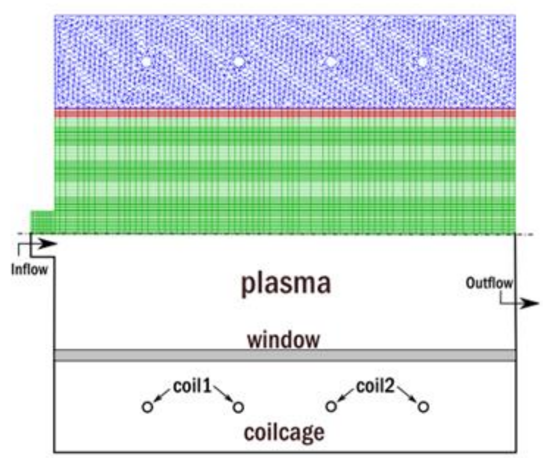


***Figure 1:*** **Geometry and computational mesh for Inductively Coupled Plasma (ICP) discharge.**

 

The above class of flow-through plasma discharges are encountered in applications such remote-plasma materials processing reactors and in plasma abatement of contaminants from a semiconductor process reactor.

The computational mesh contains a total of 11,530 cells, and is divided into 5 physical sub-domains: the coilcage, which houses coil pairs coil1 and coil2, an annular dielectric window and the plasma sub-domain that represents the region where the plasma is generated. *VizGlow* gives the user complete flexibility in choosing the type of mesh (triangles, quadrilaterals, or a mix of both in two-dimensional problems). The plasma subdomain is meshed with a pure rectangular mesh while the outer coilcage is meshed with triangles.

The ICP plasma is modeled using the quasi-neutral approximation; although *VizGlow* provides self-consistent plasma modeling option that is used to simulate other classes of plasma discharges (see other *VizGlow Application Notes* for examples).For ICP discharges, which produce relatively high charge densities, the plasma sheaths are typically thin and the quasi-neutral formulation provides is a reasonable approximation. The advantage of the quasi-neutral approximation is the large simulation time-steps and relatively low computational cost. The RF-driven coils generate an electromagnetic (EM) wave in the domain which is modeling using the frequency domain option; a time-domain EM wave option is also available in the *VizGlow* software. The gas flow is solved with the compressible Navier-Stokes solver that is also an option in the *VizGlow* software package.

The coupled model is solved to a steady-state which takes about 500 microseconds in "electron time". Figure 2 shows the convergence of the solution to a steady-state as judged by monitoring important plasma variables (e.g. potential, charge species density, radical densities, etc.) at specific locations "trace points" in the discharge volume. More than one location is often required to judge convergence. Note that this "trace point" check for simulation convergence is the safest approach to judge convergence. Other convergence tests such as monitoring of volume-averaged variables are known to trigger premature (false)

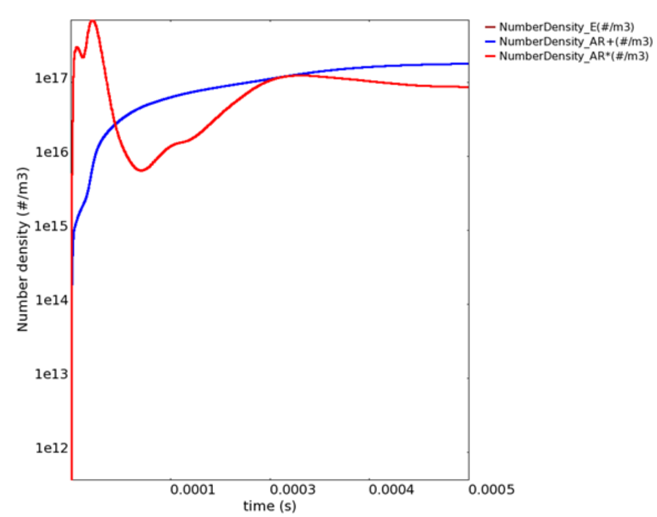


***Figure 2:*** **Transient profiles of important plasma parameters at a volume "trace point" in the discharge that shows convergence of solution to a steady state.**

steady-states much earlier in the simulation.The problem was solved on a single 2.66 GHz Intel® processor in ~ 4 hours of wall clock time.

The real and imaginary components of the EM wave field phasors are shown in Figure 3. The 180$^{o}$ phase difference between the two sets of RF coil currents is reflected in the wave structure shown in the figure. Since the problem is axisymmetric, the coils drive a pure azimuthally polarized wave in the domain (i.e. only the azimuthal component of the wave field is non-zero). The wave field magnitude on axis is zero for this polarization as shown in the figure.

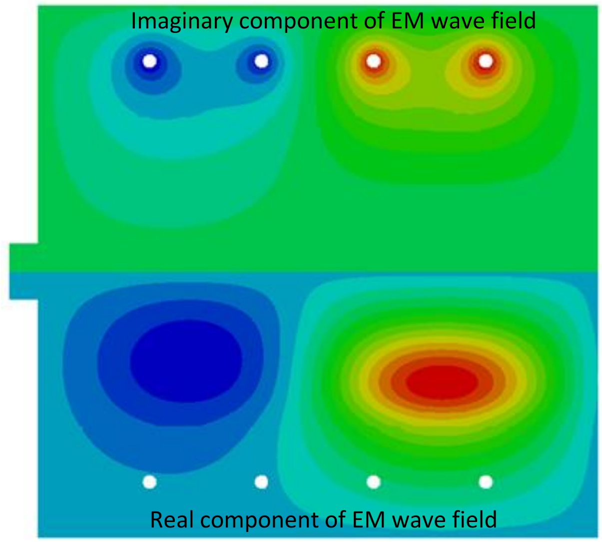


***Figure 3:*** **Imaginary (top panel) and real (bottom panel) components of EM wave field phasors in frequency domain.**

The top panel of Figure 4 shows the EM wave power deposited into the plasma (electrons) as a consequence of electron Joule heating determined by the EM wave field and the induced plasma currents. The wave power deposition is concentrated near the coils, adjacent to the dielectric tube wall with a peak power density of 1.3e6 W/m$^3$. This localized power deposition is a consequence of the plasma skin depth effect. Note that the power deposition is greater for the second set of "coil2" since the RF currents through this set of coils is greater than for set "coil1". The bottom panel of Figure 4 shows the electron density in the discharge. The peak electron density of ~6e17 m$^{-3}$ is localized on axis below the coil set "coil2". Note that location of peak electron density does not correspond to the location of peak EM wave power deposition. This is a consequence of non-local effects

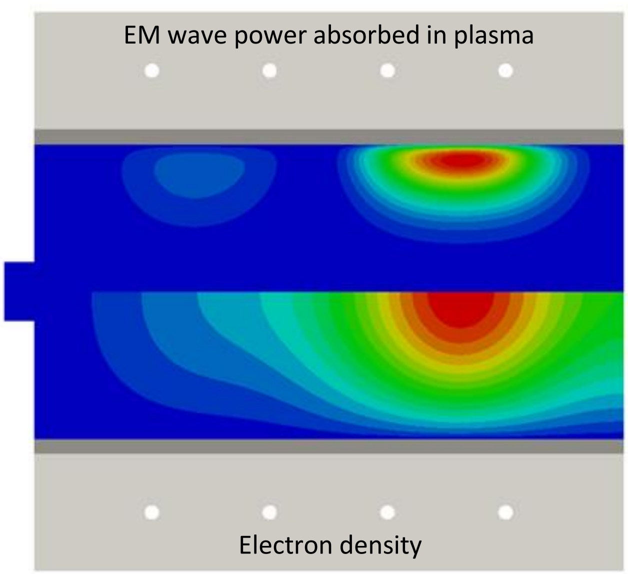


***Figure 4:*** **EM wave power deposition into plasma (top panel) and the electron density (bottom panel).**

at low pressures.

Finally, the argon metastable radical density contours are shown in the top panel of Figure 5. The radicals are produced with the much lower threshold energy than the charged species and hence significant densities of these radicals are observed under both sets of coils, the density below the second coil set "coil2" being higher. The peak metastable radical density shown is ~2e17 $m^{-3}$. The magnitude of the gas flow velocity is shown in the bottom panel of Figure 5. The gas velocities are highest at flow inlet nozzle location on axis and have a maximum velocity of 66 m/s. The flow expands and moves to towards the outflow boundary at much lower velocities. The plasma structure is largely unaffected by these flow velocities. For the imposed flow rate of the 100 sccm the flow velocities remain subsonic, although supersonic choked flow conditions are often encountered for high flow rates. For such higher flow conditions significant flow-induced modifications to the plasma structure, especially the neutral species, can occur because of flow.

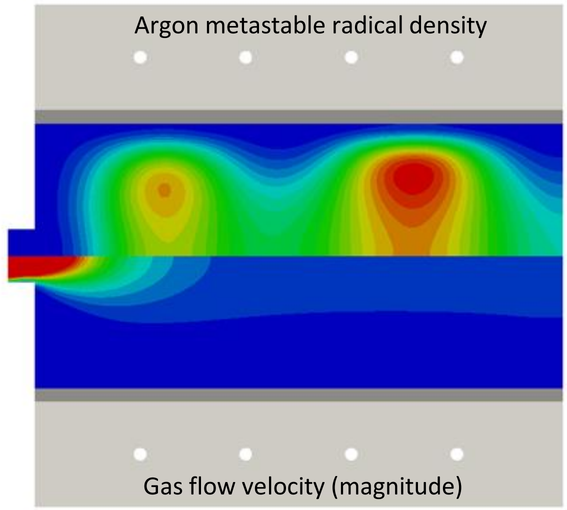


***Figure 5:*** **Argon metastable radical density (top panel) and the gas flow speed (bottom panel) in the reactor.**

In summary, the *VizGlow Plasma Modeling Software Package* provides a wide range of physical models and options that allows one to simulate complex coupled phenomena that are encountered in most plasma discharges. The *VizGlow Plasma Modeling Software Package* is part of the *Overviz* framework suite which provides an intuitive interface to set-up a project to be solved using *VizGlow*, manipulate multiple projects for parametric studies. *VizGlow* is provably fast, robust, and easy-to-use software and currently a leading industrial plasma simulation tool.

For further information on this application note or details about the *VizGlow* and other software packages you may contact us at

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