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INITIAL CHARACTERIZATION OF A MODULAR HEAT EXCHANGER WITH AN INTEGRAL HEAT PIPE

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ABSTRACT

As part of the Civil Space Technology Initiative (CSTI) Advanced Technology program, a conceptual design of the Stirling space engine (SSE) was generated. The overall goal of the CSTI high capacity power element is to develop the technology base needed to meet the long duration, high capacity power requirements for future NASA space missions. The free-piston Stirling engine (FPSE) has been chosen as the growth option in the CSTI program. A major goal during the conceptual design of the SSE was to reduce the number of critical joints. One area of concern was the heat exchanger assemblies that typically have the majority of critical joints. The solution proposed in the SSE conceptual design used 40 modular heat exchangers. Each module has its own integral heat pipe to transport heat from the heat source to the engine.

A demonstration of the modular concept was undertaken before committing to the detailed design of the SSE heat exchangers. An existing FPSE was modified as a test bed for modular heat exchanger evaluation. The engine incorporated three heat exchanger modules, each having a sodium filled heat pipe. The thermal loading of these modules was intended to be similar to the conditions projected for the SSE modules. The engine was assembled and tests are underway.

This paper briefly describes the design and fabrication of the heat exchanger modules and the engine used for these tests. Evaluation of the individual heat pipes before installation in the engine is described. The initial test results with the modules in operation on the engine are presented. Future tests involving the engine are outlined.

INTRODUCTION

The free-piston Stirling engine (FPSE) has been chosen as the growth option for the Civil Space Technology Initiative (CSTI) Advanced Technology program. The goal of this program is to develop the technology needed to allow for the development of a 100 kW electric power system for use in future space missions. Heat will be generated by a nuclear reactor and the Stirling engine will then be used to convert that heat to electricity through a free-piston Stirling engine/linear alternator configuration.

As a part of this Advanced Technology program, the conceptual design of a free-piston Stirling space engine (SSE) was generated. This was performed under a NASA contract and has been reported in Ref. 1. The 777 °C (1050 K) superalloy SSE is an intermediate test condition between the 377 °C (650 K) space power demonstrator engine (SPDE) and the eventual 1027 °C (1300 K) refractory version of the SSE. For nuclear space power applications, system optimization based on minimum mass indicates that these engines should operate with the temperature ratio at 2.0.

The SSE is a single cylinder free-piston Stirling engine (FPSE) designed to produce 25 kW of electric power. The engine must satisfy both efficiency and mass goals while operating at a temperature ratio of 2.0. The difficulties in creating a highly efficient and low mass FPSE while being limited to a temperature ratio of 2.0, was first investigated with the SPDE. The SPDE program has been reported in Refs. 2 to 4.

Future missions utilizing the CSTI power system require both long life and reliability. These requirements caused the SSE designers to propose a unique heat exchanger module concept that would drastically reduce the number of critical joints. This modular heat exchanger was proposed as a replacement for the previously used tube and shell heat exchanger.

Only 40 heat exchanger modules are required to power the 25 kW SSE. This was considered an improvement over previous heat exchanger designs such as used in the SPDE which had approximately 3200 brazed tubes in the heater and 3800 brazed tubes in the cooler. The larger number of brazed joints in the SPDE was a result of the decision to use standard tube and shell heat exchangers. Each braze joint represents a potential single point failure. The preliminary design of the SSE is currently being performed by Mechanical Technology Incorporated (MTI) of Latham, NY, under contract to NASA Lewis Research Center.

This report presents a brief description of the design, fabrication, and operation of the heat exchanger modules. Evaluation of the individual heat pipes before being installed on the engine is also described. Results from the initial test runs are presented and discussed.

MODULAR HEAT EXCHANGER CONCEPT

The modular heat exchanger concept was proposed for use in the SSE in an effort to reduce the number of critical joints that form the pressurized boundary of the engine. Each module contains (1) a heat exchanger used to transfer heat to the working fluid of the engine, (2) a regenerator, and (3) a cooler to remove waste heat from the cycle. A heat pipe was proposed as the heat transport device used to deliver heat to the module. Evaluation of the modular cooler was not included in this project. Figure 1 shows a model of one heat exchanger module.

A decision regarding the general type of heat exchanger to be used in the SSE was required early in the preliminary design effort. The tube and shell concept, the modular heat exchangers, along with other candidates were being considered. Because the SSE preliminary design effort could lead to a long term commitment to a particular heat exchanger, a prototype test program involving modular heat exchangers would be in the best interest of the overall SSE project. A test using an existing facility along with existing engine hardware, to demonstrate the modular heat exchanger concept, was developed. This test was designed to provide modular heat exchanger test data at a very small cost in a timely manner, long before a commitment to a particular heat exchanger was made.

HEAT EXCHANGER MODULE TEST ENGINE

Existing hardware from the RE-1000 FPSE was used as the basis for the heat exchanger module test rig. Sensitivity tests involving the RE-1000 were described in Ref. 5. As was the case with the RE-1000, this engine was designed to operate at 7.0 MPa helium mean pressure, and at 30 Hz engine frequency.

The design and fabrication of the heat exchanger modules and engine components were performed by Sunpower Inc., of Athens, OH, under contract to NASA Lewis. Thermacore Inc., of Lancaster, PA, performed the heat pipe design, fabrication, and processing. While the SSE conceptual design contained 40 modules around the engine cylinder, three modules around this smaller engine simulate the SSE module thermal load within acceptable limits. A cutaway of the engine is shown in Fig. 2.

Slots embedded in the wall of the condensers of the heat pipes act as the helium passages forming the heater of the engine. Adjacent to the engine heater section of the module is the regenerator cavity. Any one of several different types of regenerators can be installed in this cavity. The cavity can be completely filled with the regenerator matrix, or as was the case in the NASA Lewis tests, an annular regenerator can be used. The annular regenerator was chosen because it was less susceptible to flow maldistribution for this particular geometry.

The highest temperature data points reported in the sensitivity test results were at 600 °C average heater tube temperature. Because sodium is used for the liquid metal heat transport system in the SSE, it was also used in the test modules. Most tests will be conducted at temperatures between 527 °C (800 K) and 677 °C (950 K). Special tests have been planned with the evaporator temperature ranging as high as 777 °C (1050 K) for short periods. During the sensitivity tests the maximum power output was approximately 1500 W. Because the modular heat exchangers were designed to operate at higher temperatures than in past RE-1000 tests, the engine should be capable of producing nearly 2000 W of indicated power.

Due to the nature of this research and the test facility environment, the design philosophy used in this project required the heat pipes and heat exchangers to be made more rugged than the eventual space flight hardware. The heat pipes and the modules in general do not represent a design optimized for high performance or minimum mass, but rather a design with a high probability of successful and safe operation. The walls of the heat pipes were sized such that they could withstand full engine pressure in the event of a leak in the heat exchanger that allowed the pressurized helium into the heat pipe. These somewhat thicker walls require a higher temperature drop to drive the heat into the sodium along with another temperature drop as the heat is transferred from the sodium to the engine working fluid.

Heat pipes typically contain some amount of excess working fluid. This excess is in the form of a liquid pool. Because of the variation in the density of the vapor, the amount of excess liquid will change as the vapor temperature changes. In a zero gravity environment the excess fluid has a tendency to accumulate at the condenser of the heat pipe. This could potentially be altered by some form of inventory control, however this was not attempted in this test program.

The heat exchanger module test engine is shown in the test cell in Fig. 3, and a closer view of the modules is shown in Fig. 4. The evaporators of the three heat pipes are located above the condensers and therefore, due to the fluid forces and gravitational forces, the excess liquid will accumulate at the end of the condensers of the heat pipes. In this case the liquid pool will be adjacent to the regenerator. Liquid sodium has approximately the same thermal conductivity as the stainless steel heat exchanger body. The presence of relatively low thermal conductivity liquid sodium pool at the end of the engine heater increases the overall thermal resistance of the heat exchanger and hence compromises its effectiveness.

The test stand and mounting brackets for the engine were designed so that the entire engine could be inverted and operated with the condensers of the heat pipes above the evaporators. In this gravity assisted mode of operation, the excess liquid sodium inventory should collect as a pool in the evaporator. The condenser will therefore have no excess liquid to inhibit heat transfer to the engine working fluid, and should allow heat to be transferred effectively to the helium working fluid of the engine along the entire length of the helium flow passages. A noticeable effect on the temperature gradient of the heater near the regenerator is anticipated. A series of thermocouples have been located in the wall of the heater near the regenerator to allow this change to be measured.

The heat pipes were designed, fabricated, and processed by Thermacore. These heat pipes use a sintered powder metal wick with two arteries per pipe. Figure 5 shows a cutaway view of one of the heat pipes. Although the pipes are capable of operating with only one artery, the second artery was incorporated to provide a degree of redundancy. The heat pipes were evaluated several times during the fabrication process to verify their performance relative to the design specifications. The evaluation was done with the evaporators above the condensers in order to verify the ability of the wick and arteries to operate against gravity. A water cooled gas gap calorimeter was mounted around the condenser and used as the thermal load. The temperature of each heat pipe was varied as the test proceeded. These tests verified the heat flux capability of the heat pipes and the experimental sonic limit of the heat pipes agreed with the analytical predictions.

TEST PLANS

Current plans are to characterize the heat exchangers with evaporators above the condensers as the baseline case, and then invert the entire engine and repeat the test matrix. The test matrix has been kept relatively small in an effort to make these tests more timely. Engine performance will be studied and compared to computer predictions. More specifically, the temperature gradient of the regenerator end of the heater will be measured for both orientations and compared to predictions from several different computer simulations.

Other tests have been proposed for this engine that are not directly related to the use of heat pipes or modular heat exchangers. Effects of seal clearances, heat exchanger manifolding, center port systems, and other parameters may be studied. If the need arises, alternate heat pipe and modular heat exchanger designs can be tested. The present set of modular heat exchangers are mechanically attached to the engine and can be removed and reinstalled.

TEST RESULTS

The engine was initially operated in September 1988. Limited testing has been performed with the heat pipe evaporator temperatures ranging from 875 to 1050 K. All of the testing to date has been with the evaporators physically located above the condensers.

The initial goals of these tests were to demonstrate the feasibility of the modular heat exchanger and to provide operational experience with modular heat exchangers on an engine using liquid metal heat pipes. These goals have been accomplished and operation of the modular heat exchanger has been demonstrated. Performance of the engine with the modules is currently being studied.

During these tests, the engine has not been operated at conditions necessary to produce maximum power, yet the thermal loading in the heat pipes and heat exchangers has verified feasibility of the modular design and agreed well with predicted performance. The reduced power output of the engine has been caused by a short displacer stroke. This reduced displacer stroke causes the pressure phase angle to decrease. Excessive leakage from the displacer gas spring or improper damping within the heat exchanger flow path may be the cause of the reduced stroke. Because this displacer utilizes wear couples instead of gas bearings, a small amount of wear is expected in the displacer gas spring with use. Engine performance will improve as the test program continues with components being upgraded as needed.

Measured and calculated temperature profiles along the heat pipe are in agreement. Figure 6 shows a comparison of the measured and calculated temperatures for one of the data points recorded. Based on the thermal energy being transported through the heat pipe, temperature drops at both the evaporator and condenser were calculated. The temperature drops through the stainless steel wall and the saturated wick have been taken into account. A correlation published in Ref. 6 was used for the thermal resistance of the sintered powder metal wick. This correlation is a function of resistivity of the sodium and the wick material. The summation of the evaporator and condenser temperature drops were compared to the measured value.

The calculation predicts a 69 °C temperature drop while the measured value was 79 °C. The calculation assumed that vapor within the heat pipe acted isothermally. In reality there was some small pressure and temperature drop in the sodium vapor. The data point chosen for this example was not near the sonic limit, therefore a vapor temperature drop of 10 °C is quite plausible [6]. Although this assumption was reasonable at the conditions of the sample data point, it would not be appropriate were the heat pipe operating at the sonic limit.

Analysis of the data also suggests that the measured temperatures may be in error by up to 20 °C due to aging effects of the type K thermocouples. The integrity of the thermocouples and the installation techniques used are being evaluated. Appropriate corrections will be made and quality measurements of the temperature profiles of the heat pipe, the heat exchanger, and the engine working gas will be made in future runs.

With these results, the performance of similar heat transport systems can be evaluated. This comparison was based on bulk temperature at each end of the heat pipe and does not look at the temperature gradient anticipated at the condenser, caused by the nonuniform thermal draw of the engine.

SUMMARY

Conceptual design of an advanced FPSE for space power application, the SSE, proposed the use of a new concept in heat exchanger design which replaced conventional tube and shell heat exchangers. The SSE represents an advance in technology from the 377 °C (650 K) SPDE toward the technology needed for the 1027 °C (1300 K) engine. The new heat exchanger module concept was offered as a means of drastically reducing the number of critical joints in the heat exchanger assembly. Since the SSE preliminary design task requires choice of a heat exchanger concept that will have long lasting implications, a relatively low cost, near term demonstration of the heat exchanger concept was undertaken to benefit the overall program.

An engine was designed with modular heat exchangers which simulated the operating conditions of the SSE. The test engine used only three heat exchanger modules instead of the 40 that would be required for the proposed SSE design; however, the operating condition of each module was the same as on the SSE. The three modules, along with other necessary hardware, were built and engine testing started.

The concept of modular heat exchangers with integral heat pipes has operated successfully on the engine. Measured characteristics of the heat pipes agree well with the analytical models. Temperature drops and the conditions at which the sonic limit is encountered also agree with models. These tests have established feasibility of the modular heat exchanger concept for use in future FPSE designs. The engine is currently operating at reduced power levels. Testing will continue as improvements are made to the hardware to increase the performance.

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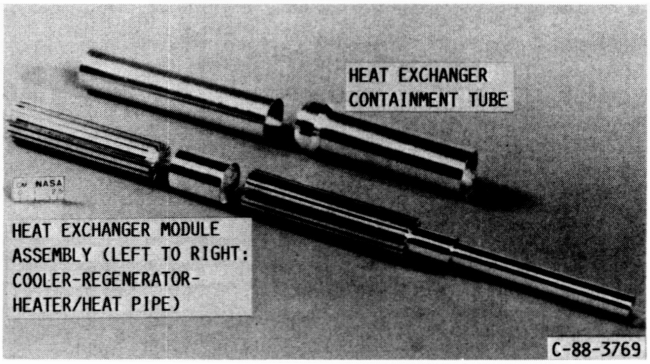

FIGURE 1. - STIRLING MODULAR HEAT EXCHANGER ASSEMBLY.

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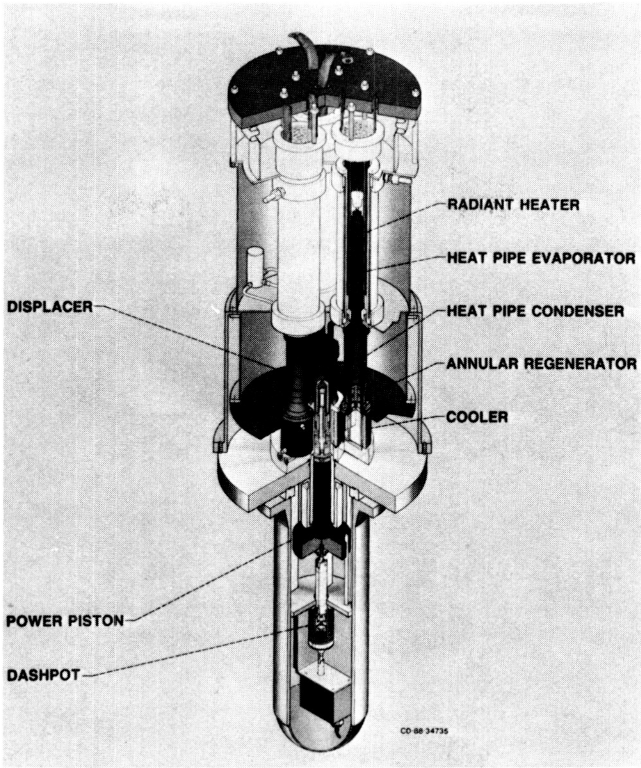

FIGURE 2. - CUTAWAY OF HEAT EXCHANGER TEST ENGINE.

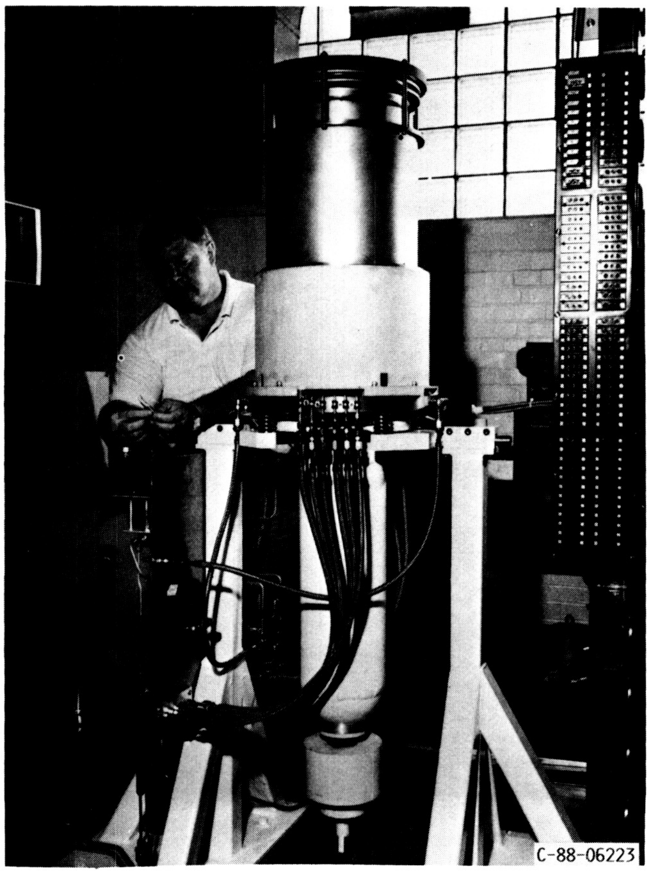

FIGURE 3. - HEAT EXCHANGER TEST ENGINE BEING READIED FOR TESTING.

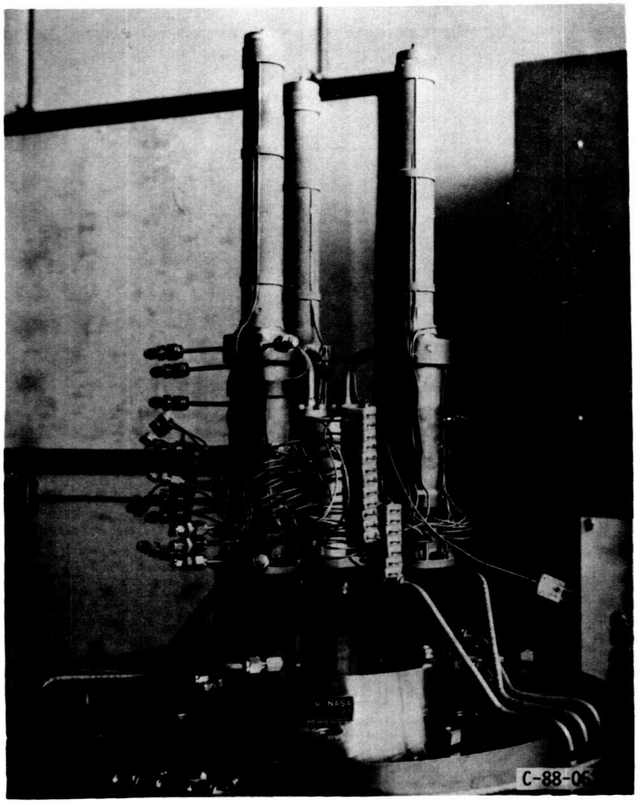

FIGURE 4. - HEAT EXCHANGER MODULES ATTACHED TO THE ENGINE.

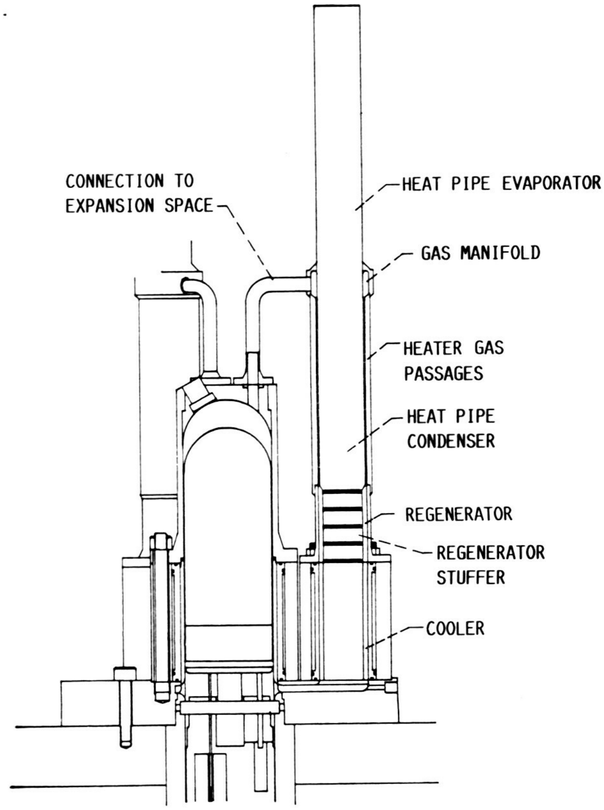

FIGURE 5. - COMPONENT LAYOUT OF A HEAT EXCHANGER MODULE.

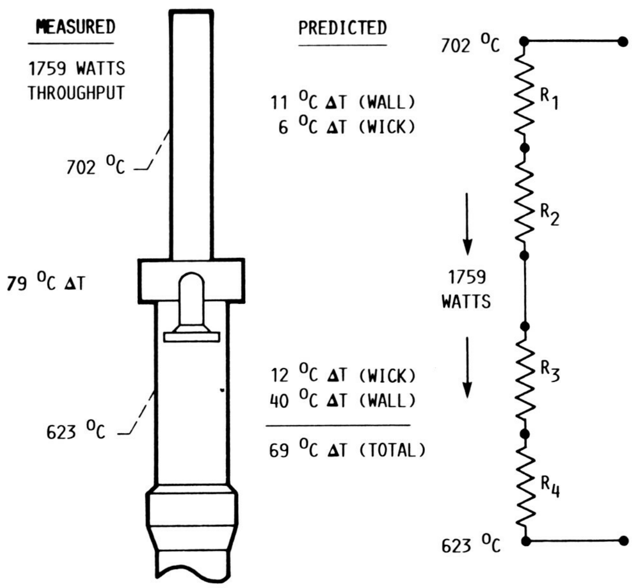

FIGURE 6. - COMPARISON OF THE CALCULATED AND MEASURED TEMPERATURE DROP ALONG THE HEAT PIPE.

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16. Abstract

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