Exploring Plasma-Assisted Combustion in a Jet Stirred Reactor Using Particle-In-Cell Simulation

Carrie Lai, Shihyao Huang, Paul D. Ronney*
Department of Aerospace and Mechanical Engineering
University of Southern California, Los Angeles, CA 90089
Contact info: yichenla@usc.edu

USC Viterbi School of Engineering

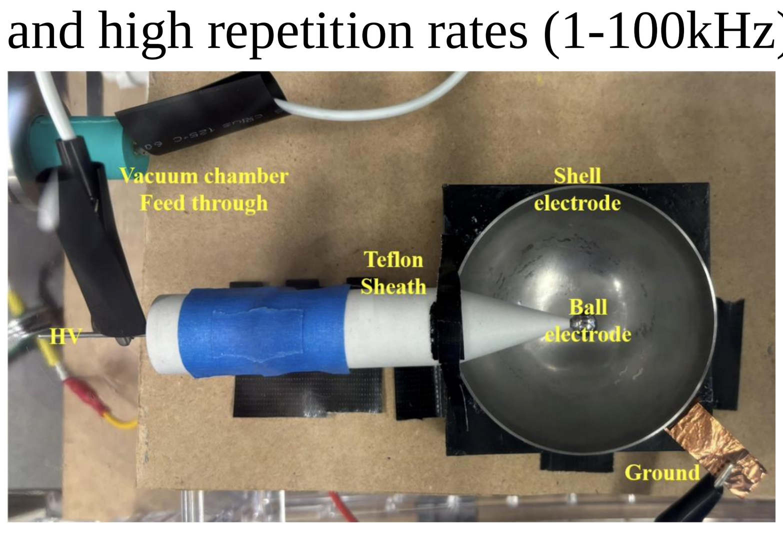
Motivation and Objective

- This research aims to analyze plasma distribution in a jet-stirred plasma reactor by using Particle-in-Cell (PIC) simulations
- Unlike fluid-based plasma model, PIC approach can capture individual particle motion, charge separation, sheath dynamics and non-equilibrium plasma phenomena
- Accurate plasma modeling is essential for understanding electric field distribution and charged particle transport, while also exploring pulse-duration optimization to better align with particle transit dynamics, potentially enhancing ionization efficiency and plasma uniformity

Introduction

What is a plasma/jet-stirred reactor (JSR)?

- A Jet-Stirred Reactor (JSR) is designed to create a well-mixed reaction environment by ensuring uniform distribution of reactive species. The Concentric Inlet and Outlet (CIAO) geometry minimizes directional flow biases by placing the inlet and outlet at the same location [1]
- This study uses a spherical CIAOJSR that is shown in figure (a). The non-thermal plasma is generated using Nanosecond Repetitively Pulsed Discharges (NRPD) with short discharge durations (~10-100ns) and high repetition rates (1-100kHz)



(a) The setup consists of a ball electrode (inner) and a shell electrode (outer) with 8 mm inner diameter and 3-inch outer diameter

Why Non-Thermal Plasma (NTP)? Why Nanosecond Pulse (20kV for 10ns)?

- NTP has higher electron and ion temperatures relative to gas temperature, producing energetic electrons and excited species that initiate unique kinetic pathways and enhance reaction efficiency
- The short-duration, high-voltage nanosecond pulse creates rapid, high-energy ionization events, efficiently producing highly reactive species while preventing excessive gas heating losses

Methodology

What is Particle-in-Cell (PIC) Method?

- Particle-in-cell method treats plasma as a collection of individual charged particles, which are pushed through phase space according to Newton's laws under electromagnetic fields. The fields are updated on a grid using Maxwell equations

1D Model

- A 20kV pulse is applied to the right boundary for 10ns, while the left boundary remains grounded (0V), capturing transient sheath formation, charge separation, and plasma oscillations
- Plasma Species: 5000 superparticles for electrons and ions (Maxwellian distribution)
- Time Evolution: Electric fields accelerate plasma species, leading to transient plasma behavior and output the results of electron every 0.1ns and ion distribution per 10ns

2D Model

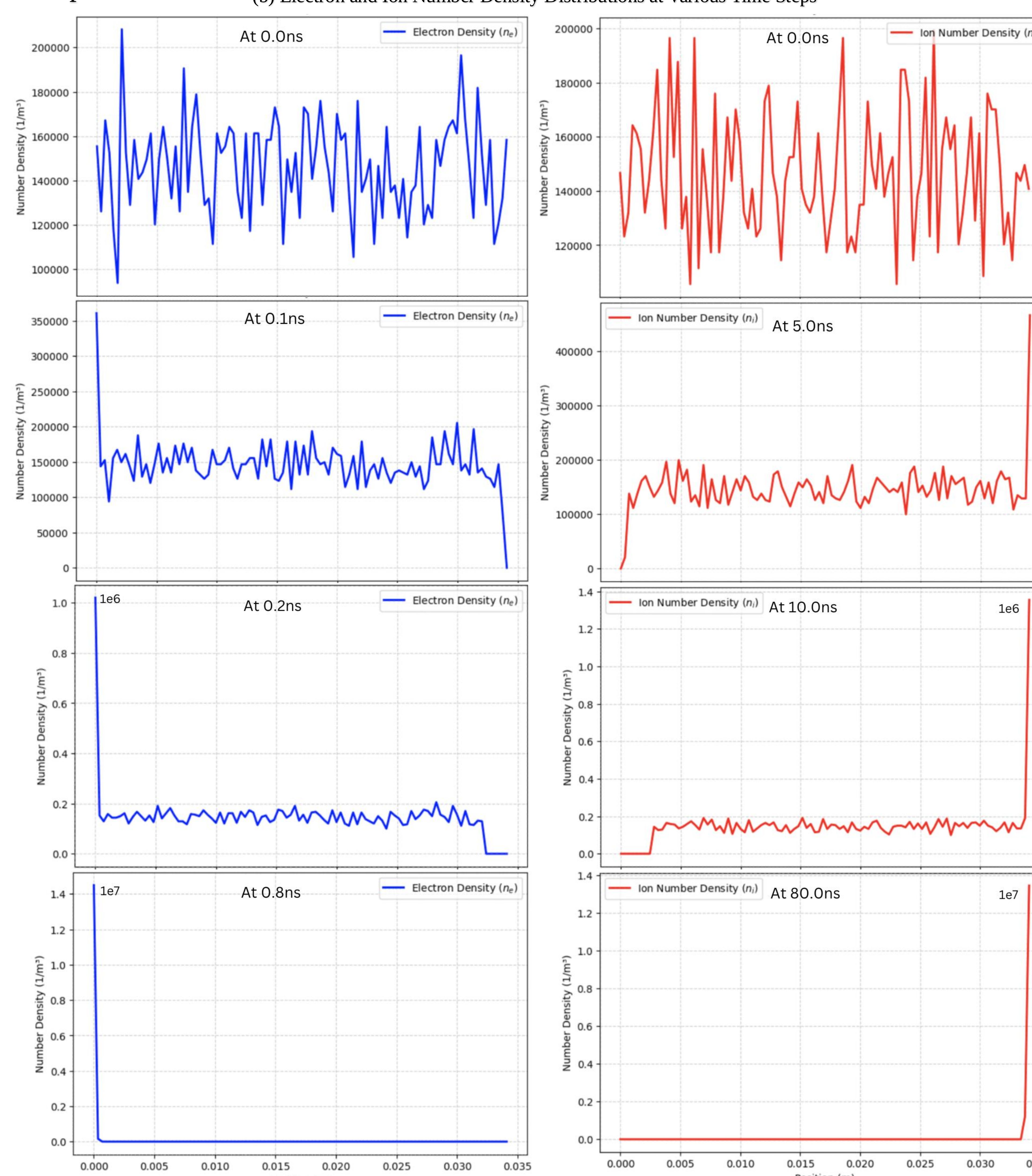
- Starfish is a 2D plasma and gas simulation code written in JAVA [2]
- The simulation domain is structured using 2D Cartesian or body-fitted stretched meshes, allowing for accurate representation of complex geometries
- Reactor boundaries and internal components are defined using linear and cubic spline approximations to capture the geometry of the spherical jet-stirred plasma reactor

Results and Discussion

Electron and Ion Number Density Evolution – Sheath Formation (1D)

- At early times (0.1ns – 0.8ns), most of the electrons have already reached the grounded boundary due to their significantly lower mass
- By 10ns (pulse end), ions remain distributed throughout the domain, with some accumulation near the right boundary
- Post pulse (80ns), most of the ions drifted and lead to further charge separation

(b) Electron and Ion Number Density Distributions at Various Time Steps



Charge Separation and Plasma Oscillations Post-pulse (1D)

- Delayed ion movement shows that plasma responds differently on different time scales
- Charge separation lasting longer than pulse suggests that plasma effects continue even after the external field is removed
- Possible oscillations may develop as the system relaxes back to equilibrium
- A potential optimization strategy: Adjust the pulse duration to better match ion transit dynamic. If the pulse duration is well-tuned, ionization efficiency could improve, and the plasma distribution become more homogeneous

Electric Potential and Field Distribution over Time (2D)

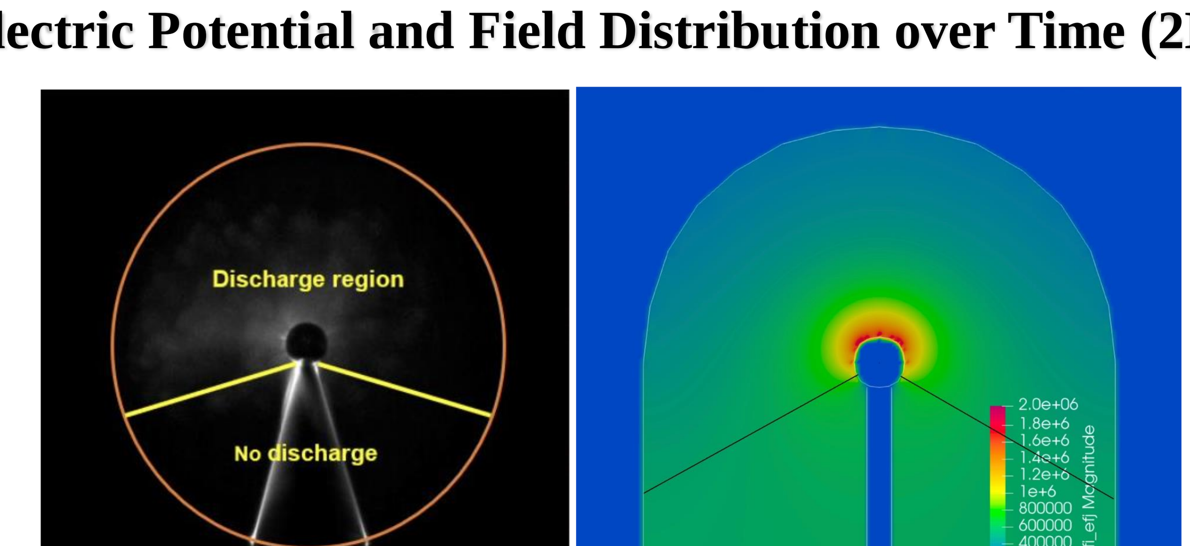


Figure (c) was taken by the high-speed camera to identify discharge region during the experiment

Figure (d) demonstrated the electric field distribution simulated by Starfish

[1] Abbasali A. Davani and Paul D. Ronney. "A jet-stirred chamber for turbulent combustion experiments". In: Combustion and Flame 185 (2017), pp. 117–128

[2] L. Brieda and M. Keidar, "Development of the Starfish Plasma Simulation Code and Update on Multiscale Modeling Hall Thrusters", in AIAA Joint Propulsion Conference, Atlanta, GA, 2012