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Performance of a Kilowatt-Class Stirling Power Conversion System in a Thermodynamically Coupled Configuration

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Abstract

A pair of 1-kWe free-piston Stirling power convertors has been modified into a thermodynamically coupled configuration, and performance map testing has been completed. This is the same configuration planned for the full-scale 12-kWe power conversion unit (PCU) that will be used in the Fission Power System Technology Demonstration Unit (TDU). The 1-kWe convertors were operated over a range of conditions to evaluate the effects of thermodynamic coupling on convertor performance and to identify any possible control challenges. The thermodynamically coupled convertor showed no measureable difference in performance from the baseline data collected when the engines were separate, and no major control issues were encountered during operation. The results of this test are guiding controller development and instrumentation selection for the TDU.

Introduction

Free-piston Stirling power conversion has been identified as a viable option for potential Fission Power Systems (FPSs) on the Moon and Mars (Mason 2006a; 2006b). Recent studies have examined the use of Stirling convertors coupled to a low temperature (<900 K), uranium-dioxide fueled, liquid-metal-cooled reactor for potential lunar application in the year 2020. The system is considered a low development risk based on the use of terrestrial-derived reactor technology and conventional materials (Fission Surface Power Team, 2010). In addition, all materials and components are compatible with the lunar and martian environments. Therefore, Mars-based power conversion system designs are expected to be very similar to lunar designs in configuration, set-up, and operations (Geng 2008).

NASA Glenn Research Center (GRC) has been involved in Stirling convertor research in support of FPS development over the past several years. In 2007, two P2A (formerly known as EG–1000) 1-kW free-piston Stirling power convertors were procured from Sunpower Inc., of Athens, Ohio. The P2As are designed to produce 1.1 kWe at their design operating conditions of 550 °C hot-end temperature, a 50 °C cold-end temperature, and a mean working space pressure of 3.0 MPa. The P2As are typically configured with a gas burner for thermal energy input; however, the P2As as initially delivered to GRC were configured with electric heater heads to simplify testing. In 2008, a performance map test (over various hot- and cold-end temperatures and piston amplitudes) was conducted at GRC to establish the baseline Stirling convertor performance (Briggs 2010a). The P2As were operated for about 48 hr during this baseline testing. After the performance map test was completed, the convertors were reconfigured; the electric heater heads were replaced with GRC designed and developed NaK heat exchangers. The NaK heat exchangers enabled the Stirling convertors to be operated with a NaK liquid metal pumped loop for thermal energy input. In addition to the NaK heat exchangers, the Stirling cold-end heat exchangers were also replaced. The original P2A coolers utilized o-rings to contain the cooling water. To minimize the chance of a water leak, new coolers were built and installed that utilized braze joints to contain the cooling water. The convertors were then tested in the Marshall Space Flight Center (MSFC) pumped NaK loop test facility during the summer of 2009 (Briggs 2010b; Polzin 2010). This was the first-ever attempt at powering a free-piston Stirling engine with a pumped liquid metal heat source. The tests included a) performance mapping the convertors over various hot- and cold-end temperatures, piston amplitudes, and NaK flow rates, b) transient test conditions to simulate various startup and fault scenarios, and c) simulated nuclear reactivity feedback control tests. The P2As were operated for about 66 hr during testing at MSFC.

After the successful test at MSFC, the convertors were reconfigured a second time. The NaK heat exchangers were removed from the convertors and replaced with a modified electrically heated head. The new heater head is basically the two original heater heads joined at their domes. A short stainless steel joining ring was fabricated and welded to the heater head domes of each engine. The joining ring contains a passage along its axis of symmetry that connects the expansion spaces of the two convertors. There are three advantages associated with this type of arrangement: 1) the common expansion space helps to synchronize the frequencies of the two convertors, thereby reducing vibration, 2) the footprint of the dual power convertors is reduced (the engine pair is about 18 in. shorter in the new arrangement), and 3) electrical control of the convertors is potentially simplified. This new configuration is referred to as the "thermodynamically coupled arrangement" since the expansion spaces of each convertor are now in direct communication.

In late 2010, the performance map test (over various hot- and cold-end temperatures and piston amplitudes) was repeated for the thermodynamically coupled configuration. The P2As were operated for about 26 hr in this configuration. The data from this test were then compared with the baseline data so that any changes in performance due to the new configuration could be evaluated. After correcting the data for slight differences in the experimental test conditions, it was determined that performance data from the thermodynamically coupled configuration was essentially the same as the baseline data.

Nomenclature

FLDT Fast Linear Displacement Transducer
FPS Fission Power System
GRC Glenn Research Center
MSFC Marshall Space Flight Center
MTI Mechanical Technology Incorporated
RTD Resistance Temperature Detector
SPDE Space Power Demonstrator Engine
TDU Technology Demonstration Unit

Thermodynamically Coupled Engine Configuration

Joining a pair of free-piston convertors at their expansion spaces is not a new concept. Mechanical Technology Inc. (MTI), of Latham, New York, designed, built, and tested the Space Power Demonstrator Engine (SPDE) in the 1980s, which was configured in a thermodynamically coupled arrangement (Brown 1987; Dhar 1999). The SPDE was a 25-kWe free-piston Stirling power convertor that consisted of two 12.5-kWe engine submodules that operated with a linearly opposed piston/displacer motion. The SPDE was designed for steady-state operation at its design point (Thot = 630 K, Tcold = 315 K, and Frequency = 105 Hz), and as such, had no control system. MTI learned that for the two engines to operate at a 180° phase relative to each other, a stable power flow path needed to exist between the two engines. MTI identified two potential flow paths: 1) electrical—by connecting the two alternators in series or in parallel with each other, or 2) mechanical—by connecting the two engines thermodynamically at their expansion spaces. The SPDE utilized both power flow paths to ensure stable operation with the alternators connected in parallel.

Sunpower also explored the thermodynamically coupled configuration in the past. Sunpower joined a pair of 2.5-kWe free-piston Stirling engines at their expansion spaces (Lane 1996). The coupled engine pair ran smoothly; no instability was observed over the full power range tested.

Many Stirling engine designers believed that the thermodynamically coupled configuration would not have a negative impact on engine performance. The work described in this paper was performed in an attempt to verify this belief experimentally.

A photograph and sketch of the joined P2A heater heads are shown in Figure 1. The heater head is electrically heated using 12 cartridge heaters per engine. The cartridge heaters are mounted in a nickel ring that is brazed to the expansion space dome, adjacent to the Stirling heat exchanger. Also shown in the picture are the thermocouple locations for measuring the heater head temperatures. The passage connecting the two expansion spaces is tapered from a diameter of about 14 mm down to 6 mm. The helium gas flow through this passage is extremely low since the pressure waves in each engine are in phase.

Figure 2 shows the P2A engines mounted on the test stand at GRC. In this figure, the heater head is covered with several layers of Kaowool insulation and contained within a stainless steel can. The Fast Linear Displacement Transducers (FLDTs) that are used to measure the piston and displacer positions protrude from the alternator housings. Two of the four cooling water temperature measurement locations are also shown. The convertor pair is supported on a pair of springs that allow movement in the axial direction, but are firm in the radial direction.

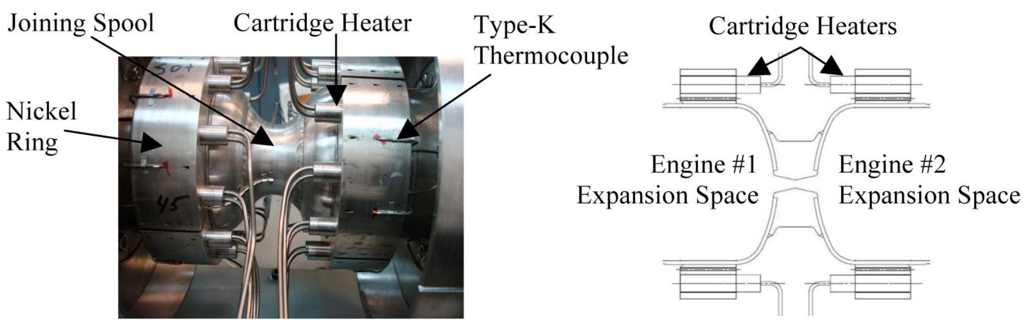

Figure 1.—P2A Stirling heater heads joined at expansion space.

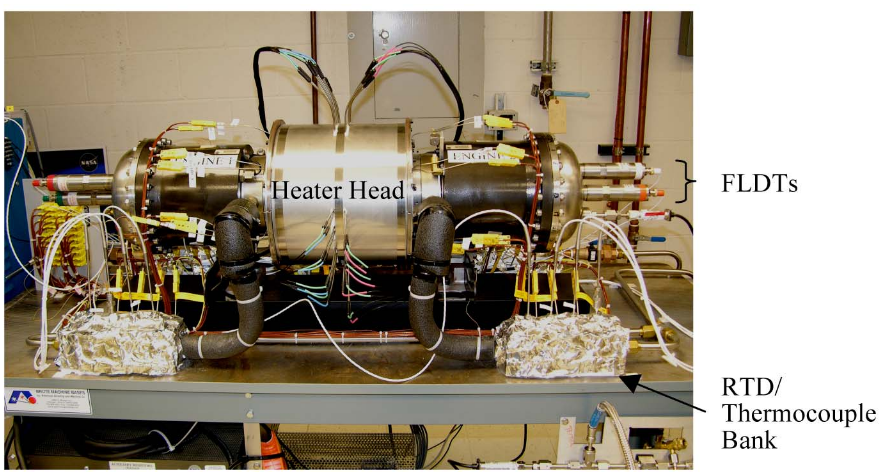

Figure 2.—Thermodynamically coupled 1-kWe Stirling convertors.

Performance Map Testing

Test Setup

Testing was conducted on the 1-kWe thermodynamically coupled Stirling engine pair in the Stirling Research Facility at GRC. The test rig, shown in Figure 3 and represented schematically in Figure 4, consists of two Variacs (one for providing power to each engine heater head), two free-piston Stirling convertors, a chiller for heat rejection, a helium fill station, two alternating current (AC) power supplies (used for piston control), and a data acquisition system.

Power is provided to the cartridge heating elements through two Variacs that receive 208 VAC from the facility power grid. Piston frequency and amplitude, as well as convertor synchronization were controlled using two AC power supplies that apply an AC voltage across the alternator of each convertor. Electric power produced by the alternators was dissipated using 39.7 Ω load resistors. Waste heat was rejected to a circulating water loop that is cooled by a Neslab HX–300 recirculating chiller. Hot-end, cold-end, and alternator housing temperatures, as well as all coolant inlet and exit temperatures, were monitored using type-K thermocouples. Cooling water flow rates were measured using turbine flow meters on the cooling supply line. Piston and displacer amplitudes were calculated from FLDT position sensor measurements.

A key improvement to the test setup (from when the baseline data was obtained) was the addition of several Resistance Temperature Detectors (RTDs) on both the cooling water inlet and outlet lines. The RTD measurements were averaged for each the inlet and outlet to obtain the cooling water temperatures. These RTDs have made a dramatic improvement to the calculation of the thermal energy removed from the convertors and in the overall energy balance. During the baseline testing, single thermocouples were used to measure each of the cooling water inlet and outlet temperatures.

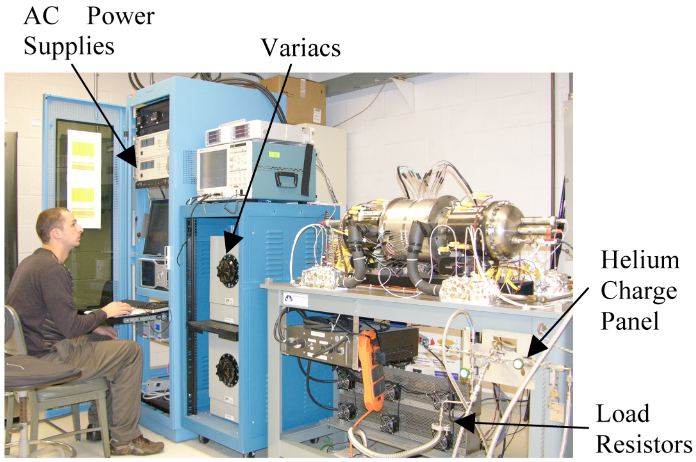

Figure 3.—A 1-kWe dual-opposed Stirling engine test rig.

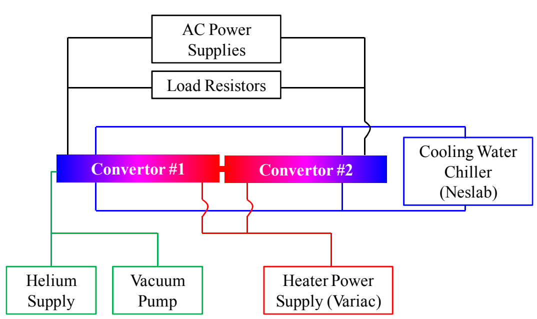

Figure 4.—Schematic of test rig.

Method

Performance map testing involved measuring power output and gross thermal efficiency (Crowley 1983) of each convertor over a matrix of hot- and cold-end temperatures and a range of piston amplitudes. These convertors were designed to operate at a charge pressure of 3.0 MPa, a hot-end temperature of 550 °C, and a cold-end temperature of 50 °C, at a piston amplitude of 10 mm. During performance map testing, the convertor hot-end temperature was varied between 400 and 550 °C, in increments of 50 °C, at cooling water inlet temperatures of 30, 50, and 70 °C. At the design hot- and cold-end temperatures, the power piston amplitude was varied from 6 to 11 mm in increments of 1 mm. At all other hot- and cold-end temperatures, the power piston amplitude was varied from 9 to 11 mm in increments of 1 mm.

Due to a constraint on the AC power supplies used to control the pistons, the power factor was maintained above 0.93 for all test conditions. Some of the planned data points were omitted from the test matrix to prevent this constraint from being violated. This constraint came into play at high piston amplitudes, low hot-end temperatures, and low cold-end temperatures during both baseline testing and thermodynamically coupled testing. However, the power factors observed during thermodynamically coupled testing were higher than those observed during baseline testing at nearly every operating condition, particularly for engine 1; as a result, more data points were obtained during the thermodynamically coupled testing. The reason for the higher power factors measured for engine 1 might be due to a change in its motor constant. This change is discussed in more detail later in the paper.

Results

The performance maps of the thermodynamically coupled configuration are shown in Figures 5 and 6. Each data point shown in these maps is the average of 150 measurements taken at 2-sec intervals over a 5-min. period. Each 5-min. period began when the alternator gas temperature (the last temperature to reach steady state) changed at a rate of no more than 1 °C over a 5-min. period. The legends shown in Figures 5 and 6 indicate the hot- and cold-end temperatures of the convertors in Celsius. As expected, power increased approximately linearly with piston amplitude especially close to the design operating condition. Efficiency reached a maximum at about 8 mm of piston amplitude. Efficiency plots for the various hot- and cold-end temperatures, but at similar temperature ratios lie in good agreement with each other. For example, the 550/70 (temperature ratio = 2.40) and 500/50 (temperature ratio = 2.39) efficiency curves are almost identical. This is all consistent with results observed previously for the baseline testing.

Comparison With Baseline Configuration

The performance of the convertors in the thermodynamically coupled configuration is approximately the same as the baseline measurements. Although the data recorded during this test are slightly below the baseline data in terms of performance, the major reasons for these differences are not related to the thermodynamically coupled configuration. Differences in the experimental conditions are the biggest reason for the differences in the data. First of all, there were slight differences in the Stirling convertor cold-end temperatures between the baseline and thermodynamically coupled data. A single thermocouple was used to measure the cooling water inlet temperatures during the baseline testing. A set of three RTDs were averaged to measure the cooling water inlet temperatures during the recent test. In addition, the cooling water inlet temperatures during baseline testing were adjusted using a crude correlation to obtain the desired cooler metal temperatures. During the thermodynamically coupled configuration test, this correlation was not used to adjust the cooling water inlet temperature. This implies that the thermodynamically coupled Stirling convertors were tested at slightly higher cold-end temperatures (i.e., lower engine temperature ratios) than the baseline configuration. The approximate loss in engine power due to the reduced temperature ratios is about 1 percent per engine. As a result, the loss in convertor power output is approximately 10 W per convertor at the design operating conditions.

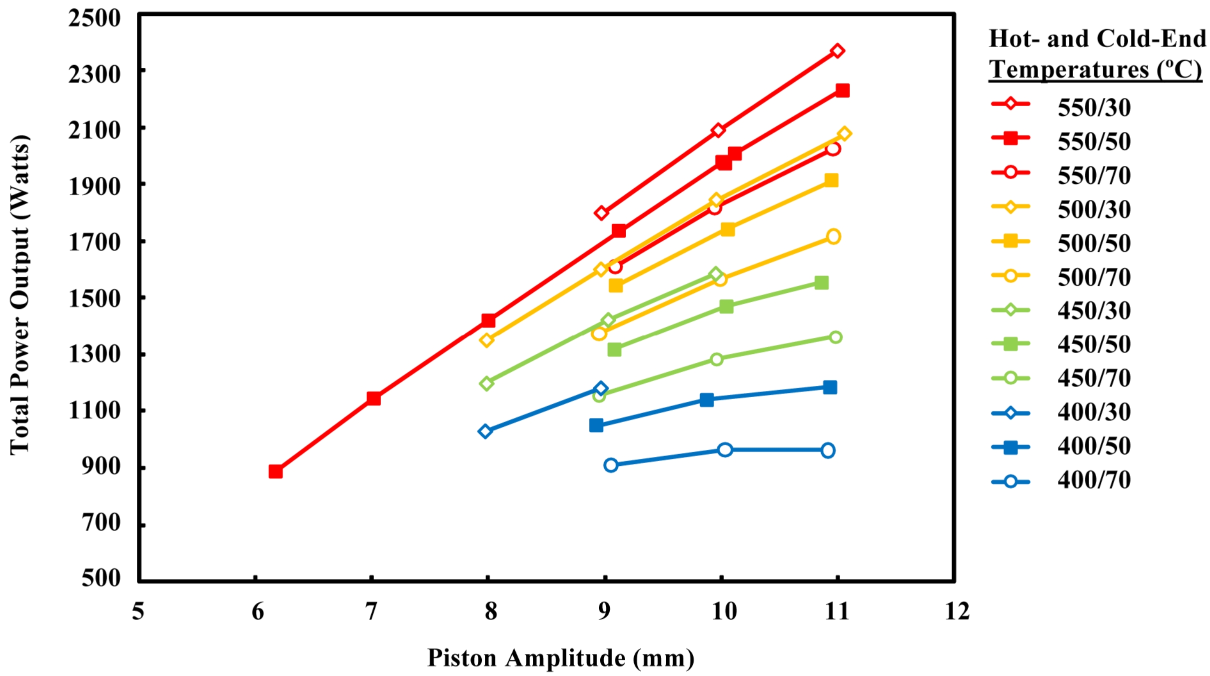

Figure 5.—Total power output of thermodynamically coupled convertors versus Piston amplitude.

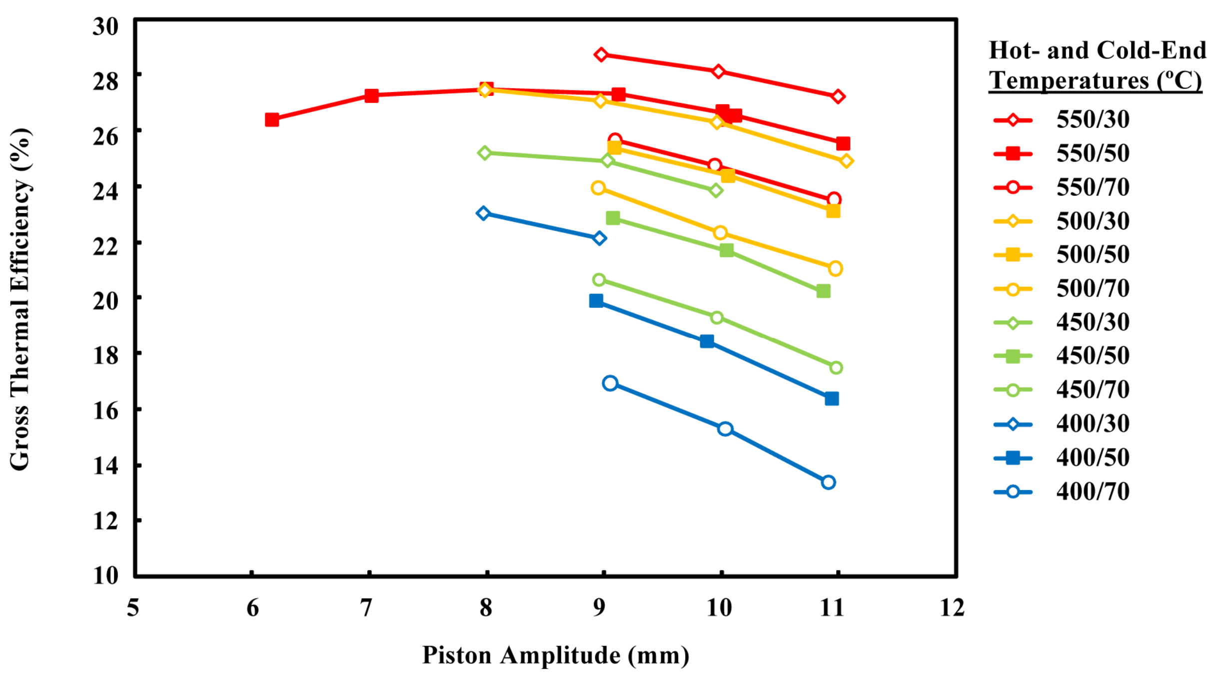

Figure 6.—Gross thermal efficiency of thermodynamically coupled convertors versus Piston amplitude.

A second reason for the slightly lower performance of the thermodynamically coupled configuration is that the motor constant of one of the two alternators was about 1.9 percent lower than what it was during the baseline testing at design operating conditions. The motor constant of the second alternator had not changed. The impact of the lower motor constant is that the alternator voltage has dropped by about 1.9 percent while the current has increased by about 1.9 percent at a given piston amplitude and frequency. The additional alternator current increases the I^2R loss by about 3.5 percent, which in turn reduces the measured alternator output power by about 0.4 percent (assuming a 90 percent efficient alternator). The reason for the change in the motor constant is most likely due to a reduction in the flux density of the magnets in one of the alternators. Since both alternators have experienced similar temperatures and operating conditions throughout the entire test program, differences in the intrinsic coercivities between the sets of magnets could be the cause. The intrinsic coercivity of a magnet has a direct impact on its demagnetization temperature in a given application. At the design operating conditions, the loss in convertor power output due to the motor constant degradation is approximately 3 to 4 W.

In Figure 7, the total power output of the thermodynamically coupled engines is compared with that of the baseline configuration. The data shown in this figure were acquired for the convertors operating at a hot-end temperature of 550 °C and cold-end temperature of 50 °C. The thermodynamically coupled data are shown both as recorded and as corrected for the differences in the experimental conditions as described previously. The actual and corrected data are in good agreement with the baseline data over the range of piston amplitudes tested. At design operating conditions (Thot = 550 °C, Tcold = 50 °C, and Piston Amplitude = 10 mm), the thermodynamically coupled convertors produced approximately 2 kWe as expected.

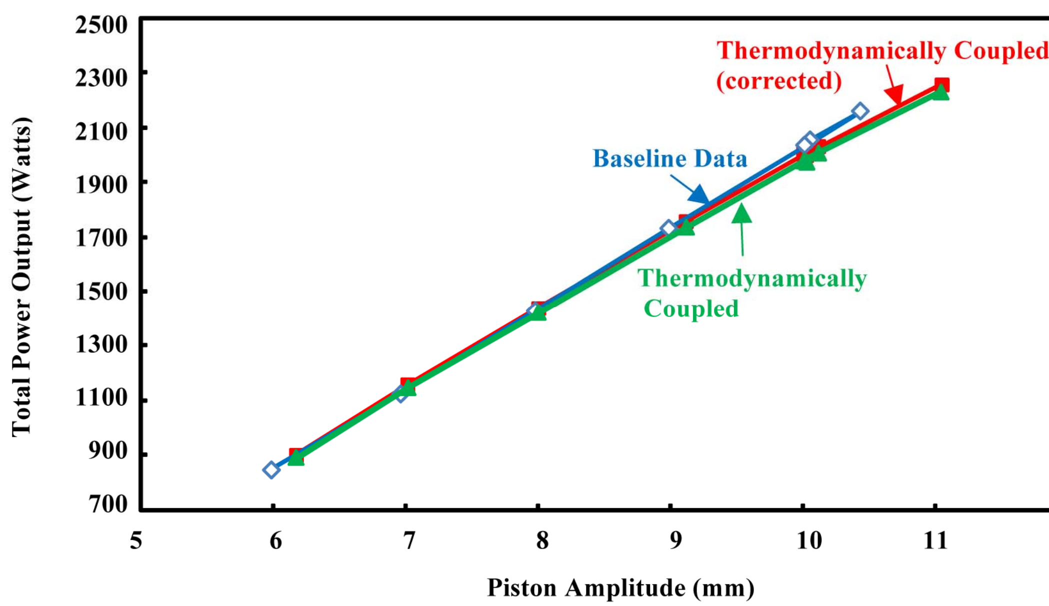

Figure 7.—Comparison of total power output of thermodynamically coupled configuration (Corrected for differences in experimental conditions) with baseline data.

The minor differences in performance between the two configurations, as shown in Figure 7, can be attributed to the small increase in dead volume associated with the thermodynamically coupled configuration. The joining spool that is used to connect the expansion spaces of the two convertors adds approximately 5.6 cc of dead volume to each convertor. With the baseline P2A engine working space volume of 537 cc, the joining spool adds only 1 percent of additional volume. Sunpower computer simulation of the P2A convertors predicted about a 0.5 percent power degradation (per engine) with the additional 5.6 cc dead volume in the expansion space (Wood 2011).

Conclusions

Significant progress has been made toward reducing the risk associated with the development of Stirling power conversion technology for potential FPS applications. A pair of proven 1-kWe free-piston Stirling power convertors was used to demonstrate that free-piston Stirling convertors can be joined at their expansion-spaces without dramatically affecting engine performance. The advantage of this type of configuration is that it can reduce the size and weight of the convertor pair, and also simplify thermal energy input for Stirling convertors interfaced with a pumped-NaK loop, as planned for the FPS Technology Demonstration Unit (TDU). Stirling technology is becoming a viable option for FPS applications.

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