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ABSTRACT

Free-piston Stirling power converters are a candidate for high capacity space power applications. The Space Power Research Engine (SPRE), a free-piston Stirling engine coupled with a linear alternator, is being tested at the NASA Lewis Research Center in support of the Civil Space Technology Initiative. The SPRE is used as a test bed for evaluating converter modifications which have the potential to improve converter performance and for validating computer code predictions. Reducing the number of cooler tubes on the SPRE has been identified as a modification with the potential to significantly improve power and efficiency. This paper describes experimental tests designed to investigate the effects of reducing the number of cooler tubes on converter power, efficiency and dynamics. Presented are test results from the converter operating with a reduced number of cooler tubes and comparisons between this data and both baseline test data and computer code predictions.

INTRODUCTION

The NASA Lewis Research Center (LeRC) is currently testing free-piston Stirling engines in combination with linear alternators to develop an advanced power converter for space electrical power generation. This testing is being conducted in support of the NASA Civil Space Technology Initiative (CSTI) High Capacity Power Program. Much of this testing is being conducted using the Space Power Research Engine (SPRE), built under contract to NASA by Mechanical Technology, Inc. (MTI) of Latham, New York. The SPRE was originally one half of the Space Power Demonstrator Engine (SPDE), a two cylinder, opposed-piston power converter used to demonstrate the feasibility of free-piston Stirling converters for meeting CSTI high capacity power goals. After successful demonstration, the SPDE was modified into two separate single cylinder converters (SPRE I and SPRE II) which serve as test beds for Stirling technology development and design code validation. Both SPRE power converters are currently at NASA LeRC.

The SPRE power converter was designed to produce 12.5 kW of electrical power at 15.0 MPa mean pressure, 2.0 temperature ratio, 100 Hz frequency and 10.0 mm piston amplitude. Figure 1 is a photograph of the SPRE, mounted to a vibration absorbing mass, suspended in the test cell. A cross section of the SPRE, showing the major components and how they are arranged, is presented in figure 2. The SPRE incorporates two moving parts, the piston and the displacer. Other major components include a tube and shell type heater and cooler, a felt metal regenerator, a linear alternator, gas springs, and hydrostatic gas bearings. SPRE testing is conducted using helium as the working gas. Thermal energy is supplied to the converter by circulating molten salt through the heater, while waste heat is removed by circulating water through the cooler. The electrical power produced by the linear alternator is absorbed by an electrical resistance load. Over 430 hours of total SPRE run time has been accumulated at Lewis. Further descriptions of the Lewis SPRE test facility and previous testing can be found in [1-4], and overviews of the Stirling space power development program can be found in [5, 6].

The performance of the SPDE did not meet the design goals of 25 kW electrical power and 25 % overall conversion

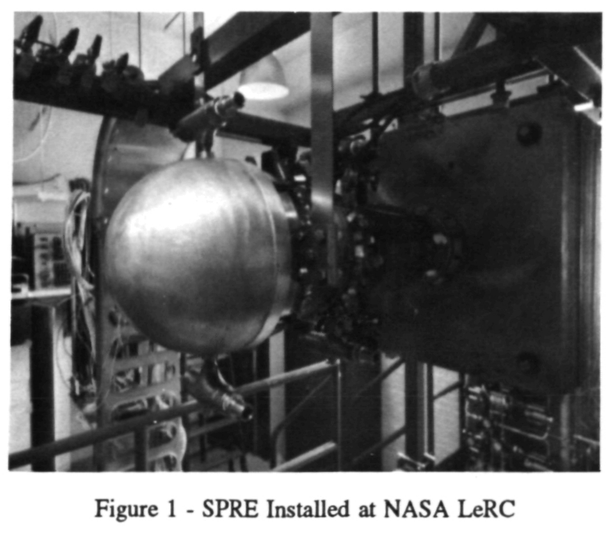

Figure 1 - SPRE Installed at NASA LeRC

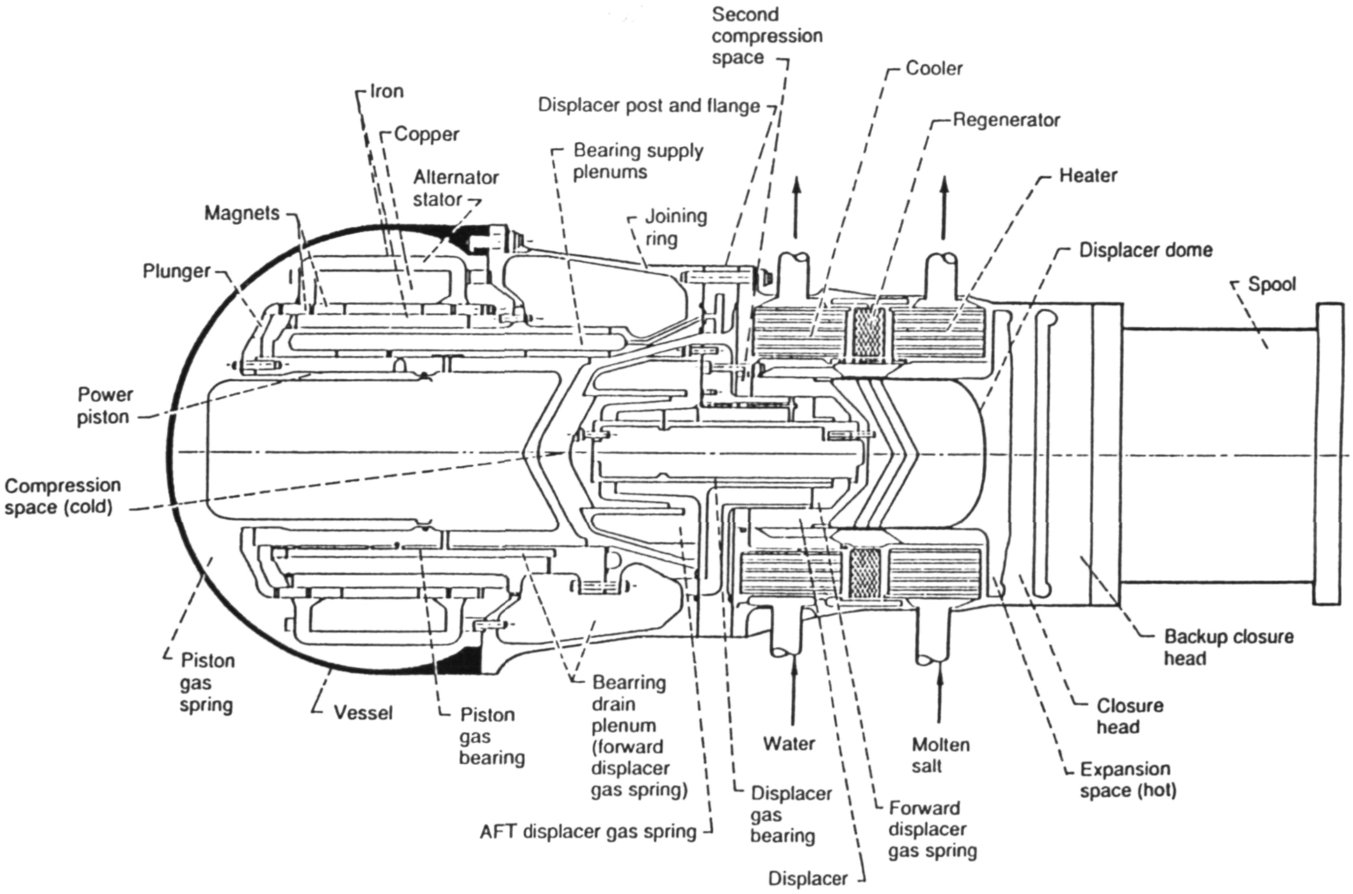

Figure 2 - SPRE Cross Section

efficiency [7]. As a result, MTI conducted a study to determine various methods of improving converter performance which could be incorporated into the SPRE. One method to improve performance that was identified, was to reduce the number of tubes in the converter cooler. The study estimated that by reducing the number of cooler tubes from the original 1584 to an optimum of 900, the piston PV power would increase by 1.6 kW and the piston PV efficiency would increase by 0.8 percentage points. Testing has been performed to investigate the effect of reducing the number of cooler tubes on power, efficiency and converter dynamics. This paper presents the results of these tests and compares this data to both baseline test data and computer code predictions.

TEST OBJECTIVES

The objectives of the reduced cooler tubes test were:

1. to determine the sensitivity of the piston PV power (rate of work of the compression space pressure against the piston) and the piston PV efficiency (percentage of the heat rate into the engine that is converted into piston PV power) to the number of cooler tubes over a wide range of SPRE operating conditions, i.e. piston amplitude, engine mean pressure, and temperature ratio,

2. to determine the effects of reducing the number of cooler tubes on displacer dynamics and compression space dynamic pressure,

3. to compare the experimental test results to HFAST code predictions.

TEST DESCRIPTION

Most of the parts of the SPRE I and the SPRE II power converters are interchangeable. For the reported testing, the best available parts from each converter were used. Parts from the SPRE I are: the cooler, post and flange displacer drive, dome pressure vessel and the piston position sensors and sensor mounting cap; from the SPRE II: the heater head which includes the heater and regenerator, the joining ring, piston cylinder, piston plunger and linear alternator. The converter configuration for the reported tests was identical except for the number of cooler tubes and the displacers that were used; the baseline test was run with a 3.5 mil radial clearance displacer while the reduced cooler tubes test was run with a new displacer which had a 2 mil radial clearance. Previous SPRE testing has shown that this difference in displacer clearance has a minimal effect on piston PV power and no effect on piston PV efficiency [1].

The SPRE was first run with 1584 cooler tubes to obtain baseline reference data, then with 1320 cooler tubes.

Although the MTI sensitivity study indicated that the optimum number of cooler tubes is 900, the number of tubes was reduced by a smaller, more conservative increment to 1320. Tubes were blocked by inserting insulated electrical wire of the proper diameter into the tubes; a diagram depicting the procedure is shown in figure 3. The plastic insulation surrounding each wire was stripped and ground to a taper at one end to allow easy insertion into the cooler tube. The insulation was epoxied to the wire to prevent the plastic from being stripped off during insertion. A lubricant was applied to the wires before pulling them through the tubes. A photograph of the cooler with one sixth of its cooler tubes blocked is shown in figure 4.

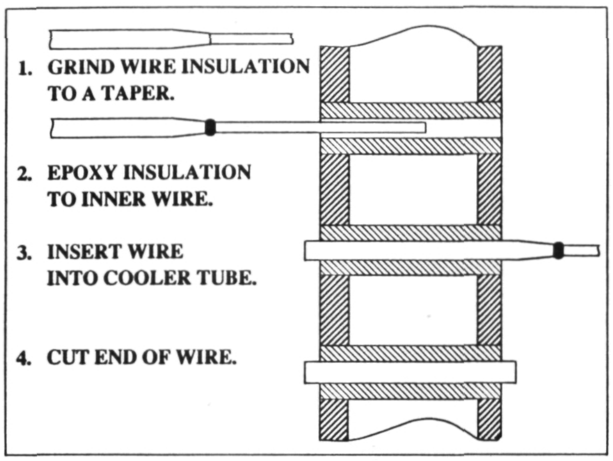

Figure 3 - Procedure for Blocking Cooler Tubes

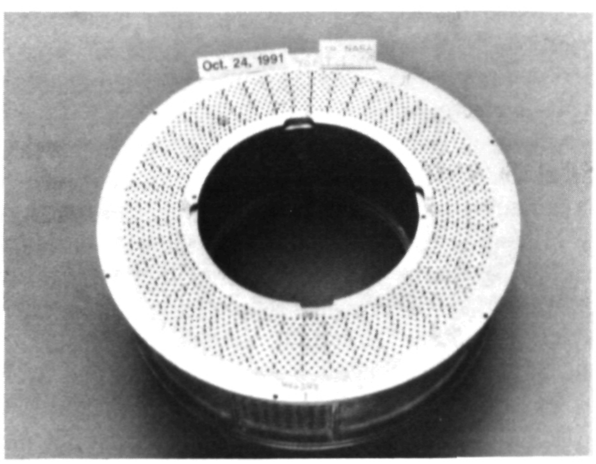

Figure 4 - SPRE Cooler with 1/6 Tubes Blocked

CODE ANALYSIS

The Stirling computer code, HFAST version 2.00E, was used to model the effects of reducing the number of cooler tubes. HFAST was developed by MTI under contract with NASA. Only thermodynamic modelling was performed; dynamic motions in the engine are not predicted. To assure proper modelling of the SPRE, measured dynamic test parameters describing piston and displacer motion, operating frequency, pressure and temperature were used as inputs to HFAST.

TEST RESULTS

Piston PV Power and Efficiency

Piston PV power is plotted in figure 5 as a function of piston amplitude, at 15.0 MPa mean pressure and 2.0 temperature ratio. Shown on the plot is data from the tests with 1584 cooler tubes and with 1320 cooler tubes; also shown are HFAST prediction curves for both converter configurations. Figure 6 is a similar plot showing piston PV efficiency as a function of piston amplitude. At design conditions (15.0 MPa mean pressure, 2.0 temperature ratio, 10.0 mm piston amplitude), the test with 1320 cooler tubes resulted in 14.4 kW piston PV power and 21.4 % piston PV efficiency, while the baseline test resulted in only 12.0 kW PV power and 19.5 % PV efficiency. Converter performance with fewer cooler tubes showed an improvement over baseline performance of 2.4 kW in piston PV power and 1.9 percentage points in piston PV efficiency.

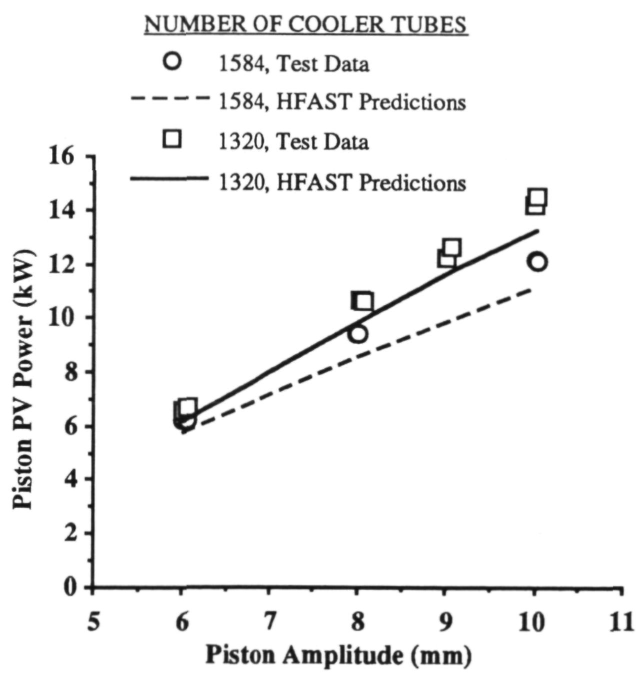

Figure 5 - Piston PV Power vs. Piston Amplitude
(15.0 MPa mean pressure, 2.0 temperature ratio)

The trends of the HFAST predictions are consistent with the test data, however the predictions tend to under-predict converter performance. Both the test results and HFAST predictions indicate that, at 15.0 MPa mean pressure and 2.0 temperature ratio, the converter performance is more sensitive to the number of cooler tubes at larger piston amplitudes. This sensitivity is especially noticeable in the piston PV power which showed improvements in the test

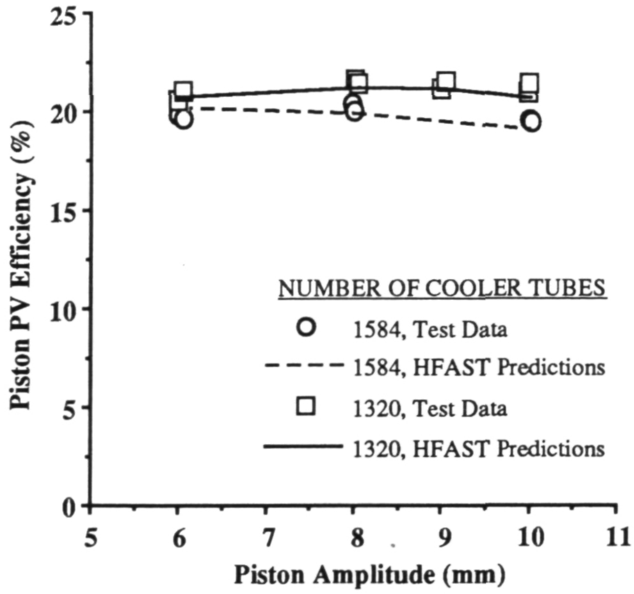

Figure 6 - Piston PV Efficiency vs. Piston Amplitude
(15.0 MPa mean pressure, 2.0 temperature ratio)

data with fewer tubes of only 4.8 % at 6.0 mm piston amplitude and as much as 20.0 % at 10.0 mm piston amplitude; corresponding improvements in the HFAST predictions are 7.0 % at 6.0 mm piston amplitude and 19.1 % at 10.0 mm piston amplitude.

The sensitivity of piston PV power and piston PV efficiency to mean pressure, at 10.0 mm piston amplitude and 2.0 temperature ratio, is shown in figures 7 and 8, respectively. Test data and HFAST predictions are shown for both 1584 and 1320 cooler tubes configurations. Both the test data and the predictions indicate that piston PV power is more sensitive to the number of cooler tubes at

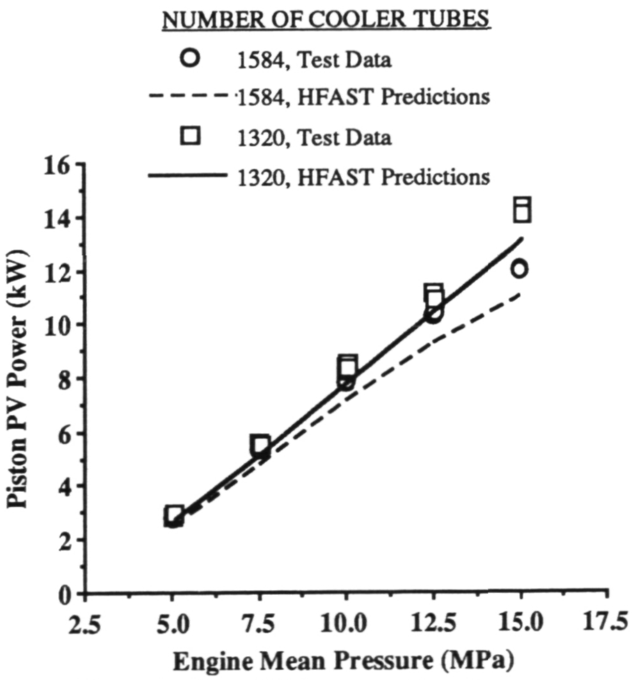

Figure 7 - Piston PV Power vs. Mean Pressure
(10.0 mm piston amplitude, 2.0 temperature ratio)

higher converter mean pressures. At 5.0 MPa mean pressure, the PV power with 1320 tubes is greater than the power with 1584 tubes by 7.1 % for the test data and 8.0 % for the prediction, while at 15.0 MPa the corresponding improvement in PV power is 20.0 % for the test data and 19.1 % for the prediction.

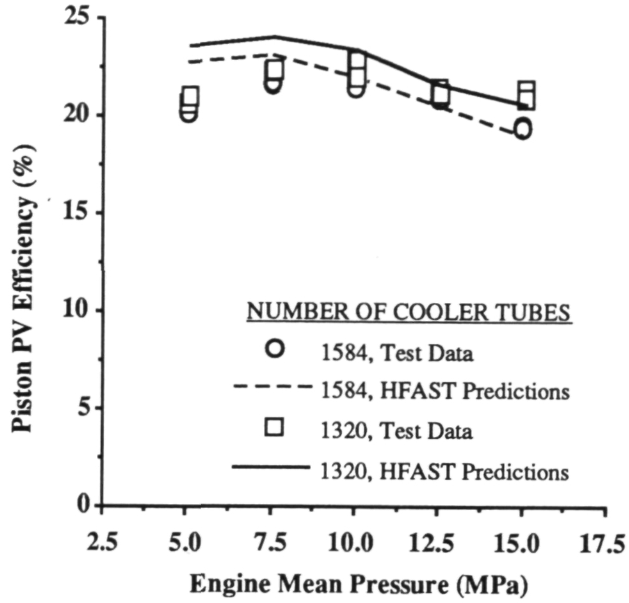

Figure 8 - Piston PV Efficiency vs. Mean Pressure
(10.0 mm piston amplitude, 2.0 temperature ratio)

Compression Space Dynamic Pressure

The improvement in power and efficiency due to the reduction in the number of cooler tubes can be seen in the compression space dynamic pressure; piston PV power is proportional to the compression space pressure amplitude and the sine of the compression space pressure phase lag behind the piston motion.

The compression space pressure amplitude, for the test data and the HFAST predictions with both converter configurations, is plotted as a function of piston amplitude at 15.0 MPa mean pressure and 2.0 temperature ratio in figure 9. The test data shows an increase of 2.1-3.2 % in the compression space pressure amplitude by reducing the number of cooler tubes to 1320, whereas the HFAST code predicts negligible change.

A plot showing the compression space pressure phase lag behind the piston motion as a function of piston amplitude at design pressure and temperature ratio is shown in figure 10. The test data and the HFAST predictions indicate that the compression space pressure phase lag is higher with fewer cooler tubes, and is more sensitive to the number of cooler tubes at a higher piston amplitude. Test results with fewer cooler tubes indicate an increase in the compression space pressure phase lag of 4.2 % at 6.0 mm piston amplitude and 15.4 % at 10.0 mm piston amplitude; the corresponding increase in the HFAST predictions are 8.1 % at 6.0 mm piston amplitude and 18.8 % at 10.0 mm piston amplitude.

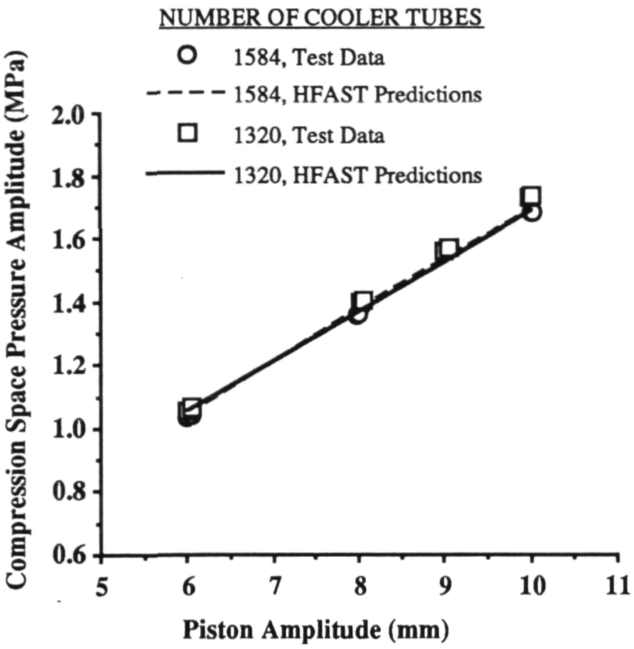

Figure 9 - Compression Space Pressure Amplitude vs. Piston Amplitude (15.0 MPa mean pressure, 2.0 temperature ratio)

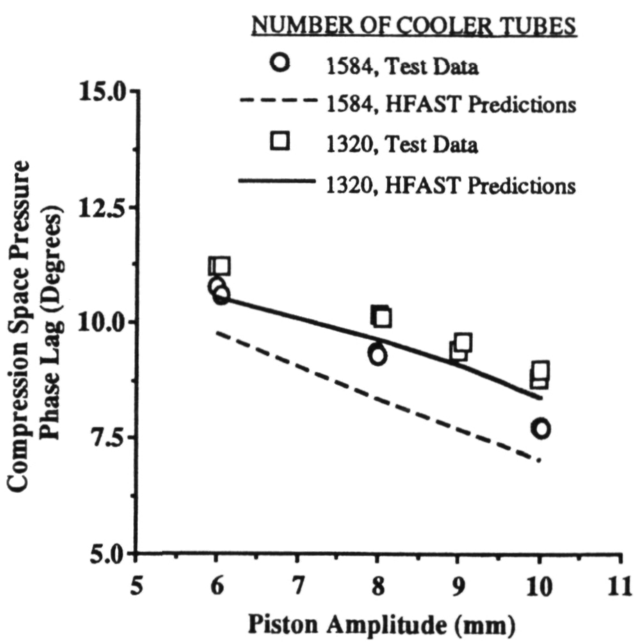

Figure 10 - Compression Space Pressure Phase Lag vs. Piston Amplitude (15.0 MPa mean pressure, 2.0 temperature ratio)

Displacer Dynamics

Figure 11 shows the sensitivity of the displacer amplitude to the piston amplitude for the test data at design pressure and temperature ratio for both the baseline and the reduced cooler tubes converter configuration. The displacer amplitude is represented as a ratio of displacer amplitude to piston amplitude. This ratio increases significantly with fewer cooler tubes. The change in the displacer to piston amplitude ratio with fewer cooler tubes is an increase of 5.2 % at 6.0 mm piston amplitude and 13.5 % at 10.0 mm piston amplitude.

Figure 12 is a plot of the displacer phase angle relative to the piston motion as a function of piston amplitude at design pressure and temperature ratio. From this figure, it can be seen that the displacer phase angle decreases with fewer cooler tubes and is more sensitive to the number of cooler tubes at larger piston amplitudes.

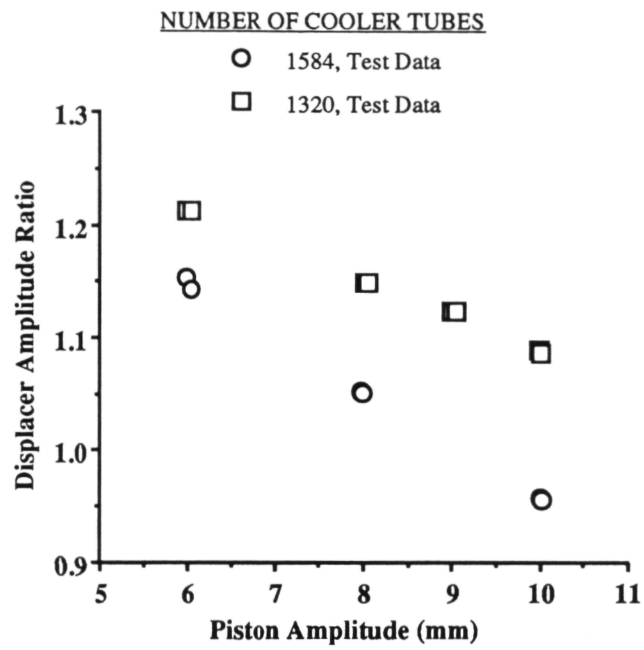

Figure 11 - Displacer Amplitude Ratio vs. Piston Amplitude (15.0 MPa mean pressure, 2.0 temperature ratio)

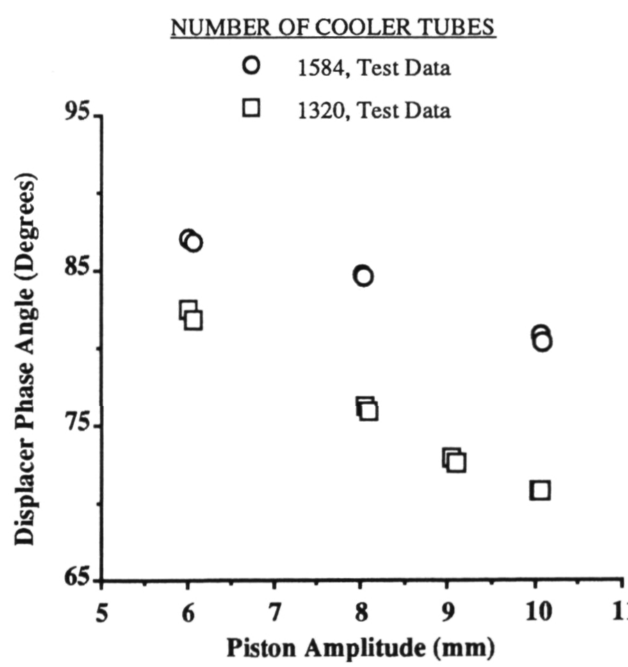

Figure 12 - Displacer Phase Angle vs. Piston Amplitude (15.0 MPa mean pressure, 2.0 temperature ratio)

Effects of Temperature Ratio

At present, the test data on the effect of the number of cooler tubes as a function of temperature ratio is incomplete; the test run with 1320 cooler tubes was terminated prematurely due to difficulties with the load-control system. As a result, no test data is available at 15.0 MPa mean pressure and temperature ratios less than 1.9. Figure 13 plots piston PV power as a function of temperature ratio at design piston stroke and pressure. Both the existing test data and the corresponding HFAST predictions indicate that piston PV power is higher with fewer cooler tubes at a temperature ratio of 2.0. This performance improvement, however, appears to decrease at lower temperature ratios; in fact, at a temperature ratio of 1.9, piston PV power with 1320 tubes is lower than with 1584 tubes.

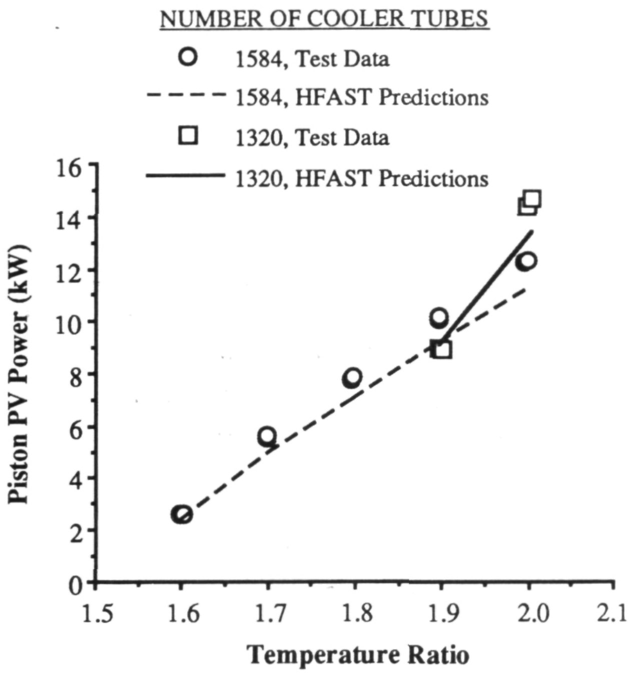

Figure 13 - Piston PV Power vs. Temperature Ratio (10.0 mm piston amplitude, 15.0 MPa mean pressure)

EXPERIMENTAL ERROR ANALYSIS

An analysis was performed to estimate the experimental error in the piston PV power and efficiency results. The errors are based on the uncertainties of the measured parameters which are used to calculate the PV power and efficiency. These parameters include pressure, temperature, displacement and flow rate measurements.

Table 1 shows typical error analysis results for the test with 1320 cooler tubes at design pressure and temperature ratio. At 10 mm piston amplitude, the error in the piston PV power is $\pm$ 0.23 kW which is equivalent to an error range of 3.2 % of the power. The corresponding error in the piston PV efficiency is $\pm$ 0.7 efficiency points which is equivalent to an error range of 6.5 % of the efficiency.

The improvements in SPRE performance which resulted from reducing the number of cooler tubes to 1320, were significantly greater than the expected "error bands" for both PV power and efficiency.

CONCLUDING REMARKS

Both the SPRE experimental test results and the HFAST code predictions indicate that the piston PV power and efficiency improve significantly by reducing the number of cooler tubes from 1584 to 1320. In addition, it appears that the sensitivity of piston PV power and efficiency to the number of cooler tubes is greater at higher piston amplitudes and higher mean pressures. Although the HFAST predictions tend to under-predict converter performance, the predicted trends agree very well with the test results.

The improvement in converter performance due to the reduction in the number of cooler tubes can be seen in the compression space dynamic pressure. Running the SPRE with fewer cooler tubes caused an increase in both the compression space pressure amplitude and in the phase lag of the pressure with respect to piston motion; both of these effects increase the piston PV power.

Reducing the number of cooler tubes appeared to have interacting thermodynamic and dynamic effects on the converter. With fewer cooler tubes, the working space

Table 1 - Error Analysis Results for the Test with 1320 Cooler Tubes at 15.0 MPa Mean Pressure and 2.0 Temperature Ratio

Piston Amplitude (mm)	Piston PV Power (kW)	Error in Piston PV Power (kW)	Piston PV Efficiency (%)	Error in Piston PV Efficiency (%)
6.0	6.49	$\pm$ 0.16	20.5	$\pm$ 0.9
8.0	10.48	$\pm$ 0.20	21.4	$\pm$ 0.8
9.0	12.53	$\pm$ 0.21	21.5	$\pm$ 0.7
10.0	14.36	$\pm$ 0.23	21.4	$\pm$ 0.7

volume decreased and the velocity of the gas through the cooler increased. The reduction in volume should contribute to the increase in compression space pressure amplitude, while the increase in gas velocity should increase cooler turbulent heat transfer and cooler flow losses. Tradeoffs between these various effects of reducing the number of cooler tubes resulted in a larger displacer amplitude and a smaller displacer phase angle. The change in displacer motion had a significant effect on the compression space pressure phase lag and amplitude.

In conclusion, the improvement in converter performance due to the reduced number of cooler tubes was a result of tradeoffs between several interdependent parameters. The extent of the improvement that can be attributed to thermodynamic effects versus dynamic effects has yet to be determined. Future tests with a further reduction in the number of cooler tubes will be conducted to investigate these interacting effects. HFAST code predictions will be used to guide the testing to determine the optimum number of cooler tubes for the SPRE.

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