WP17 – Towards Dynamic Operation of RF Plasma Sources Using Hardware-in-the-Loop Feedback Control

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Abstract

The goal of this work is to lay the foundation for a dynamic control of RF-driven plasma source to improve operational efficiency by utilizing a hardware-in-the-loop active control of device operating conditions.

Introduction

Motivation:

RF-driven plasmas are an attractive option for various technologies, including molecular propellants used for electric propulsion (EP). Our goal is to improve the ionization efficiency through a non-steady state operation.

Setup

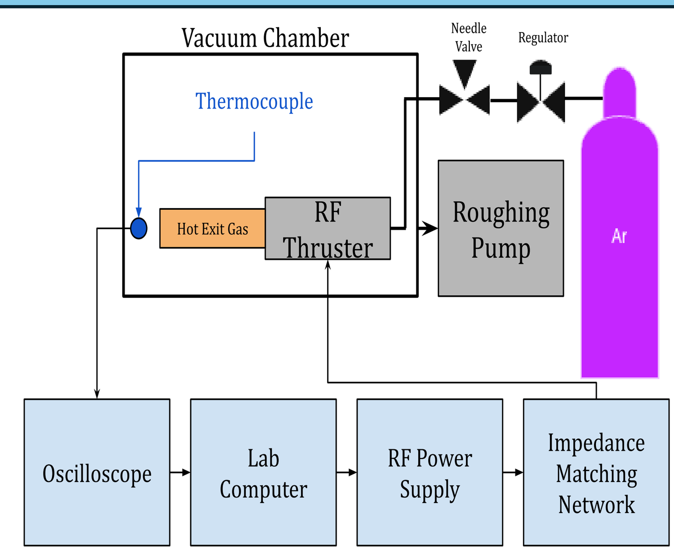
The experiment utilizes a legacy Cal Poly "Pocket Rocket" thruster [1]. A Langmuir probe and a thermocouple is used to characterize thruster condition. Data is acquired using an oscilloscope connected to a computer, which then uses a control algorithm to adjust mass flow and input power supply power.

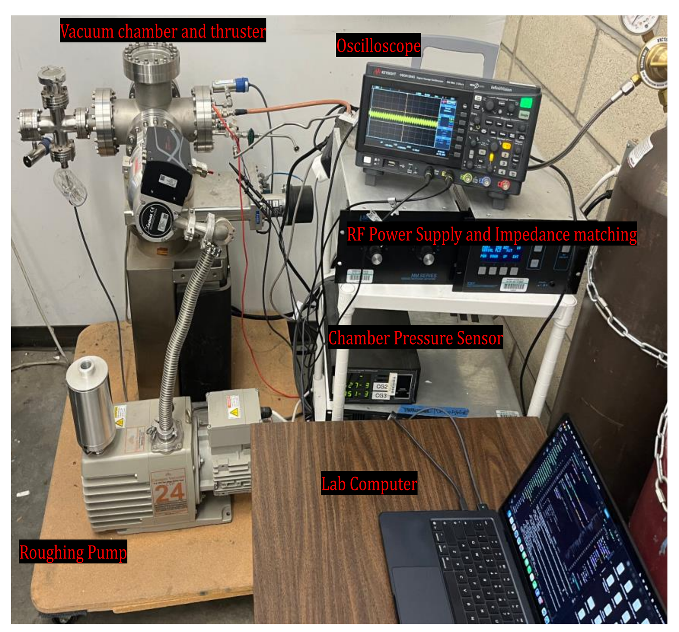
Control Hardware:

- Seren r310 RF Power Supply and manual impedence matching network
- Mass flow controller

Sensors:

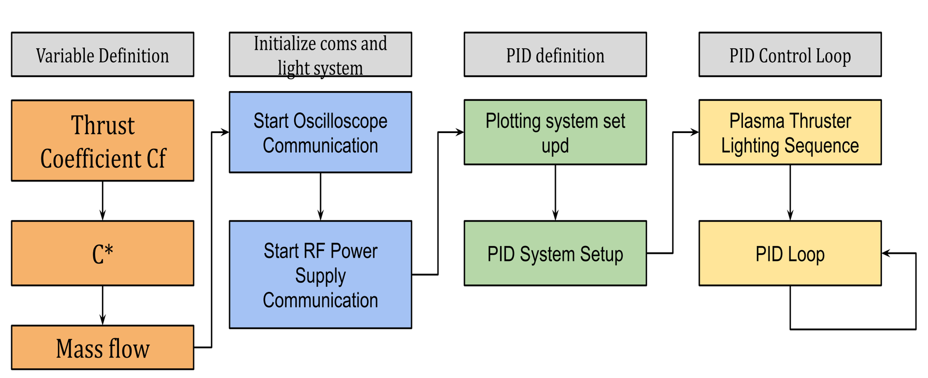
- A thermocouple measuring stagnation temperature
- Single Langmuir probe measuring ion-saturation current



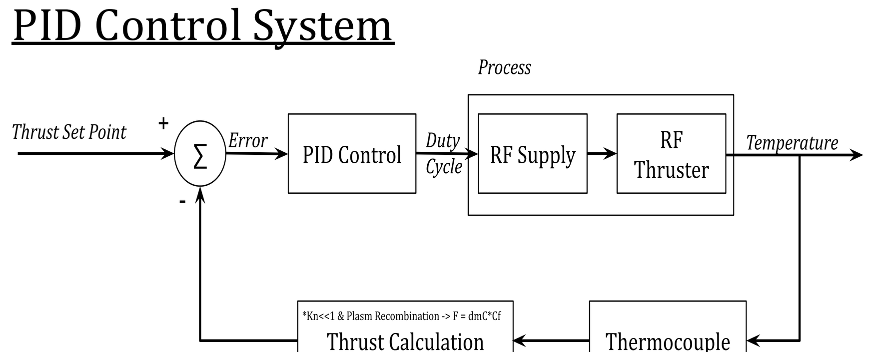


Control System Setup

Block Diagram



PID Control System



Controller code:

System is controlled via a lab computer running a script in Python. The block diagram to the left depicts the steps in code taken to initialize the system and run the loop. Initialization establishes communication with the oscilloscope and RF supply over RS232 interface. The RF supply is then commanded to deliver 30 W into the gas to initiate plasma heating. Finally, the supply is set to 25W and the PID controller modulates its duty cycle to reach the desired set point, such as derived thrust.

PID use in system design:

To throttle the thruster. A basic PID controller would use the difference between the thrust set-point and the measured thrust to adjust the duty cycle of the RF power supply

Methodology

Experimental Thermal Throttle Method

System Analysis Assumptions:

Two base assumptions apply and have been validated with sensor data taken by Alec Henken [2] of thrust at similar pressures and power into the system. In this model is it assumed that the majority of the cold non thermal argon plasma has recombined by the time that it has reached the end of the thruster nozzle. Furthermore, it can be shown at the operating temperature and pressure, the Knudsen number is much less than one meaning that the gas under reference can be analyzed as a continuum. Both observations allow us to accurately estimate the thrust with compressible gas dynamics.

Thermal Throttle Theory:

Given that the thrust is proportional to the velocity and therefore to the thermal energy of the system, researchers could obtain fine control over the thrust by actively modulating the duty cycle of the RF supply between 35%(when the plasma would collapse) and 100%.

Measurement and Control Methodology:

Desired operational state, such as thrust, is specified as an operating point for the control algorithm. The computer queries an oscilloscope to read the voltage across the thermocouple, converts that voltage to a temperature, and calculates the corresponding thrust. This measured thrust is then compared to the set point. The PID controller then interprets the error between the setpoint and measured thrust and determines a duty cycle to send to the RF power supply, which adjusts the

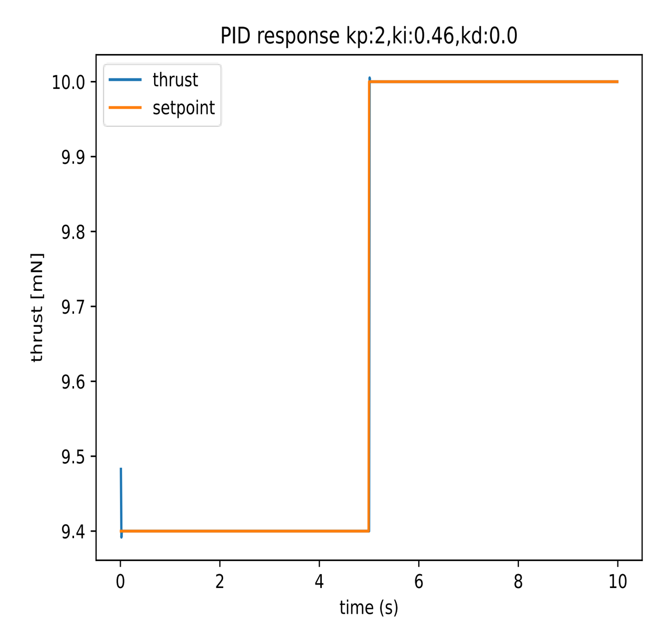
Least Squares Regression and System Simulation

System Model:

To find a starting place to choose the PID gains, researchers assumed that the plasma temperature response to power was linear.

System Response:

In the basic linear model, it can be seen that the rise time, settling time, and overshoot are all extremely small. It will be seen in the results that the system, with the gains chosen via the linear model, responds similarly to inputs in rise time; however, it has a much severe overshoot and settling time

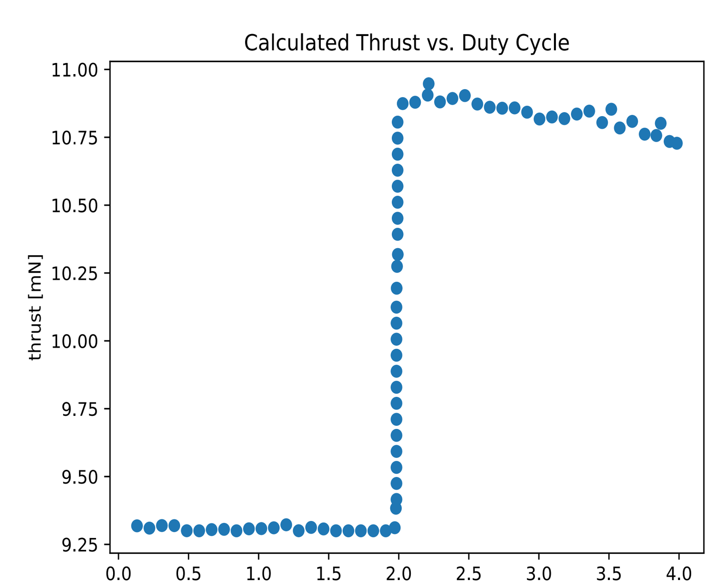


Results

9.3mN to 10.6mN Setpoint Command over 4s

HIL Performance:

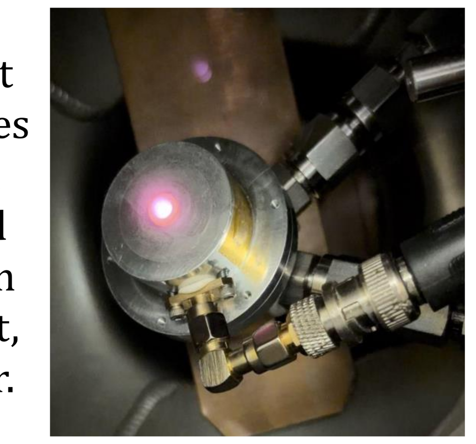
At the chosen gains, the system responds quickly to changes in duty cycle, as can be seen by the short rise time. When commanded to set the thrust to 10.75 mN, the control system suffers a much greater overshoot and a longer settling time. This is most likely caused by an improperly tuned D gain, given that the linear model used to determine the gains did not capture the thermal momentum of the plasma with the input of power.

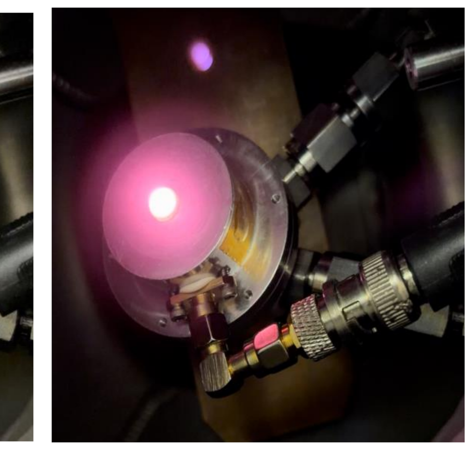


Throttling

Thrust Modulation:

It can be seen in the picture that there is a pink glow of argon in the chamber. Given that argon plasma glows violet-purple, this implies that very little plasma is being produced and that, instead, much of the gas is being excited enough to emit a photon but not to release an electron. Seen in the photo further to the left, the glow increases with the amount of power.

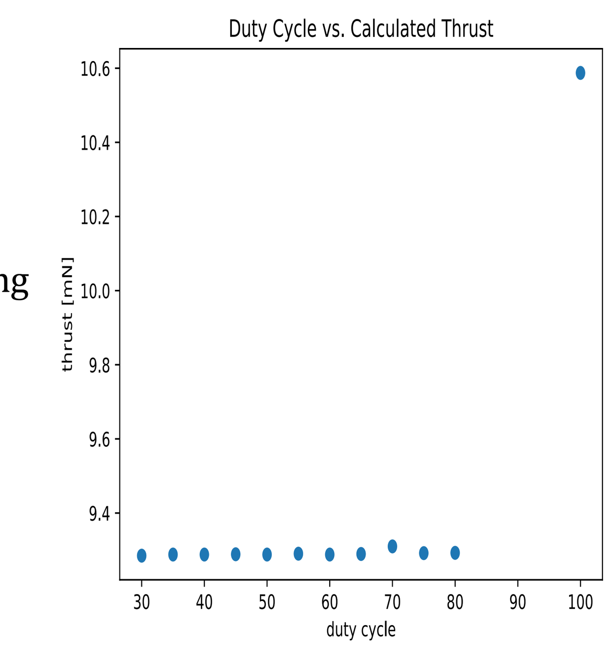




Throttling Methods

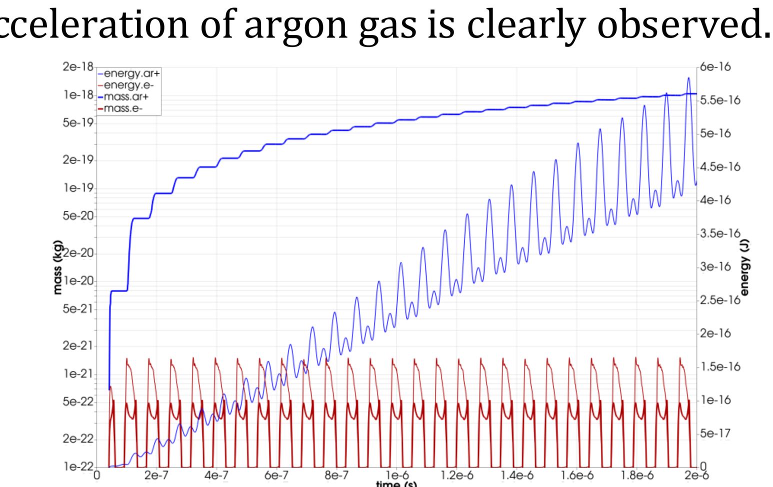
Throttling via duty cycle:

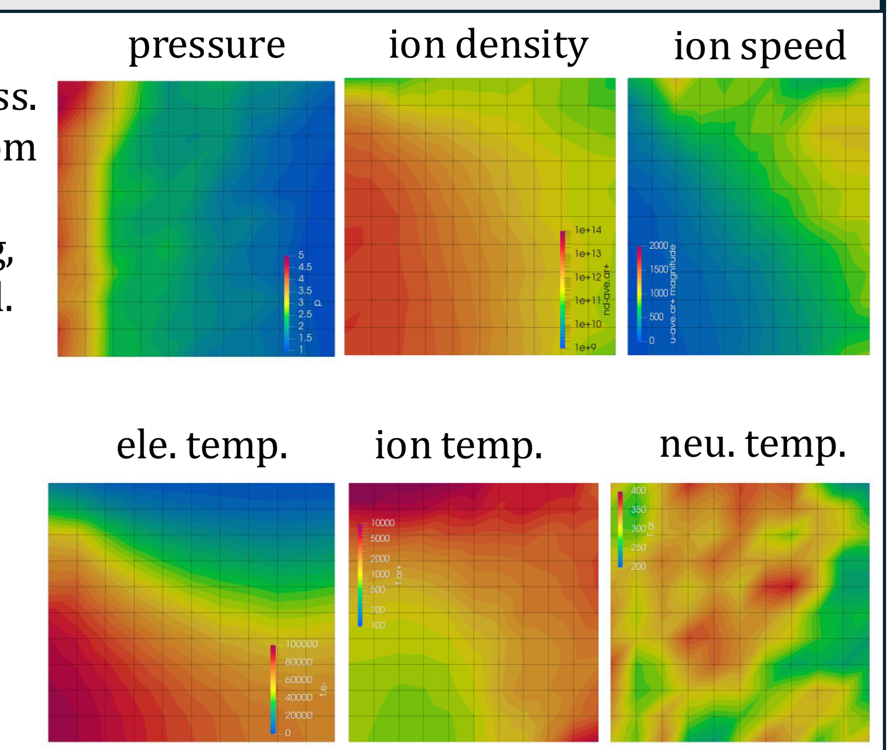
Attempting to throttle via directly changing the load into the system proved difficult, given that the impedance-matching network was manual. When throttling down, less gas would ionize, therefore increasing the impedance and decreasing the amount of energy that could be delivered. This reinforcing feedback loop would then cause the plasma to collapse. Instead, modulating the duty cycle mitigated the likelihood of extinguishing the Townsend effect. As seen in the graphic to the left, modulating the duty cycle still proved difficult. When turning the duty cycle on, the system would not meaningfully change its internal temperature and instead stagnated. When turning the cycle off or to 100%, the temperature would radically increase. Considering this behavior in the scope of the PID controller, it could be seen that the system would modulate about a temperature by rapidly changing the duty cycle from 35% to 100%.



Numerical Model

A low-resolution 2D fully-kinetic PIC simulation was used to model ionization and heating process. Neutral, approximately 1 Torr, argon injected from the left boundary. Top boundary oscillates at +/- 30 V at 13.56 MHz frequency. Ionization, heating, and acceleration of argon gas is clearly observed.





Future Work

1. Migrate simulation and control algorithms to a microcontroller / Raspberry Pi
2. Ingest data from Langmuir probe and pressure gauges
3. Include in the loop flow control and impedance matching network
4. Test operational mode as a cathode using molecular propellants, such as water and air

References

[1] Henken, A., "Thermal Modeling and Validation of Heat Profiles in an RF Plasma Micro Thruster", Master's Thesis, Cal Poly, San Luis Obispo, 2018
[2] Brieda, L., Keidar, M., "Development of the Starfish Plasma Simulation Code and an Update on Multiscale Modeling of Hall Thrusters", AIAA Joint Propulsion Conference, 2012