TESTING OF LIQUID METAL COMPONENTS FOR NUCLEAR SURFACE POWER SYSTEMS

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ABSTRACT

The capability to perform testing at both the module/component level and in near prototypic reactor configurations using a non-nuclear test methodology allowed for evaulation of two components critical to the development of a potential nuclear fission power system for the lunar surface. A pair of 1 kW Stirling power convertors, similar to the type that would be used in a reactor system to convert heat to electricity, were integrated into a reactor simulator system to determine their performance using pumped NaK as the hot side working fluid. The performance in the pumped-NaK system met or exceed the baseline performance measurements where the converters were electrically heated. At the maximum hot-side temperature of 550 °C the maximum output power was 2375 watts. A specially-designed test apparatus was fabricated and used to quantify the performance of an annular linear induction pump that is similar to the type that could be used to circulate liquid metal through the core of a space reactor system. The errors on the measurements were generally much smaller than the magnitude of the measurements, permitting accurate performance evaluation over a wide range of operating conditions. The pump produced flow rates spanning roughly 0.16 to 5.7 l/s (2.5 to 90 GPM), and Δp levels from less than 1 kPa to 90 kPa (>0.145 psi to roughly 13 psi). At the nominal FSP system operating temperature of 525 °C the maximum efficiency was just over 4%.

I. INTRODUCTION

Fission surface power (FSP) systems could be used to provide power on the surface of the moon, Mars, or other planets and moons of our solar system. Fission power systems could provide excellent performance at any location, including those near the poles or other permanently shaded regions, and offer the capability to provide on demand power at any time, even at large distances from the sun. Fission-based systems also offer the potential for outposts, crew and science instruments to operate in a power-rich environment. NASA has been exploring technologies with the goal of reducing the cost and technical risk of employing FSP systems. A reference 40 kWe option has been devised that is cost-competitive with alternatives while providing more power for less mass anywhere on the lunar surface. The reference FSP system is also readily extensible for use on Mars, where it would be capable of operating through global dust storms and providing year-round power at any Martian latitude. Detailed development of the FSP concept and the reference mission are documented in various other reports.[1-4] The development discussed in this paper prepares the way for testing of the Technology Demonstration Unit (TDU), which is a 10 kWe end-to-end test of FSP technologies intended to raise the entire FSP system to technology readiness level (TRL) 6.

The Early Flight Fission–Test Facility (EFF-TF) was established by NASA's Marshall Space Flight Center (MSFC) to provide a capability for performing hardware-directed activities to support multiple in-space nuclear reactor concepts by using a nonnuclear test methodology.[5,6] This includes fabrication and testing at both the module/component level and at near prototypic reactor components and configurations allowing for realistic thermal-hydraulic evaluations of systems.

In the FSP design, power is extracted using free-piston Stirling (FPS) converters. Testing was performed at MSFC using two 1-kW converters coupled to a pumped liquid metal reactor simulator system to demonstrate electrical power extraction.[7] Considerable effort was expended by NASA's Glenn Research Center (GRC) to retrofit the Stirling converters for coupling to the pumped NaK system at MSFC in a manner that allowed for favorable heat transfer to the converters. The custom heater heads and heat exchangers on the converters were evaluated based on performance differences that arose between baseline tests, which employed a resistive heat source, and NaK-system testing. In the pumped-NaK system the heat transfer to the converters is affected by both the liquid-metal temperature and flow rate, which could prove useful in providing two controls over the heat transfer to the Stirling units and resulting in an improved, optimized Stirling cycle power converter. The transient response of the Stirling converters was evaluated under simulated scenarios such as loss of heater power, converter stall and restart, and loss of NaK flow.

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The liquid-metal pump associated with the FSP system must be compatible with the liquid NaK coolant and have adequate performance to enable a viable flight system. Idaho National Laboratory (INL) was tasked with the modeling, design, and fabrication of an ALIP suitable for the FSP reference mission.[8] A prototypic ALIP was fabricated under the direction of INL and shipped to MSFC for testing at representative operating conditions. The measured performance is presented in this paper and another [9], and described in greater detail in a full technical report [10]. Analysis of the performance, as compared to the design predictions, as well as implications for the next ALIP design iteration, can be found in a companion report published by INL.[8] The ALIP test circuit (ATC) discussed in this paper and used to test the present pump will also be used to test future ALIPs for the FSP technology development program, including a pump designed for the TDU.

II. EXPERIMENTAL APPARATUS

Tests were conducted on both the Stirling power conversion units and the ALIP at MSFC. We proceed first with a description of the hardware employed for the Stirling and ALIP tests, followed by a general description of the test facilities at MSFC that enable the liquid-metal testing.

A. STIRLING TEST ARTICLE

Two P2A (formerly EG-1000) 1 kW free-piston Stirling power convertors (Sunpower Inc., Athens, OH) were used. The P2A units are designed to produce 1.1 kWe at the following operating conditions: 550 °C hot-end temperature, 50°C cold-end temperature, a mean working pressure of 3.0 MPa, and a piston amplitude (stroke) of 10 mm. After baseline testing at GRC using electric heating, the convertors were retrofitted with new heater heads featuring NaK heat exchangers to allow the convertors to be interfaced with the pumped-NaK reactor simulator system at MSFC. The development of these interfaces was completed by GRC, SEST Inc. (Middleburg Hts., OH), and Sunpower, Inc., and the details are provided in Ref. [7,11].

The resulting integrated liquid metal heat exchanger / P2A heater head / convertor configuration for a single convertor is shown in Fig. 1A. The dual opposed convertor configuration employed two independent heat engines - heat exchanger assemblies mounted "head-to-head" so as to minimize vibration-induced loads on the test setup. A mechanical support structure connected the alternator pressure vessel portions of the two convertors and acted as the mounting structure for the entire assembly. A common supply line provided liquid metal to each convertor. The convertors mounted in the MSFC test facility are shown in Fig. 1B.

B. ALIP TEST ARTICLE

The ATC apparatus, shown schematically in Fig. 2, was fabricated to allow for performance testing of liquid metal induction pumps. The present test circuit consists of the ALIP, an induction heater, a throttling valve, an electromagnetic flow meter, and a gaseous nitrogen-to-NaK heat exchanger. A large pipe size (3 inch sch 10 stainless steel piping) was employed to minimize the viscous flow losses throughout the loop. The MSFC-designed throttling valve was used to control the flow impedance and commensurate pressure drop around the flow path, providing the ability to adjust the flow conditions throughout the course of the test.

The primary test article is the ALIP. Three-phase power was applied to the pump to produce an axially travelling magnetic wave. This magnetic wave induces currents in the liquid metal, which subsequently interact with the

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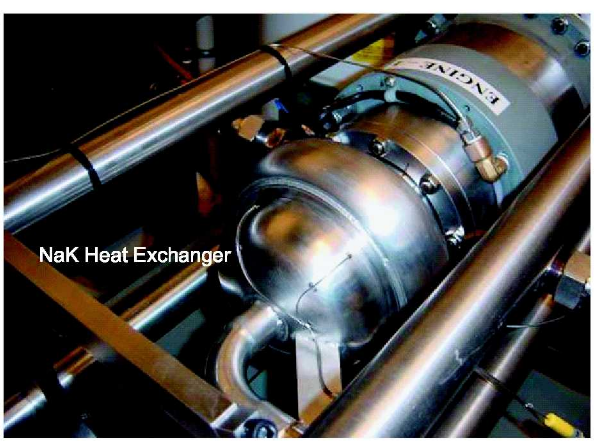

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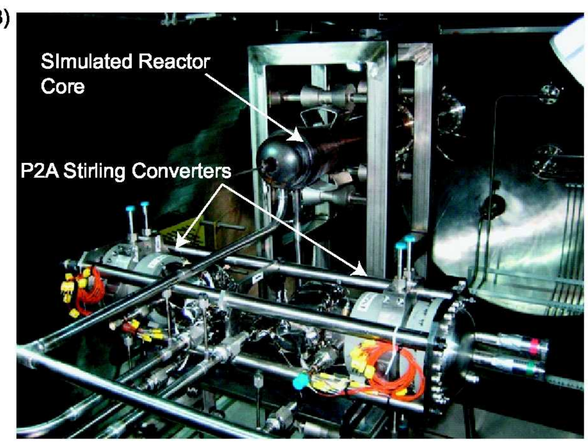

Figure 1. A) Single P2A free-piston Stirling power convertor with a NaK heat exchanger. B) P2A Stirling power convertors installed in a pumped-NaK reactor simulator.

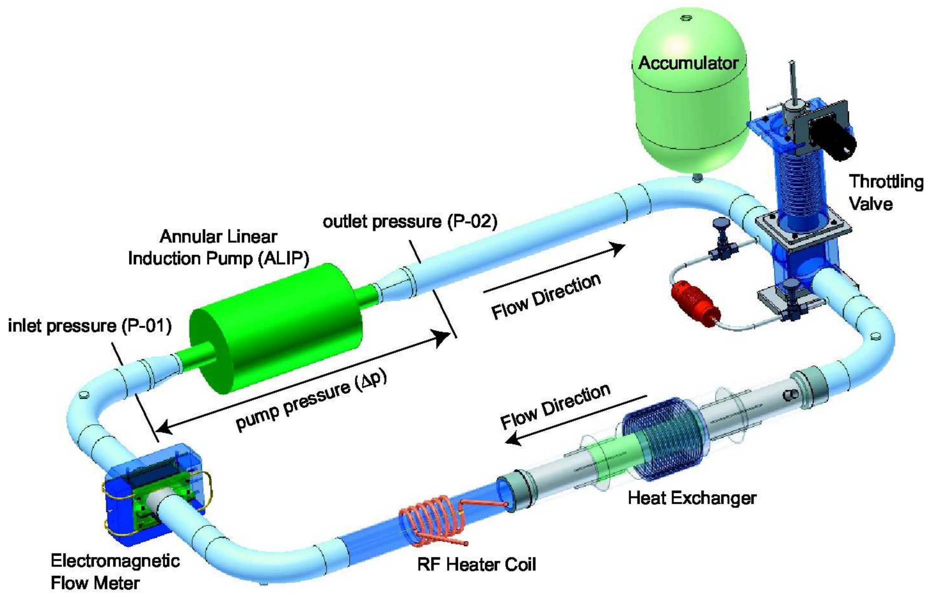

Figure 2. Schematic of the ALIP Test Circuit

magnetic field to produce a Lorentz body force on the fluid, pushing it through the system. The power could be adjusted in both frequency and voltage, allowing for testing over a broad envelope of test conditions.

Pressure rise across the pump was measured by calculating the difference between using two Delta-Metrics absolute pressure transducers. An MSFC-designed electromagnetic flow meter employing permanent magnets was employed to monitor the flow rate in the system. Finally, the input power to the pump was measured using an Ohio Semitronics two-meter wattmeter (model P-144D).

C. NASA-MSFC TEST FACILITY

Testing at NASA-MSFC was conducted in a 2.75-m diameter, 7.6-m long stainless steel vacuum chamber. The vacuum level inside the chamber was roughly 10 mtorr. The vacuum capability reduces oxidation of the test article and limits the heat transfer allowing for easier testing at elevated temperatures. It also serves as a secondary containment for any possible NaK spills.

III. TEST RESULTS

Results from testing of both the Stirling power converters and the ALIP are presented in this section. These results are not inclusive of all the testing performed, but instead are selected as representative cases illustrating the capability to perform accurate measurements using the respective test articles.

A. STIRLING TEST RESULTS

The performance of the convertors was measured at operating conditions (temperatures and piston amplitudes) for which data were acquired during baseline testing using electric heater heads. During these tests, the convertors were operated at hot-end temperatures ranging from 400 to 550 °C, cold-end temperatures from 30 to 70 °C, and piston amplitudes from 6 to 11 mm. The total NaK mass flow supplied to the converters was 700 to 900 g/s. The NaK flow decreased as the test proceeded and the pump temperature increased. Data presented in Fig. 3 show the combined power output of both convertors at steady-state conditions plotted as a function of piston amplitude. Power output increases with both temperature ratio and piston amplitude. The power output at the design condition was 2026 watts for the convertor pair. The maximum power output was 2375 watts at a hot-end temperature of 550 °C, cold-end temperature of 50 °C and piston amplitude of 11 mm.

A comparison of the power output of the dual P2A units configured with the NaK heater heads with that of the converters configured for electric heating (baseline data) is presented in Fig. 4. These comparisons are representative of comparisons at other temperature ratios. In these tests, the performance of the convertors coupled to the pumped NaK system equaled or outperformed the electrically-heated convertors. These results demonstrate that Stirling convertors can be interfaced with a pumped NaK loop and maintain power conversion performance.

Data showing the sensitivity of the Stirling convertor electrical output power to changes in NaK mass flow at

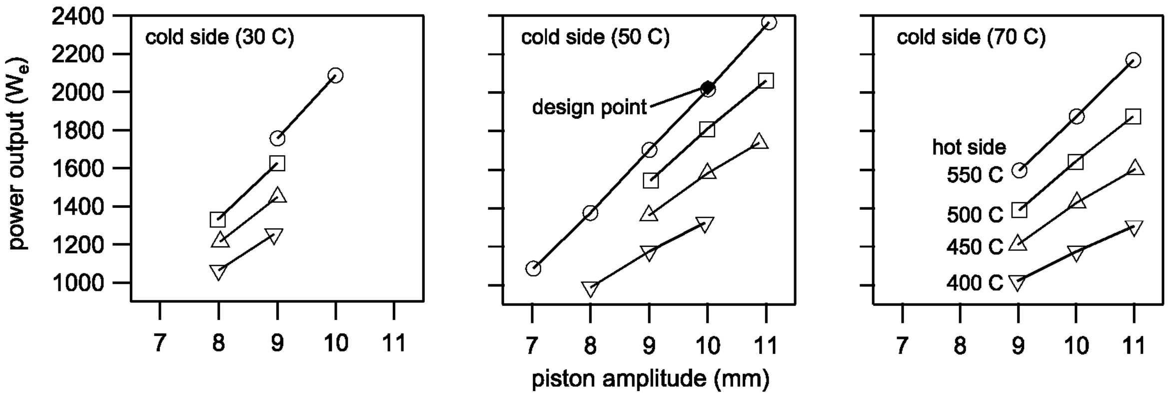

Figure 3. Combined power output of dual P2A Stirling power convertors, operating in the pumped-NaK system, as a function of piston amplitude.

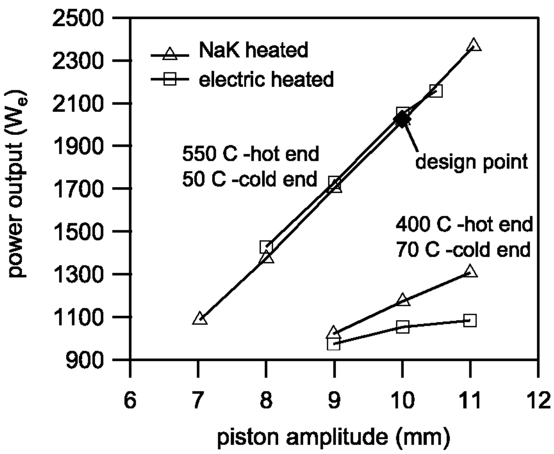

Figure 4. Comparison between electrically heated (baseline) and pumped-NaK system output of dual P2A Stirling power convertors as a function of piston amplitude.

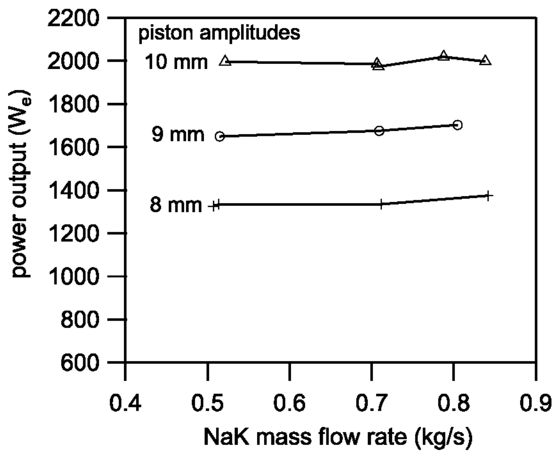

Figure 5. Sensitivity of dual P2A Stirling power converter outputs at different piston amplitudes as a function of NaK mass flow rates.

piston amplitudes of 8, 9, and 10 mm are presented in Fig. 5. These data were acquired at the nominal design hot-end (550°C) and cold-end (50°C) temperatures, and demonstrate that convertor electrical output was insensitive to reductions in NaK mass flow rate. The maximum mass flow rate in each case was limited by the capacity on the pump and the lower limit was selected to limit thermal stresses by constraining the temperature difference across the heater head.

Transient testing was conducted to study fault tolerance, start-up scenarios, and reactivity feedback response of the reactor simulator. In the scenario presented in Fig. 6A, the hot-end temperature is gradually decreased, reducing both the heat input to the convertors and the commensurate electric power output. While in this case the cooling rate is fairly benign and test apparatus limited, a faster rate on a different system could violate a thermal transient timescale constraint. This could necessitate some type of piston amplitude modification to reduce the amount of heat removed from the NaK by the convertors. Start-up scenarios all entailed the following steps, which can be observed in the time-history. The NaK pump was started to provide the desired mass flow rate and then heating was applied to elevate the NaK temperature to an initial setpoint. At the setpoint the convertors were started and operated at an initial piston amplitude of 6 mm and the system was then allowed to reach steady-state. Finally, the NaK temperature was increased to the Stirling convertor design hot-end temperature of 550 °C while the piston amplitude was ramped to 10 mm. Depending on the test, the initial Stirling hot-end temperature setpoint ranged from 200 °C to 500 °C and the NaK system mass flow rate ranged from 600 – 900 g/s. A representative start-up scenario is presented in Fig. 6B showing the increase in power extracted by the converters as a function of time.

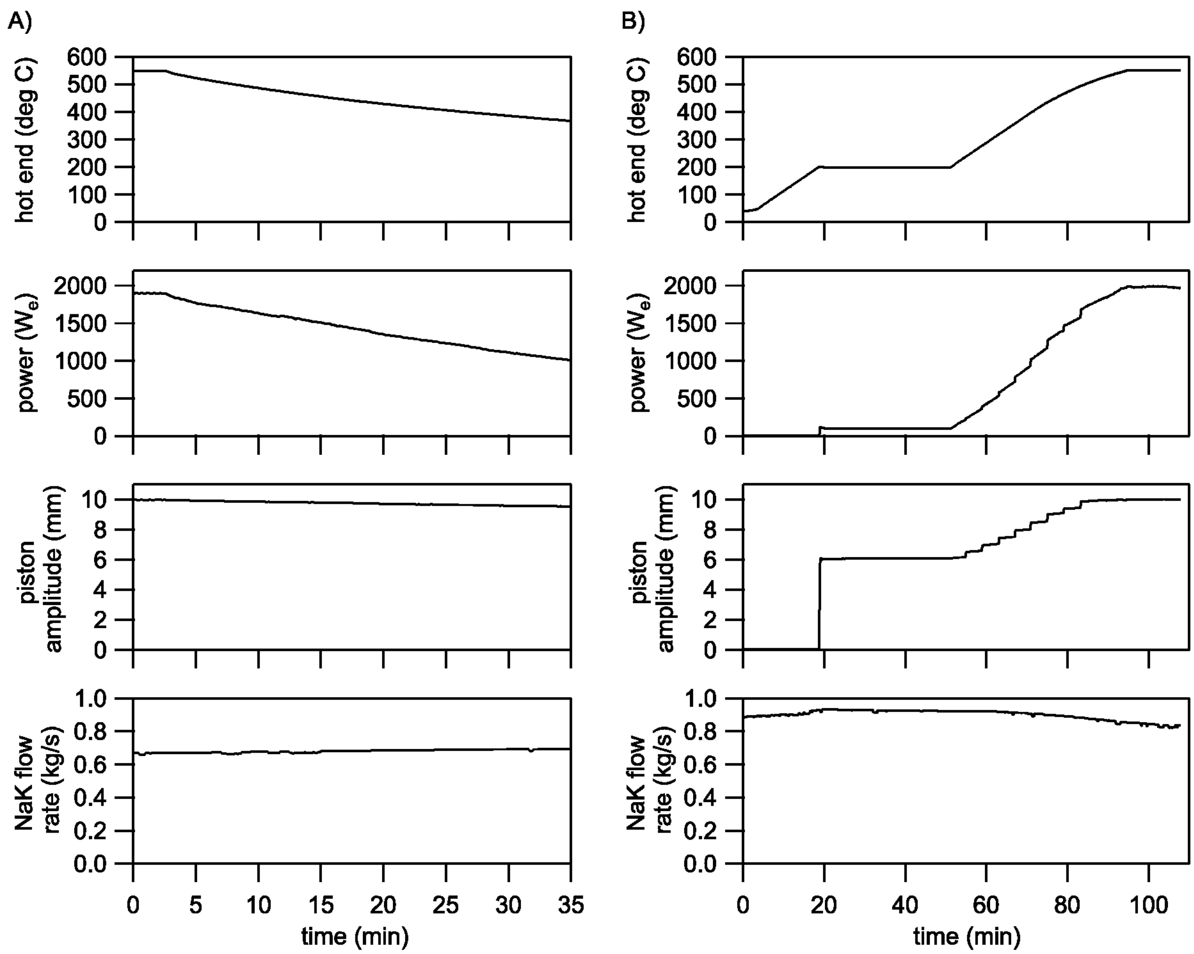

Figure 6. Transient Stirling converter data: A) high temperature cool-down, B) full flow rate low temperature start-up.

B. ALIP TEST RESULTS

Presented in this section are performance measurements obtained during the course of testing. These data consist of volumetric flow rate ($\dot{v}$), pressure rise across the pump (Δp), input power (P_{IN}), and efficiency (η). Efficiency is equal to the fluid power divided by the input electrical power and is given as

$$\eta = \frac{\Delta p \ \dot{v}}{P_{IN}} \tag{1}$$

Before presenting the measured performance data, it is important to note that this pump encountered some issues during the fabrication process that could lead to a lower than expected efficiency. A few of the major issues are summarized as follows. The copper coil windings were thicker than expected, so fewer coil turns were possible, leading to a magnetic field strength at a given applied current level that was lower than the design value. Also, there is an uncertainty in the magnetic properties of the stators and flux return of the torpedo. This could be due to low cobalt content of the alloy or improper annealing, either of which could result in reduced magnetic field strength in the channel for a given applied power. Finally, as will be shown in the data, the currents supplied to each of the three phases were not equal. This may be due to a short-circuit between coils, unbalanced mutual inductance between the different coils, or end effects causing the inductance of each leg to be slightly different. Consequently, while the efficiency of this pump is admittedly lower than was expected, these data should not necessarily be taken as representative of the best possible performance for an ALIP. These issues are detailed and addressed in a companion report.[8]

To demonstrate the remarkably clean nature of the test data, each individual data point over roughly 215 minutes of testing is plotted in Figure 7. These data were acquired at a sampling rate of 1 Hz, a NaK temperature of 325 °C, and an ALIP frequency of 36 Hz. Each line of dots in the upper graph represents operation at a constant pump voltage. Concentrations of data points represent flow characteristics measured at steady-state flow conditions while the

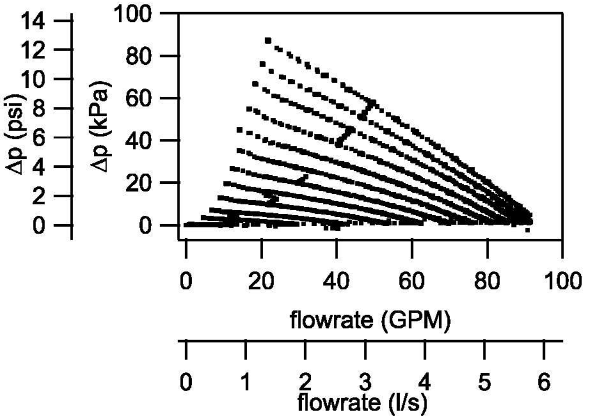

Figure 7. Raw test data (325 °C NaK temp., 36 Hz pump freq.) over 215 mins at a sample rate of 1 Hz presented as Δ*p* as a function of flow rate.

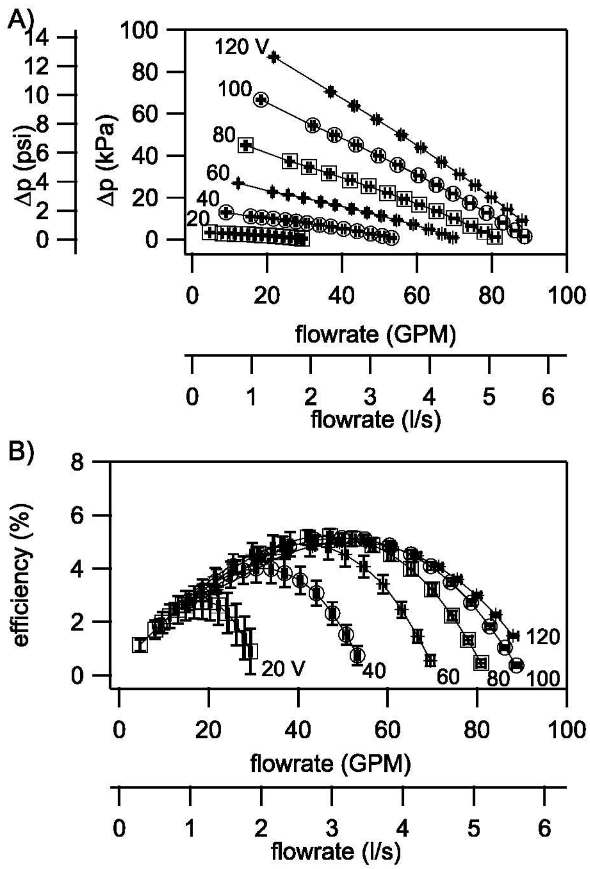

Figure 8. Reduced test data (325 °C NaK temp., 36 Hz pump freq.) at selected pump voltages presented as A) Δ*p* and B) efficiency as a function of flow rate (error bars shown).

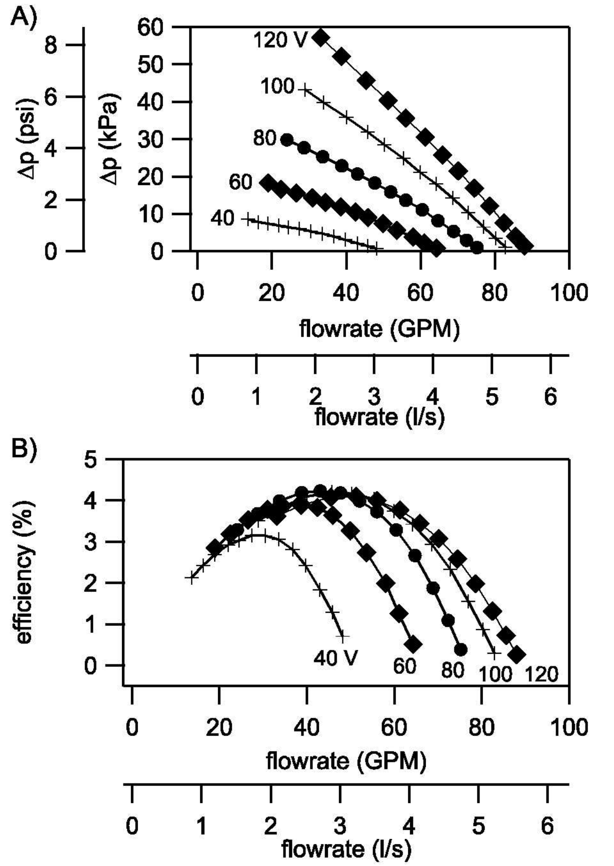

Figure 9. Reduced test data (525 °C NaK temp., 36 Hz pump freq.) at selected pump voltages presented as A) Δ*p* and B) efficiency as a function of flow rate

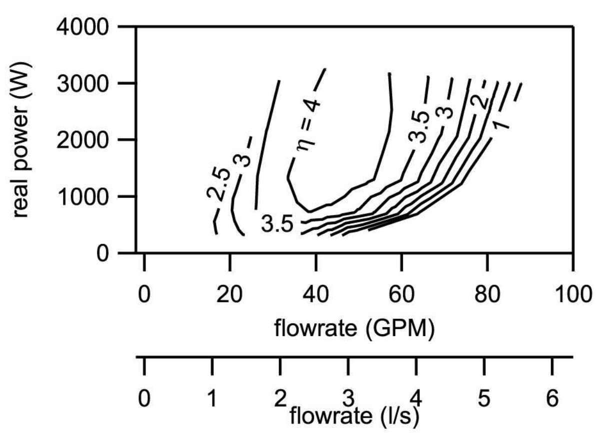

Figure 10. Measured efficiency contour plots (525 °C NaK temp., 36 Hz pump freq.) as a function of real power to the pump and flow rate.

throttling valve was stationary (roughly 40-60 s dwell time). The individual dots forming the rest of the lines represent data obtained while the valve was transitioning from one setpoint to the next. Each efficiency point was computed using the flow rate, Δp, and input power as measured and recorded on the data acquisition system.

Select data presented in Figure 7 were analyzed and are presented as pump performance curves in Figure 8. The data were analyzed at steady-state flow conditions. Each curve is labeled with the ALIP operating voltage for that particular performance curve. The error on calculated efficiency is given in the standard manner[12] assuming no cross-correlation between the errors on the three measured parameters. The error bars for the data set are small compared to the magnitude of the measurement. Those on the calculated efficiency are smallest at the highest flow rates and voltages, and grow larger as the flow rate or voltage is reduced.

Pump performance and efficiency data are presented in Figure 9 for a NaK temperature of 525 °C, which corresponds to the nominal operating temperature in the FSP system. These data show a peak efficiency of slightly more than 4% at maximum voltage. While constant applied voltage lines are an approximation of constant real power supplied to the pump, they are not, strictly speaking, the same. Consequently, a contour plot of efficiency as a function of both flow rate and input power is presented in Figure 10 to illustrate the constant power performance of the pump. The contours are as expected for a pump with higer efficiency peak in the center at higher power levels.

IV. CONCLUSIONS

The non-nuclear testing capabilities at MSFC enabled the successful evaluation of two components that are critical in the FSP reference mission system design. Stirling power converters were coupled to a pumped NaK reactor simulator system, and demonstrated performance that met or exceeded that measured in baseline testing. The units produced a maximum combined power output of 2375 watts and the test setup allowed for the varying of controllable parameters during testing, allowing for the quantification of the response of the converters to changing conditions and transients. A pumped NaK system with active heating was specially designed and fabricated to permit performance evaulation of annular linear induction pumps. The system allowed for accurate quantification of the performance, with errors on all the measurements generally much smaller than the magnitude of the measurements themselves. Pump performance spanned the range of flow rates from roughly 0.16 to 5.7 l/s (2.5 to 90 GPM), and Δp levels from less than 1 kPa to 90 kPa (>0.145 psi to roughly 13 psi). The maximum efficiency measured at the nominal FSP system operating temperature of 525 °C was just over 4%.

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