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TEST RESULTS FROM A CONCENTRATED SOLAR MICROTURBINE BRAYTON CYCLE INTEGRATION

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ABSTRACT

Capstone Microturbine and Heliofocus Solar Thermal Solutions in a partnership built an open loop Brayton cycle system using a 65 kW Capstone Microturbine and a concentrated solar energy receiver. This system was built for initial development testing to validate the ability to generate electricity on a small scale at high efficiencies using only solar energy as the input. A secondary goal was to demonstrate the ability of the receiver to transfer sun energy into the working fluid of air at efficiencies that would support the target overall system electrical efficiency of 21 %. Concentrating Solar Power systems in the 20 kW to 100 kW electrical output power range currently do not exist in the market place today. Demand for this type of power generation is high due to its small footprint per kW of energy produced, its ability to be distributed in small kW increments to meet site demand and space, its relatively high electrical efficiency and its projected low cost per kilowatt of generated electricity. This initial testing was done without the production configuration dish concentrator component and instead a solar tower with a field of Heliostats provided the sunlight to the solar generation system. Test results showed that the receiver met the efficiency goal set forth and that the overall system was capable of producing 25kW of electricity to the electric grid. The receiver efficiency measured was 89% at or near the needed airflow and air temperature levels required by the Microturbine to support an overall system efficiency of 21%. The next step in the development process would be to integrate the development system onto a concentrating solar dish and demonstrate the total conversion efficiency at the target 21% prior to commercialization.

INTRODUCTION

Solar power generation has been gaining global interest due to its ability to meet the growing energy needs without fuel cost or any harmful emissions. In the US solar thermal production saw no gains in installed capacity for the last ten years staying steady at 364 MW, but just in the last four years the total installed capacity grew by 25 % [1]. While increases in the US have been dramatic, many European countries are significantly ahead of the US in adoption of solar power generation systems. Projections for the future are even more accelerated. Just in the next five years, the installed base of global concentrated solar power production under a moderate growth projection would increase from 4000 MW to 28.5 GW [2]. It is this significant potential market that resulted in the formation of Heliofocus in 2007. Heliofocus with the help of Prof. Jacob Karni as their CTO and inventor of their patented high heat and pressure capable solar heat receiver planned to develop a product for this market. This paper takes us through the development of the product up to the testing results of the first prototype system which had the goals of demonstrating the ability to generate electricity from a solar power source and validate the solar receiver's power conversion efficiency.

NOMENCLATURE

T_{abs}	Absolute temperature of the working fluid
T_{amb}	Temperature of the surrounding environment
α	Thermal receiver absorptivity
σ	Stefan-Boltzman constant
ε	Thermal receiver emissivity
C	Geometric concentration ratio of absorber area to concentrator surface area
Φ	Solar direct normal irradiance (DNI)

SYSTEM CONFIGURATION ANALYSIS

While it is true that in solar energy generation the fuel is free, it is also true that the cost of the capital equipment impacts the funding and payback of any project. Keeping the solar energy conversion efficiency as high as possible was identified early on as critical design goal that would minimize the cost per kW of electricity the system could produce. Maximizing the efficiency of the complete system from Sun energy input to electricity produced was where the significant amount of the design effort was placed. To do this, it was required to determine the maximum efficiency of the electrical power generation cycle and the solar thermal receiver independently and combine them. Equation 1 is the Carnot cycle efficiency which is the ideal efficiency of a heat engine to convert work from two different temperatures. Equation 2 is the Stefan-Boltzman black body radiation law applied to the solar receiver assuming an ideal case of only radiation heat loss [3].

$$\eta_{Carnot} = (T_{abs}\text{-}T_{amb})/T_{abs} \quad (1)$$

$$\eta_{rec} = \alpha\text{-}\sigma\varepsilon(T^4_{abs} - T^4_{amb})/(C\phi) \quad (2)$$

Combining equation 1 and 2 gives us the ideal equation for a solar power systems efficiency as shown in equation 3. A plot of this efficiency can be seen in figure 1 where the overall ideal efficiency is shown as a function of the absolute temperature of the working fluid and the geometric concentration ratio of the solar collection system.

$$\eta_{system} = \eta_{Carnot} * \eta_{rec} \quad (3)$$

Figure 1 suggests that for a given concentration ratio there is specific optimized operating fluid temperature that will maximize the overall solar system efficiency. Once the selection of a turbine engine was made as the power generation source, the working fluid temperature could be identified to be the typical firing temperatures of turbine engine of about 1000°C. Using figure 1 with the 1000° C target, the concentration ratio that was optimized for this temperature was around 2000. This solar concentration ratio was best achieved with a dish solar collection technology, so it was the solar collection method chosen. Examples of the three typical solar collector systems identified in figure 1 can be seen in figure 2, 3 and 4 with their typical geometric solar concentration ratios listed [3].

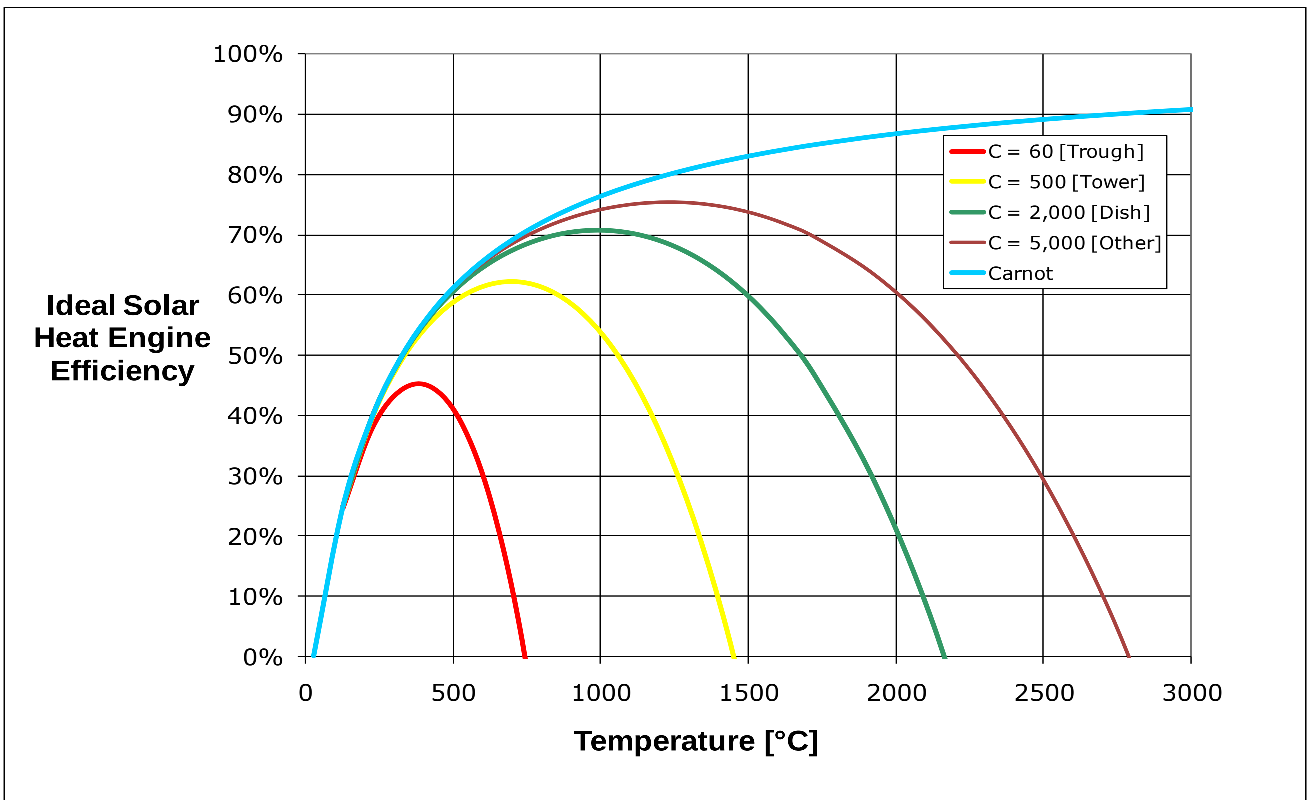

Figure 1: Plot of Idealized Solar Power Generator System

Figure 2: SEGS IV Trough Type Solar Collector System in Operation in the Mojave Desert near Kramer Junction, California [Solar concentration ratio of ~60].
Credit: National Renewable Energy Laboratory

Figure 3: Solar Two Tower Type Solar Collector System in operation in the Mojave Desert near Barstow, California. [Solar concentration ratio of ~500]
Credit: United States Department of Energy

Figure 4: Dish Type Solar Collector Systems being tested at Sandia National Laboratories in Albuquerque, New Mexico [Solar concentration ratio of ~2000].
Credit: Sandia National Laboratories

Due to physical size limitations of the dish choice, the systems electrical outputs would be limited to 500 kW and below. After an initial market search, Capstone Microturbine was chosen as the supplier of the turbine engine and controls due to their many technological advantages over their competition. There engine would not require any oil and therefore fit with the clean and maintenance free design requirement of the system. Heliofocus and Capstone partnered to build an initial prototype system for proof of concept prior to moving forward with a production system build. Figure 5 shows a conceptual drawing what the planned production system would look like. The prototype build of the system would modify an existing Capstone C65 Microturbine engine by removing the combustor and add connections for the external solar heat input using existing engine ducts. These ducts would be connected up to the Heliofocus heat receiver to allow complete cycle testing.

Figure 5: Heliofocus 65kW Solar Generator Conceptual Drawing

Initial design calculations shown in figure 6 predicted that with 310 kW of solar input, the system would output 65 kW at 21 % overall efficiency. This assumed a DNI of 1 kW/m² and a 310 m² dish area.

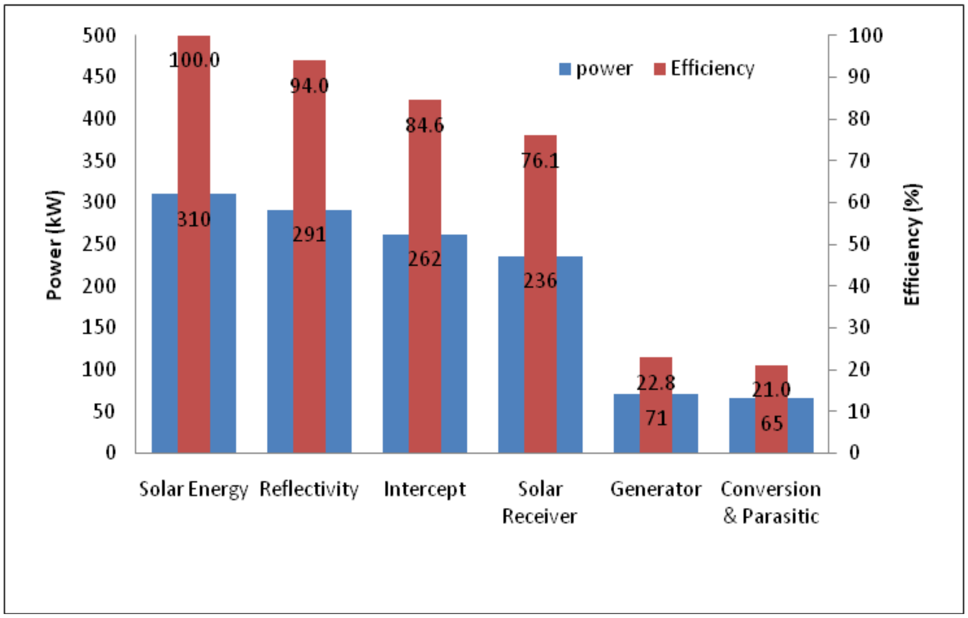

Figure 6: Heliofocus 65kW Initial Design Calculations

INITIAL MODELING PREDICTIONS

Initial work was done on a computer simulation of the prototype system. Using an existing and validated Matlab Simulink C65 Microturbine system model as the starting point, a complete 65 kW solar system model of the prototype solar system was created. As the model has a distinct engine combustor system, it was relatively strait forward to remove this module and replace it with a solar receiver model. The solar receiver model was developed from extensive test data taken from multiple solar receiver module tests. Once the model was finished, data could be collected by varying the model inputs of solar direct normal irradiance, ambient temperature, and site elevation.

Table 1. Steady State Operation Simulation Results

	ISO Ambient Conditions	122° F Ambient Temperature and 0 m Elevation
Sun Input Energy (kW/m²)	1.0	1.0
Engine Speed (kRPM)	83.4	89.8
System Output Power (kW)	39.1	33.8
Overall System Efficiency (%)	19.5	16.9
MT Engine Efficiency (%)	29.6	25.6
Solar Receiver Efficiency (%)	88.1	87.4

This new overall solar system model was used to determine the optimal system control method and to predict the performance results of the complete system more accurately than the initial simple calculations. The results from this modeling are shown in table #1. These results were taken at a microturbine engine partial load condition due to the expected solar limitations of the test facility, but still demonstrate close to the 21 % full load target efficiency.

SITE INTREGRATION

Figure 7 shows a CAD model physical layout of the complete prototype solar power generator system that was built and tested. The initial testing was planned to be done using a solar tower with Heliostats where we would have the ability to accurately control the amount of sun entering the receiver. The site chosen was the Weizmann Institute of Science solar tower test facility in Israel as shown in figure 8.

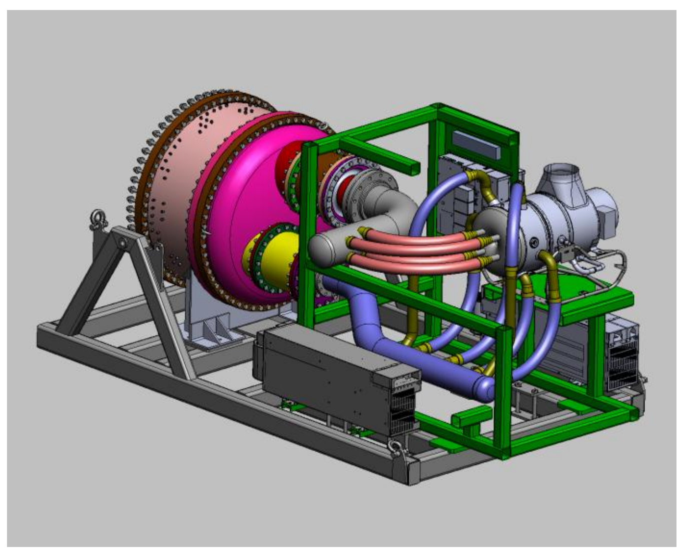

Figure 7: Prototype Heliofocus Receiver Microturbine Assembly

Figure 8: Weizmann Institute of Science Solar Tower

After the microturbine was delivered and installed into the Weizmann Institute solar tower test facility, the initial testing of the prototype was able to be scheduled for late June. This system was installed at the Weizmann Institute solar tower on the 12th floor where the current light spot in figure 8 is hitting the building. Due to tower mirror focus limitations, the tower facility was not able to focus the sun down to the receiver aperture diameter and that caused a significant amount of light spillage which reduced the amount of heat to test with. The light delivery capability to the receiver was less than 200kW for a typical sunny June summer day. This limited the output capability of the test system to well below its full capacity, but was the condition that was the modeling was done to match. After a few days of integration and test for controls tuning and communication work, the system was able to function autonomously. This capability was a significant milestone of the testing plan and demonstrated the ability of the system to regulate its operating temperatures without human control being necessary. Once that was complete, the system to be performance tested.

SITE PERFORMANCE RESULTS

Table 2 shows the ambient test conditions at the test facility for the day of June 20th 2010 when the system performance test was completed. The DNI for this test day was slightly lower than was expected, as a result of the local area's haze that reduces the amount of sunlight that reaches the surface of the earth.

Table 2: Heliofocus Prototype Test Conditions

Parameter	Value
Ambient Temperature	43.3° C
Ambient Pressure	99.15 kPa
Direct Normal Solar Irradiance (DNI)	0.825 kW/m²
Solar Input Energy to Receiver (Calculation)	175 kW

The results from the highest power test run on are shown in table 3. The results shown are a single point once full power steady state conditions were reached at peak sun intensity for that day. The data includes calculated values as listed for test result parameters that could not be measured directly. The data in table 3 is the highest power level we could achieve from the tower test facility. Solar power entering the receiver was calculated to be about 175 kW. To reach the prototypes full system capacity would require about 265 kW of solar input power.

Table 3: Heliofocus Prototype Field Testing Results

Parameter	Test Results	Model Results	Units
PCD (pressure at compressor discharge)	288.3 (41.81)	308.7 (44.77)	kPa (psig)
Receiver Inlet Pressure	273.2 (39.63)	293.5 (42.57)	kPa (psig)
Receiver Inlet Temperature	542 (1008)	550 (1023)	°C (°F)
Receiver Exit Pressure	270.3 (39.20)	289.6 (42.00)	kPa (psig)
Receiver Exit Temperature	871 (1600)	864 (1588)	°C (°F)
Turbine Inlet Pressure	Not measured	268.9 (39.00)	kPa (psig)
Turbine Inlet Temperature	Not measured	864 (1588)	°C (°F)
TET (turbine exit temperature)	563 (1046)	560 (1041)	°C (°F)
Exhaust Gas Temperature	335 (635)	319 (606)	°C (°F)
System Mass Flow [Calculated]	0.409	0.435	kg/sec
Engine Speed	96000	96000	RPM
Receiver Power In [Calculated]	173.83	172.1	kW
Receiver Power Out [Calculated]	155.14	155.1	kW
Engine Power	29.25	40.07	kW
System Power	24.04	35.22	kW
Collector Efficiency	10.75	85.00	%
Receiver Efficiency	89.25	90.07	%
Engine Efficiency	18.86	25.84	%
Electrical Conversion Efficiency	82.22	87.90	%
System Efficiency (not including collector)	13.83	20.46	%
System Efficiency ($Eff_{collector}$ value of 85% used)	11.76	17.39	%

Once the testing was complete, the model was run again at the same input conditions to give comparative values to the test results and these values are also listed in table 3. The ambient conditions run for the model data were the same as in table 2 except for the DNI value that was not used. This value could not be used in the model because the model was built using the dish collector and not the tower heliostat field of the test. The model inputs were adjusted until the Solar input to the receiver matched the value shown in table 2.

It is clear that both the engine and system power levels were about 10kW below what would have been expected for this operating condition. Looking at the model overall system efficiency value and using an arbitrary but expected typical dish collection efficiency of 85 % gives a predicted target efficiency of 17.39 % for these conditions. Meeting this efficiency would have been the equivalent of meeting the targeted ISO test condition and full power operations 21 % efficiency level.

The system was not performing at the level expected due to the loss of engine efficiency. For this input power level the expected engine efficiency would have been 25 %, but the level we measured was 18.9 %. This loss in engine efficiency combined with the loss of mass flow and system pressures points to a leak inside the engine. Figure 9 shows a production C65 microturbine engine cutaway. In this picture the powerhead, which is the part of the engine assembly with all the rotating components, was performance tested and passed prior to shipment. The power head was then assembled into the engine casing assembly. Once assembled, the entire engine could not be tested without an external heat source of 250 kW or greater capacity. As a test system of this capacity for external heat did not exist, the engine was shipped without being "Hot Tested". Looking closely at figure 7, the six cold airflow tubes (small blue tubes) and four hot airflow tubes (red tubes) that had to be welded to the production C65 Microturbine engine for this prototype build can be seen. It is very likely that the addition of all this welding to the engine caused some of the internal engine seals to be distorted and leak. This type of build error is typically caught by the final performance test that could not be done on this engine.

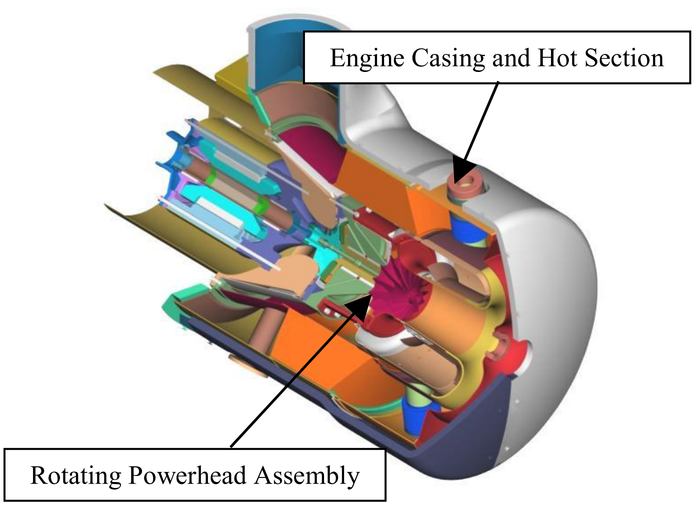

Figure 9: Production C65 Microturbine Engine

CONCLUSIONS

It was unfortunate that the engine build error resulted in not demonstrating the target overall system efficiency, but this was not really a goal of this prototype testing. The goal was to demonstrate the ability to generate electricity from sunlight. All the controls and communications verification testing was completed which provided a functional power electronic control system for a solar microturbine power generator. This working prototype system was then able to demonstrate sustained solar power energy generation of 25 kW to the electric grid. Also, the secondary goal of demonstrating the correct solar receiver efficiency of ~90 % was successful. This was the highest power test that was ever run on the prototype solar power receiver and it performed better than expected. The solar receiver efficiency accomplishment is especially important as the development of the solar receiver is the most technically difficult part of this development program. Running the solar receiver at full flow and almost its full 1000° C temperature condition (reached 870° C) was a critical accomplishment before moving forward. Once the engine leaks can be corrected and 100% solar power input can be provided, the prototype system should be capable of delivering 65 kW of solar microturbine power generation at a system efficiency of 21 %.

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