Self-Organized Plasma Patterns in DC Glow Discharges with Liquid Anodes: A Numerical Study

S. Das, S. Ahmadi, Y. Ling, T. Farouk
Department of Mechanical Engineering, University of South Carolina, Columbia, SC, USA

Abstract: This study presents a coupled Volume of Fluid (VOF)-plasma model to investigate self-organized patterns in DC glow discharges with liquid anode. The model resolves interface dynamics, plasma transport, chemical kinetics, and species transport at the interface. It provides insight into the coupling of surface patterns to perturbations occurring at the gas-liquid interface that result in interfacial flows. Simulations are conducted for a range of discharge currents to predict their role in the self-organized pattern formation.

1. Introduction

The underlying mechanism of self-organized pattern formation remains an area of active investigation. While experimental observations of such patterns have been reported, analytical and numerical studies are limited[1-3]. The experimental studies suggest electrohydrodynamic coupling and induced surface waves at the interface, the viscosity and ionic strength of the liquid, the presence of water vapor, and oxygen gas at the interface all play a role in forming these self-organized plasma patterns. The lack of a comprehensive understanding has prompted this modeling effort to elucidate the underlying physicochemical processes that drive and influence pattern formation.

2. Mathematical Model

An integrated volume of fluid (VOF)-plasma model is developed. The plasma model includes the conservation of charged species having a drift-diffusion flux assumption. Neutral species have both diffusion and convective transport resulting from fluid flow. A self-consistent Poisson's equation is solved in both gas and liquid to determine the electric field distribution. An electron energy conservation equation is considered to include possible non-local effects. The VOF model consists of a phase fraction equation and the momentum conservation equation. The plasma-liquid interface is treated with a phase indicator function α governed by:

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \mathbf{u}) = 0 \quad (1)$$

The momentum conservation includes contribution of surface tension, gravitational and electric forces:

$$\frac{\partial \rho \boldsymbol{U}}{\partial t} + \nabla . (\rho \boldsymbol{U}\boldsymbol{U}) = -\nabla p + [\nabla . (\mu \nabla \boldsymbol{U}) + \nabla \boldsymbol{U} . \nabla \mu] + \boldsymbol{F} + \rho g + \int_{\Gamma} \sigma \kappa \delta (\boldsymbol{x} - \boldsymbol{x}_s) d\Gamma(\boldsymbol{x}_s) \quad (2)$$

3. Results and Discussion

The problem geometry (**Fig. 1)** comprises an axisymmetric domain with a solid cathode at the top and a liquid water anode at the bottom. The cathode, having a micro-hollow nozzle, flows helium gas at a controlled flow rate. A significant focus is placed on the plasma-liquid interface, where charge transfer processes are essential for accurately simulating the system's dynamics and the formation of self-organized patterns.

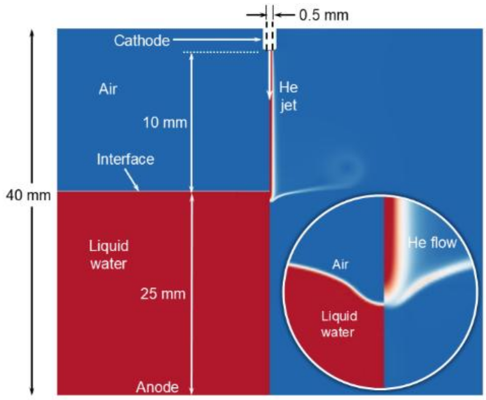

Fig. 1: The problem geometry with dimension (left half), simulated interface dynamics due to gaseous flow impingement at the gas-liquid interface (right half)

The permittivity difference at the gas-liquid interface results in a higher electric field at the interface. The locally enhanced electric field and associated electrical forces amplify the interface instability and induce non-dispersive waves. The wave patterns also contribute to further local electric field enhancements. Charged species formed near the interface also get transported across the interface to the liquid phase. The charged species however penetrate only a limited distance into the liquid. As discharge current increases, the transport of these species becomes more pronounced, leading to enhanced surface undulations and instabilities at the interface.

4. Concluding Remarks

This VOF-based model provides a framework for investigating self-organized pattern formation in DC glow discharges with liquid anodes. By incorporating key processes at the plasma-liquid interface, we can simulate the complex interplay between electric forces and fluid dynamics that leads to self-organized pattern formation.

Acknowledgement

This research has been supported by the Department of Energy under Grant No. DE-SC0025624.

References

[1] Dubrovski O, Yang J, Veloso F, et al. *Physical Review Letters* 2024 **133** 105301
[2] Almeida P G C, Benilov M S and Faria M J *Plasma Sources Science and Technology* 2010 **19** 025019
[3] Trelles J P *Plasma Sources Science and Technology* 2013 **22** 025017