

THE USE OF IMMERSION RIGS FOR HIGH TEMPERATURE HYDROGEN EXPOSURE TESTING WITHIN THE NUCLEAR THERMAL ROCKET ELEMENT ENVIRONMENTAL SIMULATOR (NTREES)

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ABSTRACT

The Nuclear Thermal Rocket Element Environmental Simulator (NTREES) was designed to perform non-nuclear testing of nuclear thermal rocket (NTR) fuel elements and materials. NTREES can simulate the thermal hydraulic environment within an NTR and has been leveraged to provide critical information on component performance and material compatibility. NTREES has the ability to expose test articles to pressurized Hydrogen gas up to 1000 psig and 225 g/s. NTREES tests are operated in a deoxygenated environment of Nitrogen or Argon pressurized up to 1000 psig. NTREES simulates fission heat through induction heating powered by a 1.2 MW AC power supply, and NTREES has recorded temperatures exceeding 3700K [1]. To perform hot Hydrogen exposure tests on materials more rapidly and earlier in the fuel development process, NTREES must be able to test small material samples on the order of 1 square inch in volume, individual fuel assembly subcomponents, and particle materials. To meet these needs, multiple testing rigs have been developed to immerse test specimens in hot Hydrogen, with each "immersion rig" varying in its capability of sample type and performance range in order to meet the broadest range of testing needs. Herein is a discussion of a selection of these "immersion rigs."

INTRODUCTION

Nuclear Thermal Propulsion (NTP) is an advantageous technology with significant advantages over that of chemical propulsion systems and an excellent candidate propulsion system for manned Mars missions as well as other interplanetary missions [2]. NTP systems produced during the Rover/NERVA program (1955 – 1973) showed that NTP engines could be built to operate at specific impulses (Isp) of approximately 900 s [3]. Modern day efforts target developing NTP systems with Isp ranges beyond 900 s and the ability to support large payloads – identifying NTP as an attractive option for deep space science missions [4].

The NTREES facility was purpose-built to perform rapid prototypic, non-nuclear testing of NTP system fuel elements and fuel materials. The NTREES facility primarily consists of a pressure vessel in which experiments are conducted, a 1.2 MW AC power supply system which can energize an induction coil at controllable power levels, gas control systems to provide both gaseous Hydrogen and inert cover gases, an industrial water cooling system, an array of instrumentation and sensors, and a data acquisition (DAQ) and control system. The NTREES experimental facility has been utilized to perform testing and characterization of proposed NTP fuel materials and geometries as well as NTP system components [1].

To test smaller fuel material samples and subcomponents more rapidly, a new class of experimental apparatus was conceptualized. These 'immersion rigs' heat gas, typically high pressure Hydrogen, upstream of a test specimen. The test specimen is then immersed in the hot Hydrogen gas, rather than being directly heated by the induction coil. During operation, instrumentation captures temperature, pressure, and composition of this gas at various locations of the experiment. This new class of test apparatus permits smaller material samples, allowing testing earlier in the fuel development process. It also allows for fuel element subcomponents to be tested, isolating thermochemical effects between specimen material and high pressure, high temperature Hydrogen gas for observation. This paper discusses an immersion rig developed and tested to analyze the thermochemical effects between hot Hydrogen and an individual flow channel liner.

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DESIGN

REQUIREMENTS

The Flow Channel Liner Immersion Rig was developed for the purpose of testing a single flow channel liner within NTREES. Flow channel liners are often used in NTP fuel designs to serve as a barrier between the inner surface of the nuclear fuel coolant channels and the highly reactive Hydrogen propellant. The experiment would consist of exposing a single liner to high temperature Hydrogen gas to evaluate thermochemical effects and overall material compatibility between the liner and the gas, informing the liner material's expected performance within an NTP system. This rig was developed to deliver hot Hydrogen gas at a performance envelope of temperature, pressure, and flow rates prototypic to NTP reactors. Since there are typically many coolant channels within NTP fuel, and many fuel elements within an engine, the mass flux through an individual liner can be relatively low and on the order of a single gram per second [1]. Targeted performance ranges for the design are tabulated below.

Table 1: Performance Targets for Flow Channel Liner Immersion Rig

Property	Value
H ₂ Mass Flow Rate	1 g/s – 1.5 g/s
H ₂ Pressure	500 – 750 psig
H ₂ Temperature (liner inlet)	2300 K – 3000 K
H ₂ Temperature Drop Across Liner	Minimized
Hold Time	10 mins

MAIN BODY, FIXTURING, AND MATERIAL SELECTION

Given the high targeted operating temperatures, a tungsten tube was opted for the Flow Channel Liner Rig's main body. The Heated Section constitutes approximately 13" of the rig's length, and is upstream of the Insulated Sample Section in which a flow channel liner sample is to be axially loaded. A boron nitride Cold Clamp Adaptor spaces the upstream Cold Clamp from Heated Section to avoid inadvertent coupling of this thermally limited hardware. It is through this Cold Clamp that Hydrogen gas is supplied. Additionally, a tungsten tube within this boron nitride spacer acts as pressure barrier for the incoming high pressure Hydrogen to avoid loading the ceramic walls of the Cold Clamp Adaptor. The hot gas is routed through an Insulated Sample Section. The hottest end of the rig is supported by a Boron Nitride Hot Clamp. The entire design layout can be seen in Figure 1 in a labelled computer-aided design (CAD) representation and a picture of the assembled rig can be seen in Figure 2 and Figure 3.

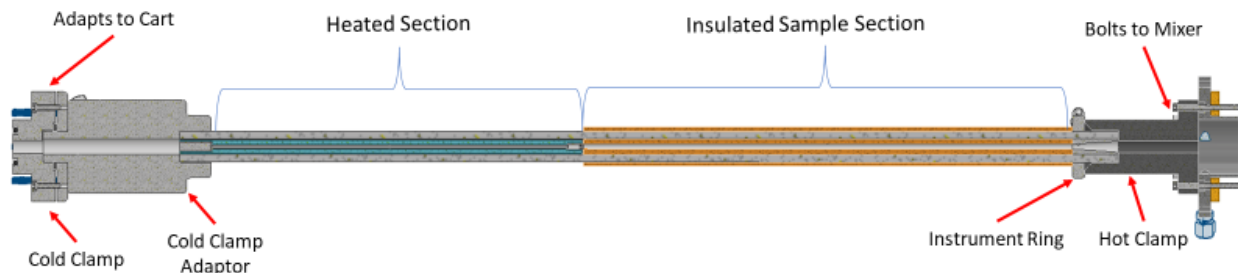


Figure 1: CAD Model of Flow Channel Liner Immersion Rig



Figure 2: Flow Channel Liner Immersion Rig



Figure 3: Cold Clamp Adaptor with Embedded Pressure Barrier Tube

HEAT EXCHANGER SECTION

The upstream Heated Section contains tungsten lattice segments through which an axial thermocouple was designed to be mounted; the sheath of which would run through the centerline hole of the segments. These tungsten lattice segments were manufactured at NASA MSFC and can be seen in Figure 4. The lattice segments are toleranced to fit snugly within the tube of the outer-body assembly with minimalized chance of bypass flow. Initial checkout tests indicated that the axial thermocouple was subject to electro-magnetic interference (EMI) from the induction coil. Thusly, the thermocouple was removed. To plug the leak path introduced by the removal of the thermocouple, the leading (furthest most upstream) tungsten lattice segment, which was designed to house the cold junction of the thermocouple, was plugged with a tungsten dowel pin, as shown in Figure 5. The furthest most downstream tungsten lattice segment contains radial holes to accommodate thermocouple sheaths. This segment as well as the Instrument Ring can be seen in Figure 6.



Figure 4: Tungsten Lattice Segments



Figure 5: Leading Tungsten Lattice Segment



Figure 6: Instrument Ring and Final Tungsten Lattice Segment

INSULATION

To minimize temperature drop across the individual flow channel liner sample, insulator segments of refractory-carbide of medium to moderate relative density were designed to house the sample within the Insulated Sample Section. These inner insulator segments are toleranced to fit snugly within the outer tube of the rig assembly with minimalized chance of bypass flow, and the segments stack up to the length of a sample. These inner insulators are shown in Figure 7, and can be seen inside the immersion rig body in Figure 1.

Additionally, a second set of refractory-carbide segments of the same density were manufactured to fit the outside of the immersion rig, over the length of the Insulated Sample Section. Without insulation, the rig would be subject to convective cooling of the dense cover gas within the pressure vessel as well as

radiative losses to the pressure vessel's walls. During operation, these outer insulators were to be removed if a thermal gradient were to be desired. These outer insulators are shown in Figure 8. They can also be seen mounted around the immersion rig body in Figure 1.



Figure 7: Immersion Rig Inner Insulators



Figure 8: Immersion Rig Outer Insulators

INSTRUMENTATION

Built-in Facility Instrumentation

The NTREES DAQ and control system takes advantage of built-in instrumentation to capture information on gas flowrates, temperatures, and pressures across the system. These values are captured and recorded during testing by flow meters, resistance temperature detectors (RTD), and pressure transducers which are built into the NTREES facility and report data displayed on the main control panel during operation. These metrics are used to set system parameters during experimentation runs, including but not limited to chamber pressure, mass flow rate of Hydrogen gas, and mass flow rate of inert cover gas.

Embedded Thermocouples

Thermocouples are mounted positionally to measure gas temperature along the path of the Hydrogen gas from inlet to outlet of the rig. Hydrogen gas inlet temperatures is captured by two thermocouples, TC06 and TC07, which sample directly from the inlet gas supply line. As mentioned in the *Heat Exchanger* section above, Hydrogen gas temperatures were originally planned to be taken by an axially mounted thermocouple sampling between the rig's Heated Section and Insulated Sample Section.

Downstream of the Insulated Sample Section, a Molybdenum (Mo) Instrument Ring, shown in Figure 9 and Figure 10, permits direct thermal sampling of the gas exhausting from the flow channel liner sample. Gas temperature as it leaves the Insulated Sample Section is measured by two thermocouples built into this ring. These two instruments are represented by TC03 and TC04 in Table 2. As the gas leaves the immersion rig the temperature is lastly taken by two thermocouples built into the Hot Clamp's Mo backing plate, represented by TC01 and TC02 (Figure 9). All thermocouples are Type C and have a Mo sheath. All thermocouples used within the design can be found listed for the reader's reference within Table 2, along with each instrument's Name, Type, Recommended Range, Hard Limit, and Accuracy.

Table 2: Thermocouple Instrumentation Table for Fuel Channel Liner Immersion Rig

Label	Type	Loc.	Range	Hard Limit	Accuracy
TC01	C	Hot Clamp	273 – 2273 K Limit: Mo Sheath	Mo Sheath Melt Temp: 2896 K	± 4.4 K (0 – 426 K) $\pm 1\%$ (426 – 2315 K)
TC02	C	Hot Clamp	273 – 2273 K Limit: Mo Sheath	Mo Sheath Melt Temp: 2896 K	± 4.4 K (0 – 426 K) $\pm 1\%$ (426 – 2315 K)
TC03	C	Liner Outlet	273 – 2273 K Limit: Mo Sheath	Mo Sheath Melt Temp: 2896 K	± 4.4 °C (0 – 426 K) $\pm 1\%$ (426 – 2315 K)
TC04	C	Liner Outlet	273 – 2273 K Limit: Mo Sheath	Mo Sheath Melt Temp: 2896 K	± 4.4 °C (0 – 426 K) $\pm 1\%$ (426 – 2315 K)
TC06	C	Gas Supply	273 – 1973 K Limit: MgO Insulation	Tantalum H2 Embrittlement: >613 K	± 4.4 °C (0 – 426 K) $\pm 1\%$ (426 – 2315 K)
TC07	C	Gas Supply	273 – 1973 K Limit: MgO Insulation	Tantalum H2 Embrittlement: >613 K	± 4.4 °C (0 – 426 K) $\pm 1\%$ (426 – 2315 K)

Pressure Drop

The Hot Clamp fixture shown in Figure 9 retains a pressure tap. At this location, exhaust gas is fed to the differential pressure transducer along with gas sampled from the supply stream. The pressure differential between these two streams is calculated and reported to the NTREES DAQ system. This value represents the pressure drop across the immersion rig.

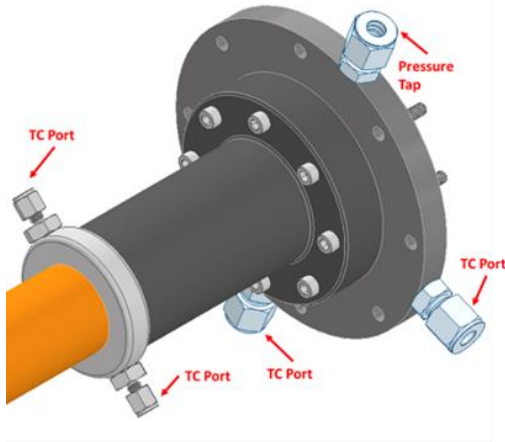


Figure 9: Instrument Ring and Hot Clamp CAD Representation

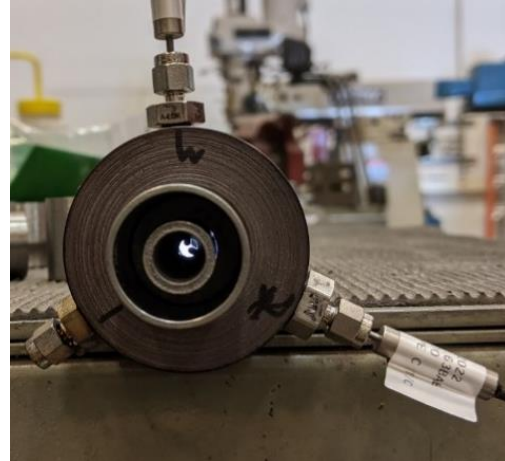


Figure 10: Instrumentation Mounted on Instrument Ring

Pyrometry

Pyrometers are used to measure outer body surface temperature of the Flow Channel Liner Immersion Rig. A cross-sectional view of a CAD model of the experimental setup can be seen in Figure 11, in which the line of sight for each pyrometer is represented as a blue cylinder. A multi-spectral pyrometer (FAR-TEMP) is used to determine emissivity values for the rig's tungsten outer surface as a function of temperature. To this end, NTREES' multi-spectral pyrometer is traditionally aimed at the outer surface location predicted by thermal modeling to be the hottest. The remaining, single-color pyrometers utilize this data to resolve surface temperature calculations. This approach is only valid if pyrometers are reading a common value. Additionally, the pyrometer spacing is discretized by the spacing of the view ports on the NTREES pressure vessel. It is for these reasons that only three pyrometers, including the multi-spectral pyrometer, are utilized in this experiment. These instruments are tabulated in Table 3.

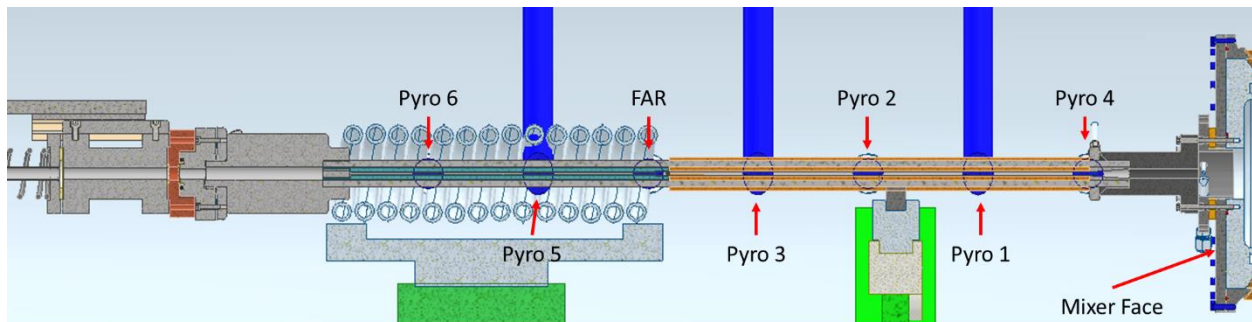


Figure 11: CAD Model of Flow Channel Liner Immersion Rig Installed w/ Pyrometer Locations Indicated

Table 3: Pyrometer Instrumentation Table for Fuel Channel Liner Immersion Rig

Name	Descriptions	Max Temp	Accuracy
PYRO-T6	Single-Color, Surface Temperature – Pyrometer	3273 K	± 0.3% of measurement
PYRO-T5	Single-Color, Surface Temperature – Pyrometer	3273 K	± 0.3% of measurement
FAR-TEMP	Multi-Color, Surface Temperature – Pyrometer	4273 K	± 0.3% of measurement

ANALYSIS

A two dimensional model of the immersion rig was analyzed in COMSOL Multiphysics utilizing electromagnetic, heat transfer, and flow modules. Setup of this model made considerations to the following: inductive heating from the coil, convective and radiative heat losses from the outside surface of the immersion rig, conductive heat transfer between solids, convective heat transfer between gas and solids, and using a porous media to account for the tungsten lattice material. Varying gas conditions were used to perform this analysis; tabulated in Table 4.

Table 4: Conditions of Thermal Simulations for Flow Channel Liner Immersion Rig

Property	Value
Hydrogen Mass Flow Rate(s)	1 g/s, 1.25 g/s, 1.5 g/s
Hydrogen Pressure	615 psi
Cover Gas	Ar
Cover Gas Pressure	1000 psi
Target Hydrogen Temperature(s)	2300 K, 2475 K, 2650 K, 2825 K, 3000 K

Power requirements were calculated using the above stated approach and tabulated conditions. These results are plotted below in Table 5. These figures are within typical performance ranges of NTREES operations.

Table 5: Power Required to Achieve GH2 Peak Temperatures as Predicted by Thermal Models (W)

	GH2 Mass Flow Rate		
Desired Temperature (K)	1 (g/s)	1.25 (g/s)	1.5 (g/s)
2300	68305	83644	99955
2475	77932	94391	112683
2650	87558	105138	125411
2825	97185	115884	138140
3000	106812	126631	150868

Peak material temperatures of the tungsten outer tube were calculated using the above stated approach and tabulated conditions. These results are plotted below in Table 6. These peak surface temperatures are determined to be within the allowable range and well below the hard limit of tungsten melting temperature.

Table 6: Peak Material Temperature at Peak GH2 Temperatures as Predicted by Thermal Models

	GH2 Mass Flow Rate		
Desired Temperature (K)	1 (g/s)	1.25 (g/s)	1.5 (g/s)
2300	2486	2568	2667
2475	2729	2798	2896
2650	2947	3007	3105
2825	3142	3196	3294
3000	3317	3368	3467

Additionally, material temperature gradients were modelled and mapped for each flow condition at the targeted peak gas temperature of 3000 K (liner inlet). An example of such a thermal map is shown in Figure 13. These maps were used to predict pyrometer readings during testing and to choose the position of the multi-spectral pyrometer during operation.

Gas temperatures over the length of the sample section were modelled in order to predict axial thermal gradients measured during operation; region shown in Figure 12. These were plotted for each targeted liner inlet gas temperature. Figure 14 displays axial thermal gradients predicted for a mass flow rate of 1 g/s. For this specific mass flow rate, the Hydrogen gas thermal gradients average to be 33 K.



Figure 12: Region Over Which Gas Temperature is Plotted within this Section.

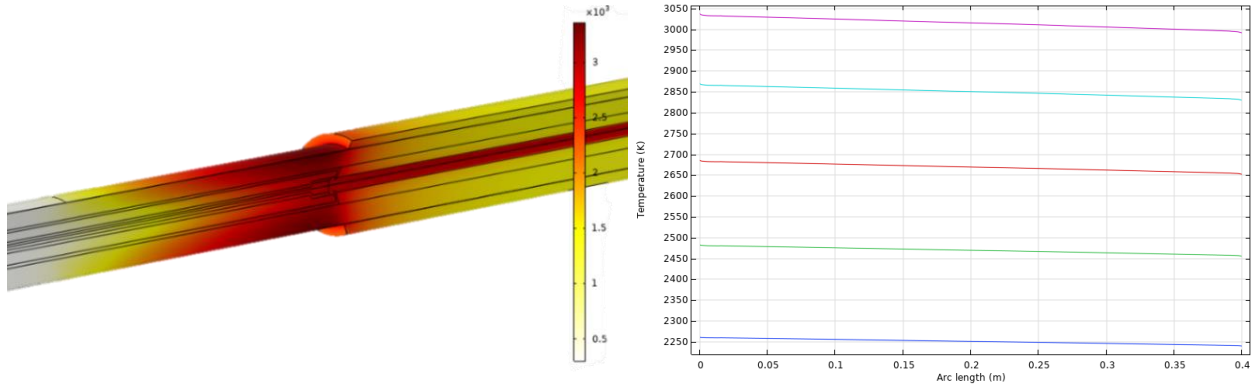


Figure 13: Material Temperature Profiles (K) for GH2 at 1.25 g/s and 3000 K

Figure 14: Hydrogen Gas Axial Thermal Gradients for Mass Flow Rate of 1 g/s

RESULTS

A series of check-out tests of this immersion rig design was performed. A photograph from an individual experiment can be seen in Figure 15, in which the rig, induction coil, and outer insulators can be seen. Results from a representative test from this series are shared and analyzed within this document.

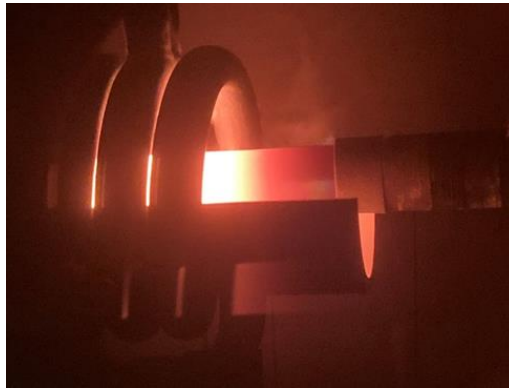


Figure 15: Flow Channel Liner Immersion Rig During Testing within NTREES

Plotted below are measurements recorded during a representative test of the Flow Channel Liner Immersion Rig. Hydrogen gas temperatures are plotted in Figure 16 as captured by thermocouples at the Gas Supply, Instrument Ring, and Hot Clamp (Table 2). Peak Hydrogen gas temperatures, those measured at the Instrument Ring, are plotted against peak material temperatures (Figure 17) and flow rate (Figure 18). Lastly, Hydrogen gas flow rate and power are plotted against each other (Figure 19).

Material temperature measurements made by the multispectral pyrometer are indicated by two plotted lines, each representing either the high domain or low domain readings. These measurements are each shown as 'clipped' when values are beyond the instrument's lower or upper limit.

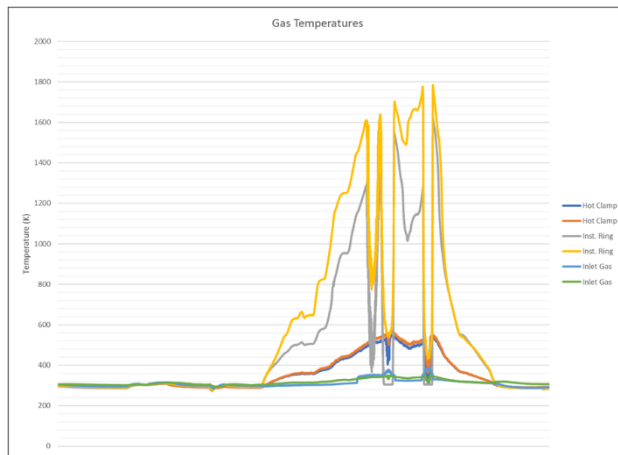


Figure 16: Gas Temperatures

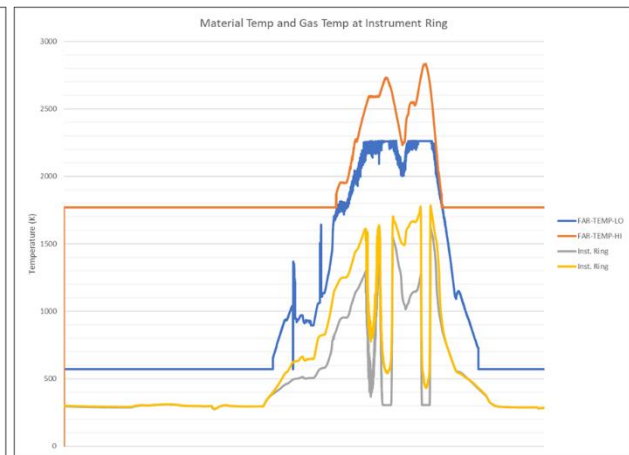


Figure 17: Material & Peak Gas Temperatures

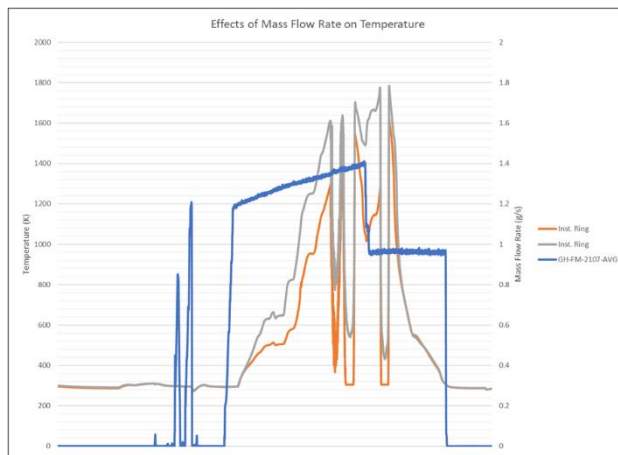


Figure 18: Peak Gas Temperatures & Flow Rates

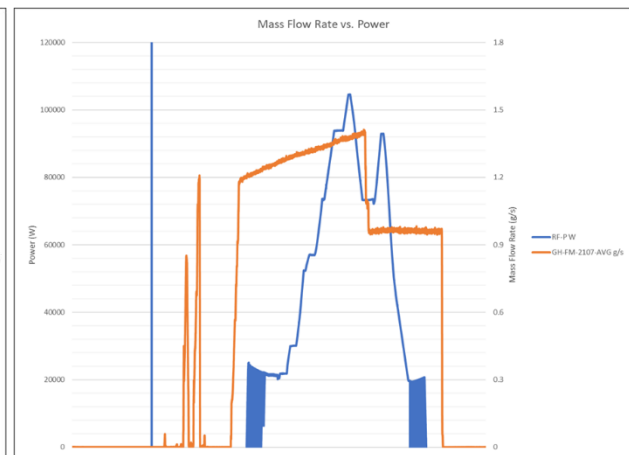


Figure 19: Flow Rates & Power

SUMMARY AND CONCLUSIONS

Two extractable data points were captured in the above data which will herein be used to correlate experimental data to the thermal models. In the first data point, the Hydrogen gas flow rate was set to approximately 1.2 g/s and climbed to approximately 1.4 g/s while power climbed to and was held at a peak value of 105 kW. At this power hold, peak surface temperature was measured to be approximately 2750 K, within 10% of the value predicted by correlating Table 4 and Table 5. Although peak gas temperature was not directly measured, this indicated Hydrogen gas at the inlet to the liner may have reached 2650 K.

The second data point of interest is a Hydrogen gas flow rate of 1 g/s and a peak power of approximately 93 kW. At this hold, surface temperatures read approximately 2825 K, once again within 10% of predicted values embedded in Table 4 and Table 5. These values similarly indicate peak gas temperatures of approximately 2650 K.

Throughout the overall series of check-out tests however, gas temperatures measured at the Liner Outlet read lower than modeling predicted. Due to lack of gas temperature instrumentation at the Liner Inlet, it is not immediately possible to determine whether the low temperature exhaust gas indicates insufficient gas heating within the Heated Section or less efficient than predicted insulation within the Insulated Sample Section.

A potential influence of suspected underperformance of the refractory-carbide insulators is densification. Both the internal and external insulators were moderately dense at the time of assembly;

however densification is likely to have occurred during testing given the high temperature performance conditions. Post-test modeling is certainly required to characterize the densification and the effects of densification of the insulator performance.

Alternative to poor insulation, Hydrogen gas may have not been sufficiently heated given the nature of the design. In post-test discussions within the experimental team, it was hypothesized that due to thermal expansion, the tungsten outer tube of the assembly may have grown radially away from the tungsten lattice segments. Induction heating is preferential to the outer surface, and heating of the tungsten lattice segments relies on thermal conduction from the tungsten outer tube. Physical separation between the two would have obviously impacted the performance of this thermal exchange. Additionally, any bypassing Hydrogen flow would have shrouded the inserts, potentially insulating them and exacerbating this effect. This potential cause of underperformance was not hypothesized until after the development and testing of the Tungsten Body Heat Exchanger Immersion Rig, discussed in the next paper in this series.

FINAL REMARKS AND FUTURE WORK

Development of this immersion rig concept is not completely concluded. It is likely possible to counteract the effects of the separating thermal boundary between inserts and the outer tube by applying to its surface area a thermal paste medium with both a suitably high operating temperature and a sufficiently high thermal conductance at relevant operating temperatures. Additionally, resolving the axial thermocouple EMI would sufficiently instrument the device to determine the specific underperformance mechanism. Lastly, the insulators can be redesigned to incorporate macro-porosity rather than relative density as a means to reduce thermal losses by limiting conduction across their thicknesses, while still providing sufficient protection from the pressure vessel's thermal loss mechanisms.

The next paper in this series will discuss an immersion rig designed to heat Hydrogen gas once again to temperatures and pressures relevant to NTP systems. That design will differ in that it delivers heated gas to a material sample containment volume. This Tungsten Body Heat Exchanger also attempts to resolve the challenge of surface preferential heating of induction power.

Further designs of immersion rigs are in the works. An immersion rig design of much higher capability leverages lessons learned in the two previous design iterations and attempts to take advantage of NTREES' full 1.2 MW power supply. At the time of this paper's publishing, this hardware has not yet been tested. However, current thermal analyses predict performance ranges far exceeding its predecessors. This upcoming immersion rig will feature a modular and scalable sample containment volume and permit rapid testing campaigns of multiple specimen.

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