SIMULATION AND EXPERIMENTAL VALIDATION OF AN INDUCTIVELY HEATED SOLID-CORE NUCLEAR THERMAL ROCKET MODEL

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Nuclear thermal propulsion allows for thrust performance akin to liquid bi-propellant rockets along with efficiency close to ion propulsion drives. The objective of the Hyperion-I project is to model nuclear thermal propulsion and experimentally validate the numerical model. A coupled magnetic and computational fluid dynamic model for a single-channel test article was created using ANSYS Maxwell and ANSYS Fluent and subjected to experimental testing conditions. A test stand capable of meeting the testing requirements of a .00025 kg/s mass flow rate at 500 psi for 15 minutes was built. Four Omega K-type thermocouples and four Omega PX309 pressure transducers were utilized pre-regulator, post-regulator, pre-test-article, and post-test-article to acquire pressure and temperature data. The outlet flow temperature of 66.85 °C was validated with an experimental temperature of 66±2 °C. Future testing includes a multi-channel test core and a full-scale core for Phases II and III of the Hyperion-1 project, respectively.

I. Nomenclature

A	=	orifice inlet area
C_v	=	flow coefficient
C_d	=	discharge coefficient
P	=	pressure
P_o	=	upstream pressure
T	=	temperature
ρ	=	density
γ	=	specific heat ratio

II. Hyperion-I Campaign Introduction

The University of Southern California's Advanced Spacecraft Propulsion and Energy (ASPEN) Laboratory's first project aims to model Nuclear Thermal Rocket Propulsion Engines (NTRE's) with its three-phase Hyperion-I engine campaign.

Liquid bipropellant rocket engines have become a staple across nearly every vehicle architecture due to their time-tested reliability. While they provide some of the highest thrust of any currently employed propulsion system, with the exception of solid boosters, specific impulses of the highest performing engines are capped near 450-460 seconds. Subsequently, required tank sizes and fuel weight severely limit the vehicle size and mission design. For smaller craft, ultra-efficient propulsion systems such as ion thrusters are frequently employed. These thrusters have specific impulses reaching well into the thousands of seconds – an order of magnitude higher than any liquid-propellant engine can achieve. However, this exceptional efficiency is met with an equally steep drop-off in thrust output, hindering the spacecraft's ability to perform corrective maneuvers and greatly increasing mission duration. By utilizing nuclear

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thermal propulsion, the high thrust of liquid propellant engines is achieved with the high efficiencies of various electric propulsion systems.

While heavy lift launch vehicles will most likely continue to utilize liquid propellant rocket engines in the foreseeable future due to their reliability, upper stages and spacecraft propulsion systems are the perfect applications of NTRE' as their thrust and efficiency performance allows them to compete with conventional chemical engines in terms of payload while offering the lowest total round-trip mission duration in a manned mission to Mars (Ref. [2]).

The overarching system of ASPEN's first engine, Hyperion-I, can be broken down into three main subsystems: the feed system, the reactor model, and the thrust chamber. The feed system utilizes inert nitrogen gas from standard commercial cylinders and regulates it to the flow and pressure requirements of the reactor subsystem, with multiple points of overpressure relief and flow isolation as well as ports for necessary temperature and pressure data acquisition. The reactor subsystem will consist of the metallic fuel element core heated by an off-the-shelf induction furnace as opposed to relying on nuclear fission as the source of heat. This is the same approach that the Nuclear Thermal Rocket Element Environmental Simulator (NTREES) facility at the NASA Marshall Space Flight Center currently takes to simulate fission-based nuclear thermal rocket engines without the risks and regulations inherent to fissile material (Ref. [1]). The inductively heated element will be additively manufactured by utilizing USC's Center for Advanced Manufacturing (CAM). The working fluid will flow axially through the channels, heating up and accelerating as it progresses through the core much like the NERVA Program's design (Ref. [3]). As Hyperion-I will not have an integrated power generation cycle to make it bimodal, the energized propellant will be directed into an exhaust plenum and then expanded through the nozzle as thrust.

With the Hyperion-I campaign, the ASPEN Laboratory aims to pioneer the coupled hardware and modeling research of NTRE's in a systematic approach consisting of three phases, ultimately testing its full engine design in Phase III (Fig. 1).

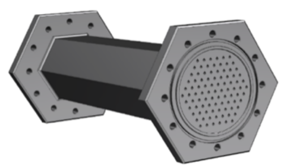

Fig. 1 Core of the proposed Phase III Hyperion-I engine.

A. Phase I Purpose and Goals

Phase I of the Hyperion-I campaign is meant to assess the functionality of the experimental design, including the feed system and inductive heating method. A standard 3/16" outer diameter stainless steel tube will integrate with the test stand instead of the full-scale core. Temperature and pressure data acquisition will still occur in the same locations as they will for the full engine test in order for ANSYS model predictions of ΔT and exit temperature for of the test article to be compared to the experimental results. Any off-nominal behavior of the systems can then be remedied for Phases II and III.

III. ANSYS Modeling

A. Model Setup

The first model created was the electromagnetic model of the single channel test article within the induction coil. The test article solid volume was modeled in Siemens NX, imported into the ANSYS workspace, and subsequently meshed with 200,000 nodes. Then, the eddy current solver within the 3D Maxwell module of ANSYS was used to generate the electromagnetic simulation. After creating a 3D model of the induction coil directly within the Maxwell environment, induction currents were assigned as boundary conditions and an initial frequency through the coil was estimated from a prior heater checkout test. The test article geometry was then imported and then positioned with respect to the coil. Additional skin-depth-based meshing was applied to the test article based on its electrical properties for increased fidelity in heating behaviors, and a region in the shape of a rectangular prism was defined around the test article and coil in which the simulation would solve. Finally, the entire system was solved with plotted outputs of magnetic field vectors throughout the region and ohmic losses within the test article.

The next models created were steady-state and transient thermal models, using the corresponding modules in the ANSYS workspace. The steady state ohmic loss contour from the electromagnetic simulation was mapped to the geometry in the thermal model, and a standard convection coefficient based on ambient conditions and tube material was applied to the surface of the tube to ensure that convection with ambient air surrounding the article was considered. These models simply served to probe the limits of the "dry-heat" behavior, defined as heating the article without any coolant gas flowing through it.

The final model created was a computational fluid dynamics (CFD) model in ANSYS Fluent. Again, the steady state ohmic loss contour from the Maxwell simulation was mapped to the solid body of the tube as a 3D volumetric heat source, and the working fluid (gaseous nitrogen) was assigned to the fluid volume of the test article. Similar to the approach taken in the thermal models, a standard convection coefficient was applied to the tube body, and the region around the tube was assigned to be standard atmosphere. Using predicted flow velocities and target mass flow rates obtained via internally developed compressible flow and nuclear thermal rocket engine sizing MATLAB scripts, a density-based solver was employed in Fluent; the pressure drop between the test article inlet and outlet was estimated in another MATLAB script using the Darcy-Weisbach method. Beyond these initial conditions and solver settings, default Fluent settings were used. While the primary metric of interest was the propellant outlet temperature profile, the temperature profile of the solid test article body was exported to the Maxwell module in a feedback configuration, enabling an iterative 2-way coupling between the electromagnetic and CFD models. These models were then re-run until both converged. The ANSYS Maxwell model setup is pictured in Fig. 2.

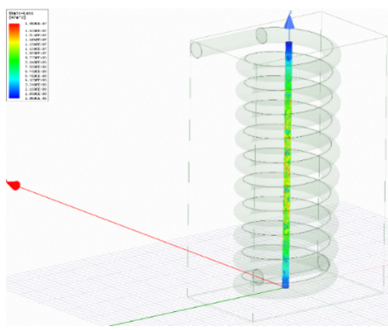

Fig. 2 ANSYS Maxwell model setup showing the test article.

B. Results

The primary result of interest was the average steady-state outlet gas temperature from the single channel article, as this is a value that is directly measured by a thermocouple inserted into the exhaust stream in the test stand setup. With an input gas temperature of 300 K (26.86 °C), the final models converged upon a steady-state average outlet gas temperature of 340 K (66.85 °C).

The next most important result was the maximum tube temperature achieved in the steady-state dry-heat thermal models, as it was imperative that the system remain safe if the coolant flow were somehow stopped while the heater remained operational. The steady-state thermal model showed a maximum dry-heat tube temperature of 400 K (126.85 °C).

IV. Experimental Setup

A. Feed System

The feed system for Hyperion-I was designed to meet the requirements of full-scale testing. These requirements include supplying gaseous nitrogen for 15 mins at a flow rate of 0.05 kg/s and pressures of up to 1000 psi at the nozzle inlet. The feed system was also built to acquire temperature, pressure and thrust data to analyze the performance of the tests articles of each phase of the engine campaign. Lastly, the test stand was also built to safely relieve high pressures in order to keep certain components and personnel safe.

For Hyperion-I Phase I testing of the single channel test article, the system was slightly modified to supply the required nitrogen flow rate of 0.00025 kg/s at a pressure of 500 psi. To acquire the desired gaseous flow a Tescom 44-1330 pressure regulator with a flow coefficient (C_v) of 0.8 that can supply pressures of up to 1450 psi was used. To ensure that the correct flow rate was achieved, it was also necessary to attach an orifice, sized to choke the flow of nitrogen gas, at the end of the feed system. To size the area of an orifice that would allow this performance Eq. (1)

was used for the choked flow of a compressible gas, where $\dot{m}$ is the mass flow rate, C_d is the discharge coefficient for a sharped edge orifice, A is the orifice inlet area, P_0 is the upstream pressure, ρ is the density of nitrogen at 500 psi and γ is the specific heat ratio of nitrogen.

$$\dot{m} = C_d A \sqrt{\gamma \rho_o P_0 \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{1}$$

From Eq. (1), an orifice with a diameter of 0.0254 cm (0.01 in) was calculated, and an orifice of that size was procured from O'keefe Controls Co. that can withstand pressure up to 4000 psi. Lastly, to ensure that nitrogen would be supplied to the test article for at least 15 minutes, two size 300CF K nitrogen bottles were attached to the feed system.

Before Phase I testing began, a leak and proof test of the feed-system was performed to qualify it for hot flow operation. During the leak test, visual inspection for leaks was performed and the leak rate was recorded at incremental pressure stages of 200 psi, 400 psi, and 600 psi. The leak rate was measured after the stage passed visual inspection. In order for the stage to pass the leak rate requirement, the leak rate had to be below 3 psi per minute. The feed system was proofed at a pressure 1.5 times the Maximum Expected Operating Pressure (MEOP) for Phase I testing (1.5*MEOP = 750 psi). The feed system passed the leak and proof test to ensure safe data acquisition during the hot flow.

B. Data Acquisition

The system that was used for data acquisition was designed specifically for use in the Hyperion-I engine campaign. This system was created to operate with three primary sensor types.

For temperature measurements, four Omega K-type thermocouples were used. These K-type thermocouples were plunged into the flow of nitrogen at the following locations: before the regulator, after the regulator, before the test article, and after the test article. The voltage signals from these thermocouples were amplified using an AD8495 breakout board. This breakout board provided a 5 V analog output signal with a range of -250°C to +410°C. This range is more than the maximum gas outlet temperature predicted for all Phases of the Hyperion-I campaign.

For pressure measurements, four Omega PX309 pressure transducers were utilized. These pressure transducers have an operational range of 0 psig to 3000 psig: a maximum operational pressure much higher than any pressure that could be present in the feed system. These sensors feature a built in 5 V amplifier circuit which outputs a 0-5 V analog signal. These pressure transducers were placed at the following locations: before the regulator, after the regulator, before the test article, and after the test article

The third type of sensor that the system is built to interface with is an Omega Subminiature Compression Load Cell with a 0 - 10 Newton range that outputs a 0 – 5 V analog signal. This load cell will be used for Hyperion-I Phases II and III in order to gather thrust values of the midscale core and full core, respectively. For Hyperion-I Phase I this sensor was not installed on the test stand as thrust was not a measurement required for model evaluation.

These three sets of sensors integrate into a central data acquisition system. The main data acquisition system primarily consists of a NI USB-6211 inside of a custom chassis. The data acquisition system has a resolution of 16 bits and runs at around 1000 Hz per channel. This system also has the capacity to control feed system solenoid actuation.

V. Results and Discussion

During the Hyperion-I Phase I hot flow test, a significant amount of information pertaining to the characterization of the system was obtained. By analyzing the thermocouple and pressure transducer data at different points on the test stand, it was possible to determine both the change in pressure between the inlet and outlet of the single channel as well as the change in temperature of the nitrogen as it passed through the single channel test article.

As mentioned in the experimental setup, the first hot flow test of the system was run at an inlet pressure of 500 psig and an induction heater current level between 306 to 310 Amps. At the start of the test, a visible increase of temperature in the single channel test article was observed. This increase in temperature was determined by the presence of steam forming on the test article clamps and was verified visually through the use of a thermal camera.

After 15 minutes of continuous heating, it was determined that the temperature and pressure of the system had reached steady-state. During this heating time there was substantial amount of electromagnetic interference from the induction coil that is seen in the pressure and temperature measurements. This led to a notable offset in the values measured during the heating process. The full transient for the pressure of the test can be seen below in Fig. 3.

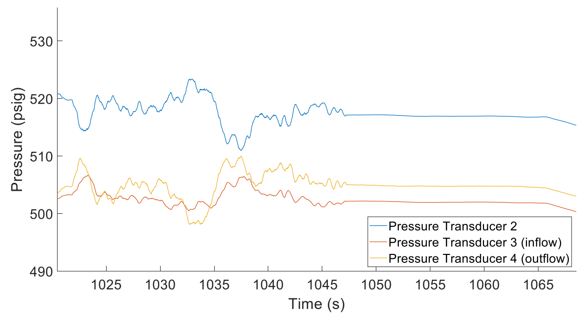

Fig. 3 Pressure Transducer 1 is not shown as it is the pressure of the nitrogen supply and non-critical to the hot flow test.

The temperature transient of the test was also extremely affected by the noise experienced by the pressure transducers. This led to a noticeable offset during the heating process. A moving average of the temperature values during this high noise transient was taken, and the values were then resampled to further limit noise for better analysis. Despite the large thermocouple offset, a clear asymptotic behavior was observed. The full temperature transient measured can be seen in Fig. 4.

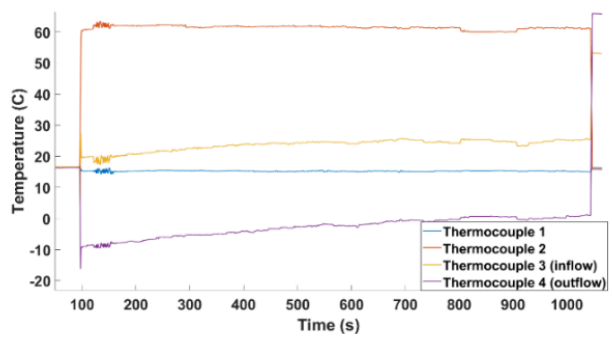

Fig. 4 Note that the steady state temperature does not contain the offsets seen during heating.

The hot flow test was allowed to run for a total of 15 minutes before the heating of the test article was shut off. Immediately after the heater was shut off the steady state temperature and pressure values were collected. These are the values calculated by the ANSYS model and therefore hold the most importance for the test. Below in Fig. 5 the steady state pressure of the system can be seen.

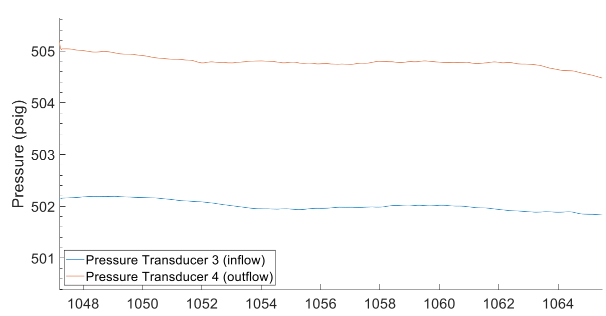

Fig. 5 Pressure Transducer 1 and 2 were excluded from the figure as they are used primarily for adjusting inlet pressure.

As can be seen in Fig. 5 the inlet pressure into the single channel test article was 502±1 psig and the outlet pressure was 505±1 psig. This resulted in a ΔP equal to 3±2 psig, thus indicating a slight pressure increase across the test article due to heating.

The most important measurement taken at steady state was the temperature of the gas at the inlet and outlet of the single channel test article. In Figure 6 these steady state temperature values can be seen.

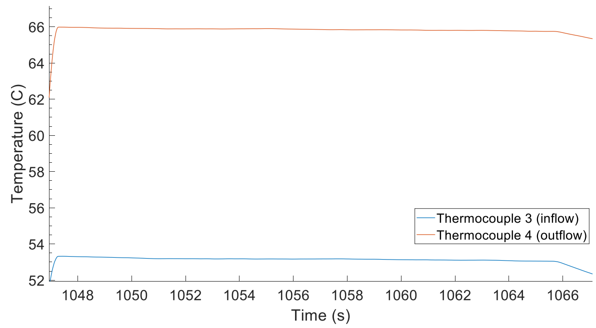

Fig. 6 Note that temperatures from Thermocouples 1 and 2 were excluded from the figure as they are used to measure gas temperature before and after the pressure regulator.

As can be seen from Fig. 6, at steady state the inlet temperature of the gas was measured to be 53±2 °C and the outlet temperature was measured to be 66±2 °C. This means that the ΔT value measure was 13±4 °C.

The outlet temperature seen from the hot flow test is equal to the 66.85 °C outlet temperature predicted by the ANSYS model of the test article. This shows that the model was setup up properly and has correctly modeled the outlet conditions of the gas flow.

The measured ΔT across the single channel test article was not equal to the predicted ΔT of 26.86 °C from the ANSYS model. This disparity between the measured ΔT and the modeled ΔT is most likely caused by equipment design. Due to the shaping of the induction coil there was an unexpected coupling between the fitting for Thermocouple 3, which resulted in heating of the metal component. This heating caused an erroneous temperature measurement in which the thermocouple measured the temperature of the metal instead of the desired temperature of the gas flow. As measured gas inlet temperature of 53±2°C. Through the use of a thermal camera, it was found that at steady state the fitting in question had a temperature of 54 ±4 °C. This is a strong indicator that the heating of the metal fitting is what resulted in an erroneous ΔT value.

Due to this error, the ΔT value from the hot flow test cannot be compared to the ΔT value seen in the ANSYS model. This error will be corrected in subsequent testing by re-designing the induction heating coil in a manner that removes heating of the inlet fitting.

VI. Conclusion

The initial testing of Hyperion-I Phase I was proven to be a partial success. The hardware design and operation of the induction furnace to heat the single channel article worked nominally and the resulting gas exit temperature matched the ANSYS model predictions.

However, due to an error in equipment design, the value of ΔT of the system cannot be compared against the ΔT predicted by the ANSYS model. This means that more testing on the Hyperion-I single channel test article must be conducted to find this ΔT value.

Despite this small setback, overall Phase I testing is close to completion. It has been shown that the hardware created to accomplish the test campaign generally functions as expected. It has also been shown that the equipment created has the capacity to gather meaningful data about the properties of the gas flow. Through small modification to pre-existing hardware it will soon be possible to finish Phase I testing and move forward with Phase II and Phase III of testing.

A. Hyperion-I Phase II

Phase II of the Hyperion-I campaign is partially underway upon the results of Phase I. No major design changes to the test stand are needed except for the previously accounted for addition of the load cell to measure thrust and I_{sp}.

The goal of Phase II is to perform a scaled-down version of full core testing with a midscale test article containing 7 channels. The test article was additively manufactured at USC's Center for Advanced Manufacturing out of DMLS MS1 Maraging Steel and post-machined at the on-campus machine shop. End caps that attach to the core and interface with the feed system have already been designed and manufactured.

Upon testing the article, the exit temperature and ΔT parameters shall be compared to the ANSYS predictions, and additional parameters such as thrust and I_{sp} will be obtained in order to prepare for full core testing in Phase III of the Hyperion-I campaign.

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