Analyzing Nozzle-Plume Characteristics of Hall Effect Thrusters by PIC Method

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***Abstract*—The Hall Effect Thruster (HET) is a type of electric propulsion system that utilizes the Hall Effect to generate plasma for producing thrust with a high exhaust velocity. They offer a more efficient and low-waste alternative to traditional propulsion systems. HETs are employed for controlling the orientation, positioning, and orbital transfer of spacecraft. In addition to their use in Earth-orbit missions by agencies such as ISRO, CMSA, and SpaceX, HETs have also been deployed in deep-space missions, such as NASA’s exploration of the asteroid belt object 16 Psyche in 2023, demonstrating their capability beyond Earth orbit. An HETs plume consists of ionized and un-ionized particles, each having significant impact on spacecraft systems and produced thrust. Modifying plume characteristics (by altering the nozzle) results in vastly different outputs for each variation, and hence can be optimized. Previously, this relationship has been analyzed by MHD (Magnetohydrodynamic) simulations or GKM (Gas-Kinetic Model) simulations representing two extremes in approach. This work aims to establish a relation between the nozzle-plume characteristics and the thrust output by means of a Particle-In-Cell (PIC) method. The simulations are conducted using picFoam, ‘a fully kinetic electrostatic Particle-in-Cell (PIC) solver, including Monte Carlo Collisions (MCC), for non-equilibrium plasma research in the open-source framework of OpenFOAM’.**

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# **1.** Introduction

The Hall Effect Thruster is an electric propulsion device deriving its name from the Hall Effect, discovered in 1879 by Edwin Hall. It represents a compelling and high-potential research area in aerospace engineering due to its wide range of practical applications.

*Working*

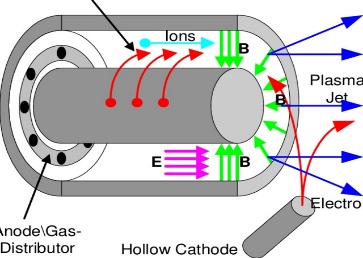
**The Hall Effect Thruster (or HET) is a sophisticated and elegant way to produce thrust by means of electric propulsion.

Figure 1. Schematic of a Hall effect Thruster

The HET is a conjunction of two of the annular channels as shown in Fig. 1.  
Neutral gas molecules enter the channel via the back boundary, which serves the purpose of an anode as well. Electrons enter the channel near the exit boundary via a hollow cathode. Due to the presence of a radial magnetic field, the electrons experience the Lorentz force which forces them into a circular current. This current is known as the Hall current. Some electrons experience the coulomb force which pulls them towards the anode. They collide with the neutral gas particles and ionize them. The resultant electrons flow into the anode and connect back to the cathode, completing the circuit. The positively charged ions are attracted towards the circulating electrons, experiencing an acceleration. They are subsequently ejected out of the thruster. In order to prevent these ions from re-entering the thruster, thus cancelling out the generated thrust, they must be neutralized. The aforementioned hollow cathode provides electrons to the ion plume, hence neutralizing them, preventing re-entry.

*Research Motivation*

Traditionally, the magnetic field within an HET is used exclusively for producing the Hall current, leading the HET to be dubbed an electrostatic thruster, rather than electromagnetic one. It, however, begs the question regarding how exactly the magnetic field can influence the output thrust, which is what this study aims to explore via simulations.

*Simulating the Thruster*

In order to carry out these simulations, the Particle-In-Cell (PIC) Method was deemed appropriate, based on similar literature regarding the simulation of an HET. It is a method implemented in cases of near zero collision environments. It corresponds to a Knudsen number . When employed with the Monte-Carlo-Method (MCC), which adds an interaction factor between particles, we end up at a slightly modified PIC Method. Here, the Knudsen number falls in the range of , bringing it closer to a transition or slip-flow regime instead of being entirely molecular.   
This study simulates the HET using picFoam, an OpenFOAM based PIC solver in order to establish the effects of changing the magnetic nozzle characteristics on the output thrust. PicFoam allows for the implementation of various collision models, of which this paper implements the ElectronNeutralCollisionModel and CoulombCollisionModel, the reasoning for which is elaborated on in Section 2.

# 2. Analysis of Relevant Parameters

In order to successfully simulate a magnetic nozzle within an HET thruster, it is important to analyze certain key physical parameters.

*Knudsen Number*

The Knudsen number in the purview of plasma physics, is used to establish the flow behavior of plasma, with one extreme indicating continuum flow and another indicating collision-free particulate flow. It is defined as

With reference to [7], it can be written as

By rearranged per the desired , we can derive the number density, which is otherwise not specific across different HET models.

*Collision Types*

Within an HET, the primary type of collision that takes place is that between electrons and neutral particles in order to produce ions. To simulate these collisions, picFoam has the ElectronNeutralCollisionModel for electron-neutral interaction and the CoulombCollisionModel for the electric effects of these collisions.

*ElectronNeutralCollisionModel­*—This collision model utilizes the xyz.

*IonNeutralCollisionModel*—The model utilizes the Coulomb force in order to establish the electric interactions between the particles

*Channel’s primary shape*

As discussed in Section 1, the HET is of a cylindrical shape. Hence, the relevant parameters are the radius and the length.

Modelling the thruster after the Psyche mission HET, we get the values of

**Table 1.** Dimensions of Channel

|  |  |
| --- | --- |
| Channel length (cm) | 56 |
| Channel inner diameter (cm) | 32 |
| Channel outer diameter (cm) | 35 |

*Boundary Conditions*

The channel being cylindrical has 3 boundaries, the back boundary from which neutral particles enter, the annular channel boundary and the exit boundary, near which the magnetic field is established. Along with the actual physical boundaries, we need to take into account the boundary patches of the anode and cathode.

*Anode* *—*A simple inlet type boundary with a specified inlet velocity for the neutral gases. For electrons, the anode functions as an absorbing boundary.

*Channel boundary—*The channel boundary behaves differently for different types of particles. Electrons suffer secondary emission upon colliding with the channel boundary. Neutral gas particles go through diffuse reflection, where they experience a delay between collision and subsequent remission. Ions collide and get absorbed into the channel wall.

*Exit* *—*The particles must all leave and hence a simple transmission boundary is to be set up.

*Cathode* *—* PicFoam provides an injection model and a cathode emission model. Utilizing both with the necessary current, energy and direction should suffice.

For the purposes of the simulation, the neutralization of ionized particles will be assumed rather than implemented by forcing a transmit condition on the exit boundary.

3. Numerical Method

The simulation is based upon the basic Maxwellian equations (3-6), the Coulomb force (7), the Lorentz Force (8).

For the collisions aspect, picFoam uses different equations for different models.

*ElectronNeutralCollisionModel*The model utilizes

in order to do xyz.

# 4. Simulation Parameters

From the above discussion, the simulation conditions have been determined to be

**Table 2.** Simulation Conditions

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Magnetic field strength, B |  |
| Particle injection velocity |  |
|  |  |
|  |  |
|  |  |

The boundary conditions, as discussed in section 2, have been implemented as

**Table 3.** Boundary Conditions

|  |  |
| --- | --- |
| Boundary | Type |
|  |  |
|  |  |
|  |  |
|  |  |
|  |  |

# 5. Results and Discussion

Submission Deadlines

Submission due dates and deadlines are given in Table 1.

**Table 1.** Summary of Due Dates

|  |  |
| --- | --- |
| **Event** | **Due Date** |
| Abstract Due  **Draft** Paper Deadline  **Final** Paper Deadline  IEEE Copyright Form Due | July 1, 2025  October 3, 2025  January 9, 2026  January 9, 2026 |

You may upload multiple paper versions until Jan 9.

Abstract

An abstract describing the planned content of the paper must be submitted to the conference website. Following review and approval of your abstract, you may submit a paper.

Review Paper

The paper submitted for review must be a complete, fully formatted, and proofread manuscript, ready for publication. **NO** paper submitted after the deadline will be admitted to the conference.

If you submit more than one version of your paper for review, the website displays the latest version.

Final Paper

Following receipt of review comments, make appropriate revisions to the paper and submit your final version for publication.

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International Traffic in Arms Regulations (ITAR) controls the export and import of defense articles and defense services on the United States Munitions List (USML) [2].

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The Conference website is a public venue. Authors must obtain any needed clearances for their work to be freely published by the IEEE. Submission of your paper implies that it has received the proper clearances from your company, affiliation, or organization.

Submission to the [www.aeroconf.org](http://www.aeroconf.org) website

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# 6. Conclusion

Prepare a presentation to be delivered at the conference, using Microsoft PowerPoint or similar software that summarizes the major concepts of your paper.

*Allotted Time*

Time allotted for presentations is 18 minutes with an additional 5 minutes for questions. The time limit will be strictly enforced.

*Projection*

A projector and screen will be set up in each meeting room. Bring your slide set on a laptop to plug in to the projector. Also bring a copy of your presentation on a USB drive, in case your session chair chooses to consolidate all the presentations on a single laptop before the session starts.

*Presentation*

Tips on giving the presentation will be sent to registered authors in advance of the conference.

*Special Displays*

Displays of hardware or software an author believes to be of wide interest to conference attendees may be set up with permission of the Technical Program Committee and by special arrangement with the Conference Manager.

# Appendices

# A. More Information

This is the first appendix.If you have only one appendix, title this section “Appendix.”

# B. Summary of Format Requirements

*Paper size:* 8.5 x 11 inch

*Number of pages*: 6–20

*Margins*

Top and bottom: 0.75 inch

Left and right: 0.75 inch

*Columns*

Number of columns: 2

Space between: 0.25 inch

*Font*: Times Roman 10 pt regular, unless otherwise noted

*Text*

Line spacing: Single

Space after paragraph: 10 pt

Paragraph indent: None

Justification: Left & right

*Title*

20 pt bold, upper & lower case, initial caps on all words except articles, conjunctions and prepositions

Centered on the full-page width

Maximum length 100 characters

*Author(s)*

10 pt bold, upper and lower case

Centered on the full-page width

Name, affiliation, postal address, phone number, and e-mail

No degrees or titles, except military rank

*Abstract:* 9 pt bold

*Acronyms*: Define acronyms on first usage

*Page numbers*: Bottom center of each page, including first page

*Footnotes*: 8 pt regular

*Headings*

Spacing before major or subheadings: Double space

Spacing after major or subheadings: 1.5 space

Major headings: 12 pt small caps, bold, centered

Subheadings: 10 pt italic, flush left, separate line

Subsubheadings: 10 pt italic, run into paragraph with em dash

*Headers and Footers*

No headers

Footers used for page numbers and Copyright notice on page 1

*Equations*

Centered in column

Equation numbers in parentheses, flush right

Include special fonts with the paper.

*Figures and Tables*

Captions and titles: 10 pt bold

Figure captions: Centered directly below figures

Table titles: Centered directly above tables

Scanned images: 300 dpi JPEG

*References*

List references at end of paper.

References numbers: In square brackets [ ]

*Biography*

Each author’s name in bold italic

Brief biography in 10 pt italic

Photo of each author

# Acknowledgements

Project sponsors may be acknowledged in this section. If AI was used in the preparation of the paper, the acknowledgement should be included here.

# References

[1] IEEE Aerospace Conference Web site: [www.aeroconf.org](http://www.aeroconf.org)

[2] U.S. Munitions List, sections 38 and 47(7) of the Arms Export Control Act (22 U.S.C. 2778 and 2794(7).

# Biography

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| --- |
| Richard Mattingly.jpeg***Richard Mattingly*** *received a B.S. in Engineering from California State University, Los Angeles in 1970. Recently retired, he had been with JPL for more than 40 years. He has been studying Mars Sample Return (MSR) and future missions in the Mars Exploration Program Office at JPL. Prior to MEP, he supervised a systems engineering group for JPL’s projects implemented in partnership with industry. He has also managed systems engineering groups for instrument and payload development and has been involved in the formulation and development of numerous planetary and Earth-orbiting spacecraft and payloads. His career started with systems integration on the Apollo program for North American Rockwell.* |
| ***Erica Deionno*** *received her B.S. and PhD degrees in chemistry from UCLA. She is currently a Principal Director in the Defense Systems Group at the Aerospace Corporation. During her 17 years at Aerospace, she has held numerous roles, including several lead positions in Aerospace’s Innovation office. She also spent over 10 years conducting research in the Laboratories at Aerospace, where her work included radiation testing and modeling of emerging resistive RAM technologies and modeling space solar cell degradation.* |