CONSOLIDATION OF A SODIUM HEAT PIPE AND STIRLING ENGINE FOR FISSION SURFACE POWER

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ABSTRACT

The Consolidated Heat Pipe (CHP) is a new design in which a sodium heat pipe is welded directly to the hot end of the Stirling engine to deliver thermal power more efficiently. The new integrated interface aims to reduce the large temperature drop (about 120 °C) that was measured across the bolted clamp joint between the Stirling engine and the heat pipes during the Kilopower Reactor Using Stirling TechnologY (KRUSTY) test from 2018[1].

Initial testing and characterization of the CHP was performed in ambient air at the NASA Glenn Research Center (GRC). In the test, the heat pipe evaporator section was heated with a tube furnace. The thermal power was then transported to the Stirling engine integrated with a linear alternator that produced electrical power. The CHP has been tested at a hot end temperature ranging from 600 °C - 800 °C and a variety of other Stirling engine parameters (cold end temperature, piston amplitude and pressure). The results show that the temperature drop between the Stirling engine and the heat pipe has been reduced to 2°C - 4 °C. An overall temperature drop of 20 °C – 60 °C was also noted within the heat pipe depending on the combination of parameters mentioned above. Overall, it has been shown that the new Consolidated Heat Pipe design significantly improved the thermal interface to the Stirling engine.

INTRODUCTION

Nuclear generators are the key to providing power in space where there is a lack of sunlight and where dust/pollutants prohibits the use of solar power. A fission-based reactor can provide thermal power that can be converted to useful work with a given power conversion technology such as a Stirling engine. A demonstration of this concept was completed in 2018 and is known as the Kilopower Reactor Using Stirling TechnologyY (KRUSTY).

In KRUSTY, Highly Enriched Uranium (HEU) was used to power an array of Stirling engines and thermal simulators. Heat pipes were used as a means for heat transport from the nuclear reactor to the Stirling engines. These Stirling engines then converted the thermal power to useful electrical power for the end user. It is important to note the heat pipes for the purpose of this paper. These heat pipes functioned as both heat transport between the reactor and the Stirling engines *and* as coolant for the reactor. The heat pipes were bolted/clamped to the Stirling engine, shown in Figure 1 below.

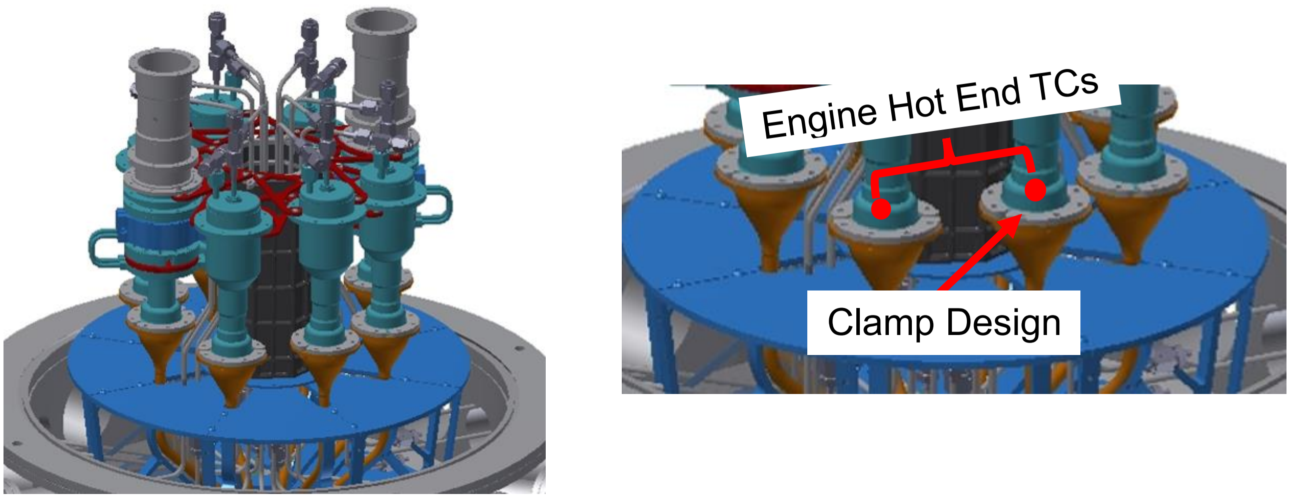

Figure 1. Bolted Clamp in KRUSTY Test.

This provided significant savings in mass and reduces the overall operational complexity. Heat pipes also have the advantage of minimizing time delays in delivering power between the core and the Stirling engine[2]. However, one of KRUSTY's reports showed that there is a temperature drop of 160 °C between the core and the hot end[1]. A significant portion of this temperature drop is between the heat pipe's adiabatic region and the engine's hot end which amounts to 120 °C.

The Consolidated Heat Pipe (CHP) Stirling Engine design was innovated and built to reduce this temperature drop and ensure the Stirling engine hot end temperature is as close to the nuclear fuel temperature as possible. The temperature drop between the Stirling engine and heat pipe has been reduced to 2 °C to 4 °C now.

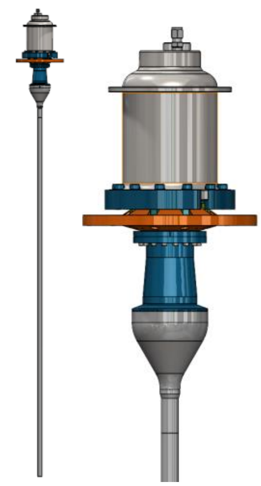

Figure 2. Overall Consolidated Heat Pipe Design.

The true significance of this technology is that the improved lower thermal resistance allows system designers to use lower temperature nuclear fuels such as Uranium-Molybdenum (U-Mo). The U-Mo is a metal alloy and so it can be designed and fabricated to any desired shape. Higher temperature nuclear fuels are restrictive in their geometries and these fuels are also not currently in production. The CHP reduces overall thermal/temperature losses, enables running the Stirling engines at a hotter temperature given the same core temperature (which helps in producing more useful power out), acts as the reactor coolant while also being a heat transport coupling mechanism, and ultimately leads to savings in system mass. Finally, this innovation is scalable to any power level.

DESIGN OF THE SODIUM HEAT PIPE AND STIRLING ENGINE

For reference, KRUSTY was designed to provide 4 kW_{th} and operate at 800 °C. Its HEU core was to provide thermal power to an array of eight 125 W_e Stirling engines. The final KRUSTY test ended up using two 80 W_e Stirling engines developed by Sunpower Inc. and six Stirling engine thermal simulators. The heat pipes used to couple the HEU core to the Stirling engines used sodium as the working fluid and was designed to operate at 800 °C.[1] These heat pipes were revised to create the new CHP design.

The CHP uses an 80 W_e Stirling engine where its Heater Head, or "hot end", was modified and is consolidated within the condenser section of the heat pipe (shown in Figure 3). This enables the working fluid to condense directly on the Heater Head ensuring direct delivery of thermal power. Sodium is used again as the working fluid, but is designed to operate at both 700 °C and

800 °C. The heat pipe itself also has an annular pipe inside as a wick that runs through the entire length enabling low gravity operation.

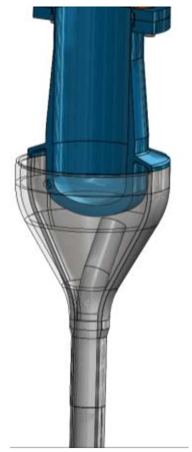

Figure 3. Consolidated Heater Head Buried within Heat Pipe Condenser.

TEST SETUP

Testing of the CHP unit was performed at the NASA Glenn Research Center in the Stirling Research Laboratory (SRL). A test stand was created to control critical parameters for both the heat pipe and the Stirling engine. Firstly, a tube furnace was used to heat the heat pipe's evaporator section. Thermocouples along the evaporator, adiabatic and condenser sections of the heat pipe provided feedback to inform control of the "hot end" temperature which was measured at the heat pipe's condenser (also the consolidated interface to the Heater Head). Next, the engine's piston amplitude was varied with a custom controller that was developed by Sunpower Inc. for this test. The hot end temperature and the piston amplitude were the two critical parameters used to characterize the performance of the heat pipe and the Stirling engine. Varying the hot end temperature allowed for control of the input thermal power, and the piston amplitude was the "throttle" to the Stirling engine. As the piston amplitude increased, thermal power extracted from the heat pipe for use in the Stirling cycle also increased. Although, the heat extracted from the heat pipe cannot be directly measured in this test, SRL's experience with similar Stirling engines shows that the Stirling engine is extracting 200-300 W_{th} from the heat pipe. Finally, the heat pipe was insulated with kaowool. Figure 4 shows the final test setup.

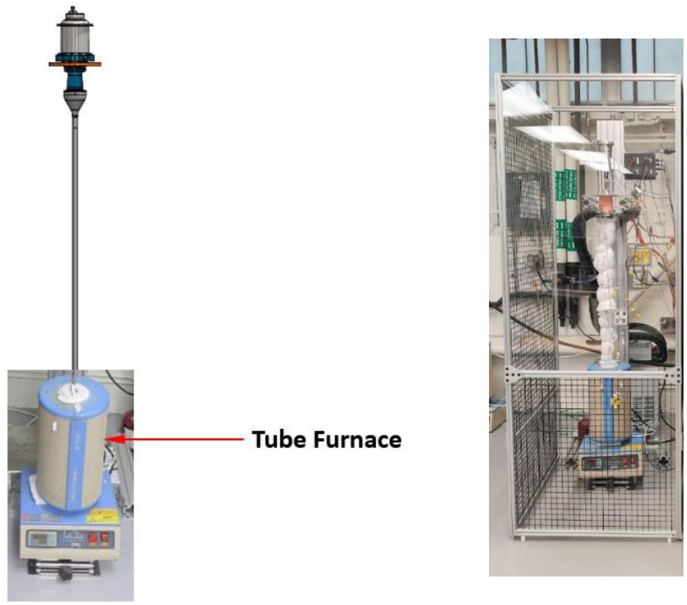

Figure 4. Final Test Setup.

Auxiliary systems such as a chiller, active balancer, and surface heaters were used to maintain the remaining Stirling engine properties. The chiller controlled the engine's cold end temperature, the active balancer counteracted any engine vibrations, and surface heaters were used to approach necessary engine body temperature easily. Some of the main parameters varied and/or maintained for this test are shown in Table 1 below.

Table 1. Test Matrix

Hot End Temperature	600 °C - 800 °C
Piston Amplitude	3 mm to 5 mm
Cold End Temperature	60 °C
Stirling Engine Pressure	500 psig (Helium working fluid)

RESULTS

Testing was split into three sections to help fully characterize the heat pipe and the Stirling engine. Firstly, the CHP was held constant at a hot end temperature of 700 °C while the piston amplitude was varied from 3 mm to 5 mm. This test was repeated for a hot end temperature of 800 °C. Finally, in the last test, the piston amplitude was held at 5 mm while the hot end temperature was decreased from 800 °C to 600 °C in 25 °C increments.

Three values are tracked in Figures 5 through 7. First, the temperature drop between the heat pipe's adiabatic section to its condenser is measured and is shown by the orange curve. This is the most important metric as it helps to characterize the new consolidated interface and is directly compared to KRUSTY's results. The blue curve shows the overall temperature drop between the heat pipe's evaporator and its condenser. Finally, for reference, the gray curve shows the useful electrical power produced by the Stirling converter.

Figure 5, below, shows that the temperature drop between the adiabatic and condenser section has been reduced to as low as 2 °C at the 5 mm piston amplitude point. This value is within the margin of error for thermocouples indicating that the adiabatic section and the condenser section are operating at the same temperature.

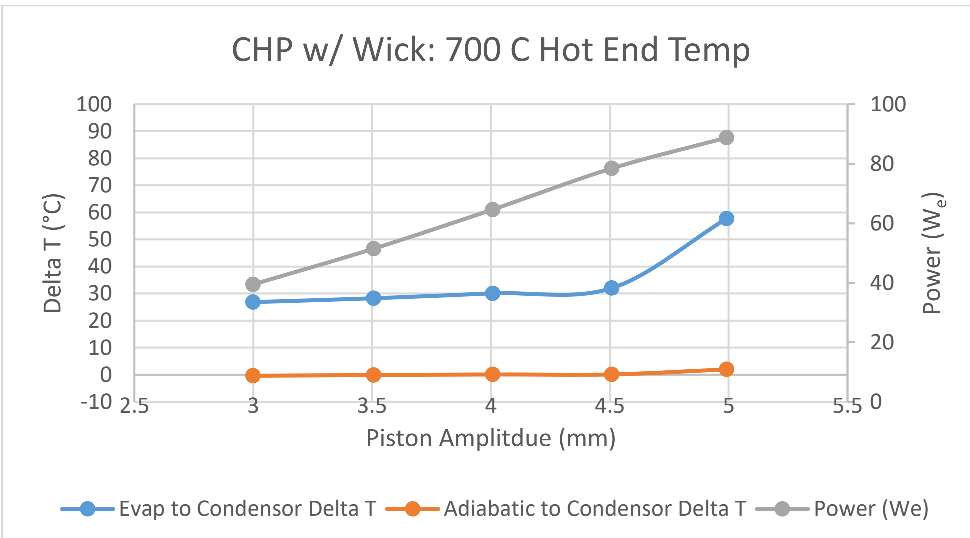

Figure 5. Results from the 700 °C Hot End Temperature Test.

Looking at the results of the second test with the 800 °C, Figure 6, it can be seen that the temperature drop between the adiabatic and condenser is about 4 °C. These results, with a temperature drop of 2°C to 4 °C between the 700 °C and 800 °C tests, are showing a significant improvement in lowering the thermal resistance between the Stirling engine's hot end and the heat pipe. Compared to KRUSTY's measured drop in temperature of 120 °C, the CHP is a successful design and ensures that thermal power can be delivered directly to the Stirling engine with lower thermal losses.

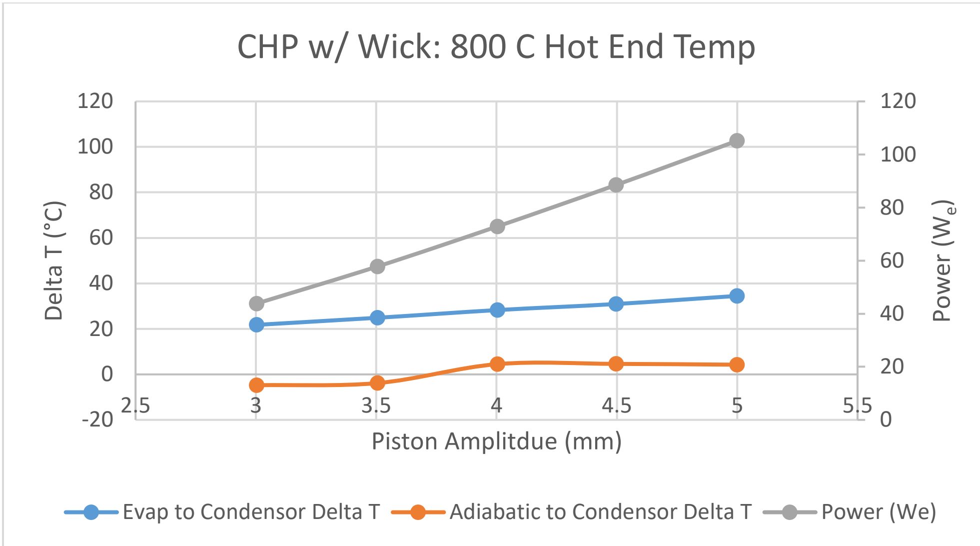

Figure 6. Results from the 800 °C Hot End Temperature Test.

At this time, it should be noted that the orange curve in Figure 6 does go negative, where the piston amplitude was 3-3.5 mm, indicating that the condenser was at a higher temperature than the adiabatic section. This anomaly was caused by an unexpected event where the chiller had failed. The CHP unit had to be shut down abruptly which caused the working fluid to freeze at the condenser. The frozen sodium then had to be manually heated with a heat gun at the condenser, thus affecting the startup process of the heat pipe.

Next, the overall temperature drop in the heat pipe which was measured between the evaporator and the condenser. In Figure 5, the overall change in temperature varied from 27°C to 58 °C depending on the piston amplitude. There is a notable "knee" in the blue curve between piston amplitudes of 4.5 mm to 5 mm. After much investigation, no apparent condition was found for this change. However, another similar test point revealed that the change in temperature between the evaporator and condenser was only 40 °C- indicating that there would be no knee in the curve. Table 2 summarizes the two similar test conditions and results. The only difference between these two tests is the pressure where the 2nd test point was 7 psig lower than the first. This should not have made a significant difference considering that the power produced by the Stirling engine was very similar. Further testing is required to find and verify the cause for this change in behavior.

Table 2. Test Matrix

	1st Test Point	**2nd Test Point**
Hot End Temperature	700 °C	700 °C
Piston Amplitude	5 mm	5 mm
Cold End Temperature	60 °C	60 °C
Stirling Engine Pressure	500 psig	493 psig
Stirling Power Output	89 W	90 W
Adiabatic to Condenser	2 °C	6 °C
Evaporator to Condenser	58 °C	40 °C

Lastly, the results for the test where the hot end temperature was varied while holding piston amplitude at 5 mm is shown in Figure 7, below, for reference.

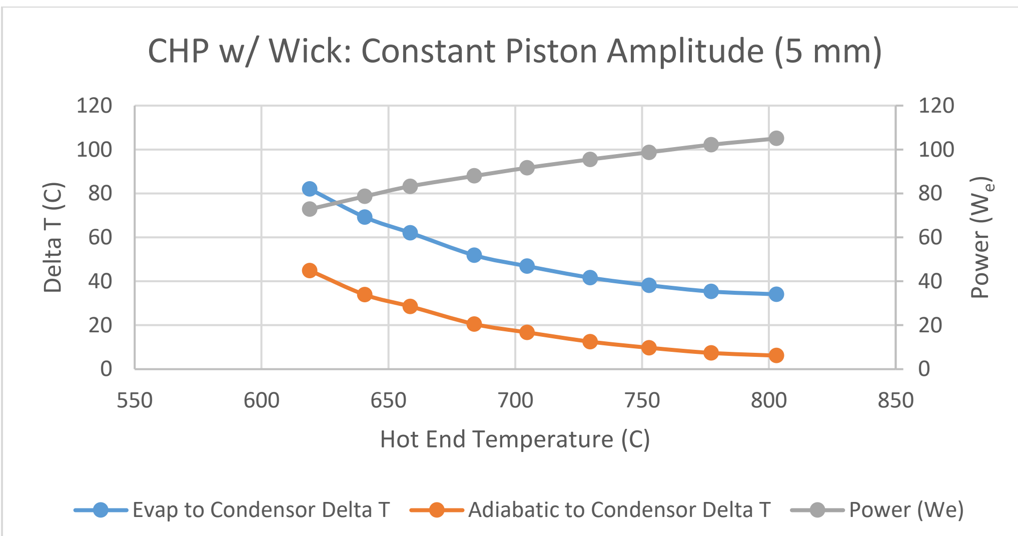

Figure 7. Results from the Constant Piston Amplitude and Varying Hot End Temperature Test.

CONCLUSIONS

The Consolidated Heat Pipe design has proven to be successful in delivering thermal power directly to the Stirling engine. KRUSTY's heat pipe to Stirling engine interface carried a thermal loss amounting to a 120 °C drop in temperature. The CHP design reduced this temperature drop to as low as 2 °C to 4 °C. The heat pipe is now able to deliver thermal power directly to the Stirling engine.

Further testing is needed to investigate the change in the overall temperature drop between the heat pipe's evaporator and condenser at the 700 °C and 5 mm condition. Testing with different heating ramp rates may provide additional insight. Also, the overall temperature drop may be further improved with better insulation and environment. The Consolidated Heat Pipe will be tested again in a vacuum environment to investigate these points in the future.

REFERENCES

1. Gibson, Marc A., et al. "Kilopower Reactor Using Stirling TechnologY (KRUSTY) Nuclear Ground Test Results and Lessons Learned." 2018.

2. Poston, David I., et al. "Results of the KRUSTY Nuclear System Test." *Nuclear Technology* (2020): S89-S117.