A Unique Design to Generate UAV Electrical Power in Flight

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As smaller UAVs are designed with more sensors and communications technology for longer missions, the additional electrical power to run them drives the need to generate onboard electric power. One way to create onboard electrical power would be to harness the remaining 80% "waste energy" produced by the two-stroke engine.

A team of engineers from Electronic Cooling Solutions and Ambient Micro designed, built, and tested an exhaust-heat thermoelectric generator (EHTEG) that can be incorporated into a UAV design to harvest and convert this waste energy into electrical power in flight [2] .

There are several sources of energy loss in a small engine all in the form of heat. The main sources are the heat rejection from the cylinder and cylinder head, loss from friction, and the heat of the exhaust stream. Though the heat from the exhaust system is the only truly usable heat source.

The EHTEG had several requirements:

- Mechanically robust and integrate into the aircraft without compromising flight safety,
- Extract the required heat without impairing engine performance,
- Provide the largest possible temperature differential across the thermoelectric modules while operating within the maximum temperature limits, and
- Designed with minimal weight and aerodynamic drag.

Figure 1. UAV with the EHTEG attached on top

Designing the Interior and Exterior TEGs

Heat exchangers on the inside of the muffler absorb heat from the exhaust as it flows through. The heat passes through exchangers to 2inch. square TEGs mounted on the outside of the UAV and finally passes through another row of heat exchangers to the open air. As the TEGs are exposed to the temperature difference between the hot inside exhaust air and the cool outside air, they generate electric current. The greater the temperature difference, the more current is generated.

The team modeled the thermal design of the system using Mentor Graphics' FloTHERM® Computational Fluid Dynamics (CFD) modeling software [1]. They simulated airflow on the outside (cool air) and the hot exhaust inside to estimate the temperature difference, which enabled them to optimize the internal and external fins of the heat exchanger and the number and location of the TEGs.

They built engineering models of several likely EHTEG configurations and ran them on a test stand using the same engine and propeller that is used in a MLB Company Bat4 UAV. The models were validated for a range of operating parameters that simulate flight conditions

The engineers used FloTHERM software that models conduction, convection, and radiation as well as the fluid flow of both the external cooling air and the hot internal

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exhaust gas. They created virtual models of the exhaust system and performed thermal analysis and test design modifications quickly and easily before building any physical prototypes. The results of the CFD models correlated well with those obtained on the engineering test bed.

The engineers used the internal volume and length for the muffler recommended by the manufacturer to make the system act as an efficient expansion chamber exhaust system. These were used to develop the first half-symmetry CFD models that would determine the number of TEGs needed to optimize the electrical output with minimal weight. The model is symmetrical, so building a half-symmetry model reduced the number of elements down to 1.04 million cells with no loss in accuracy.

The fin parameters of the internal and external heat exchangers were kept relatively constant while varying the location of the heat exchangers and the placement of the TEGs. The goal was to maximize the temperature differential across each TEG to extract the most heat energy from the 455°C exhaust gas.

13 configurations of heat exchangers and TEGs were modeled in the first optimization study. They tabulated the power output from each configuration and chose the best configuration.

After optimizing the placement of the TEGs, it was found that the central fins on the interior heat exchangers disrupted the exhaust flow and the hot exhaust gas wasn't reaching the front end of the muffler. But if they removed the center fins, the exhaust gas would not channel down the center and the exhaust pulse would not reach the front end of the muffler. So instead of removing the central fins, they placed them in a semicircular pattern. (Figure 3) This configuration kept the exhaust pulse moving through the center of the muffler and it was able to curl back symmetrically as the hot gas flowed back along the outsides and through the fins.

The interior heat exchangers decreased in temperature as the hot exhaust gas flowed from the front through the fins to the rear of the muffler and then out of the vertical exhaust pipe.

The FloTHERM simulation was able to show the exhaust gas flow pattern for the heat exchanger with the center fins removed. (Figure 4) The flow pattern is disrupted

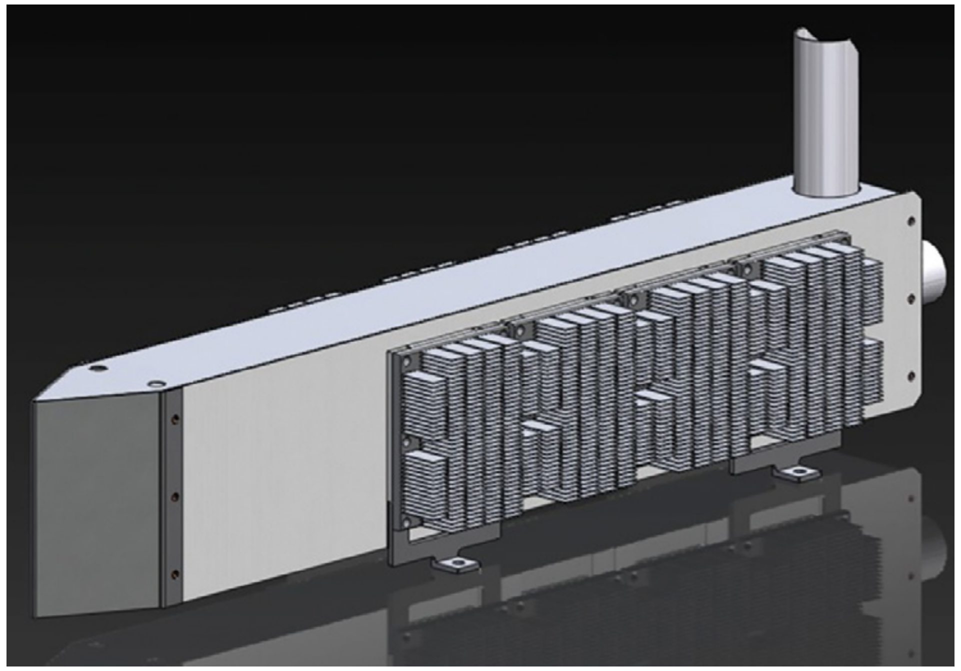

Figure 2. The positions of the external heat exchangers that resulted in the highest average power generation for the system

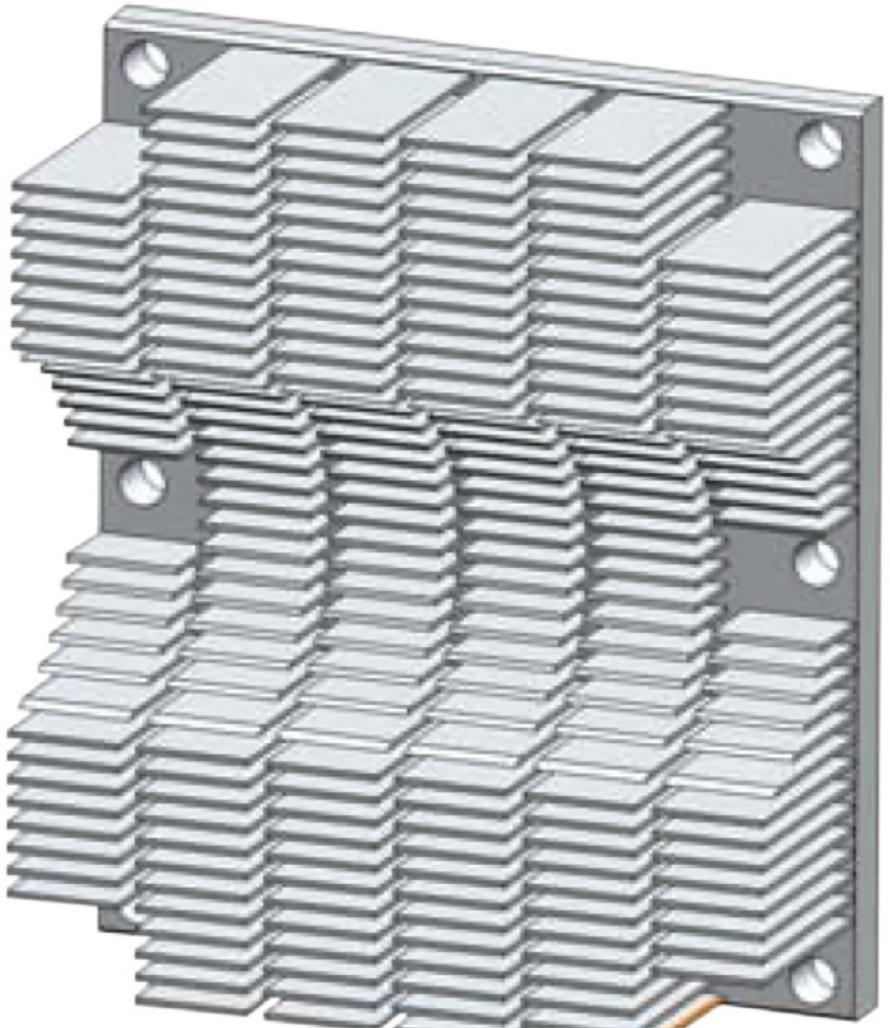

Figure 3. The interior heat exchanger with the fins in a semicircular shape in the center

before the exhaust stream reaches the front end of the muffler.

The simulations showed that when the semicircular-shaped fins are present, the flow pattern retains its shape all the way to the front of the muffler. (Figure 5) This allowed them to optimize fin placement.

Typically, the outside heat exchangers on TEGs are placed in a line. This causes an issue because the units toward the rear of the external airflow receive more preheated air than the heat exchangers that are upstream. This reduces the delta-T across the heat exchanger and the power output.

Therefore, nine configurations were analyzed to determine the optimum fin parameters for the external heat exchangers. The results were plotted against the total power generated by the TEGs. All of the custom heatsink designs analyzed out-performed the stock heatsinks for total power generation, but due to time and budget constraints, stock heatsinks were used for the first flight test model. This resulted in a reduced power output 11W compared to the custom heatsinks.

The outside TEGs were arranged in four columns by two rows on each side of the muffler. The TEGs maintained a cool side temperature below 58.3°C with external air at 18 °C and 22.3 m/s velocity, while keeping the hot side temperature below the maximum allowable temperature of 225°C. (Figure 6) The outside heat exchanger temperature ranges from 26.1°C on the leading edge of the front fins to 58.1°C on the base plate next to the hottest TEG.

Some of the first simulations demonstrated that the heat loss through all other surfaces of the muffler had to be minimized to maximize heat flow through the TEGs for maximum power generation. Mineral wool insulation was used on all the exposed surfaces to minimize the heat loss.

The power output of the EHTEG system was modeled by summing the power contribution of each pair of TEG modules. By first calculating the hot side and cold side temperatures of each TEG pair, these values could then be used to compute the open circuit voltage. The harvesting and power conditioning circuitry matches the equivalent series resistance for maximum power transfer; thus, the voltage of the load resistance is exactly half the open circuit voltage. This data defines the power harvested per TEG pair.

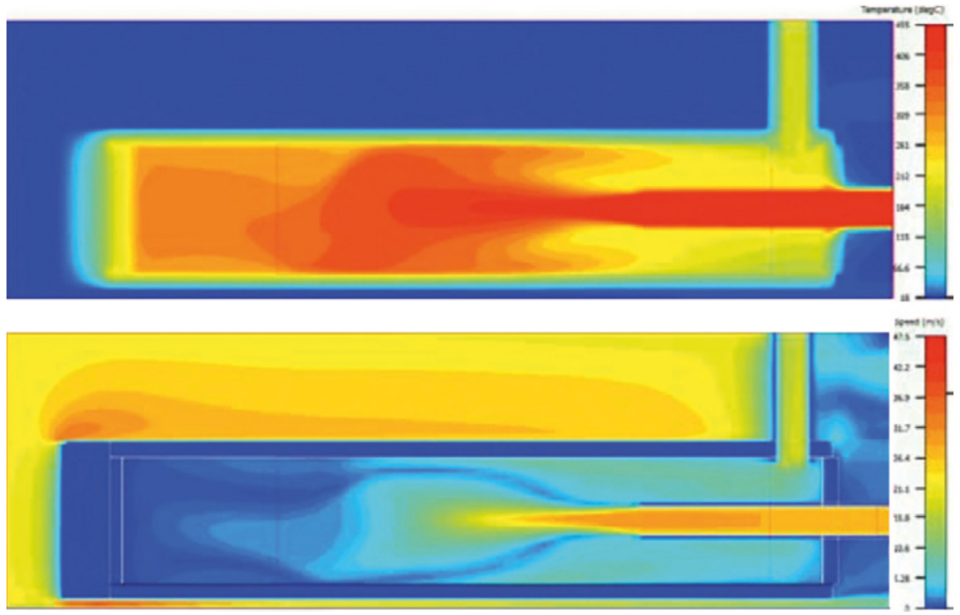

Figure 4. Thermal simulation shows the exhaust gas flow pattern without fins in the center

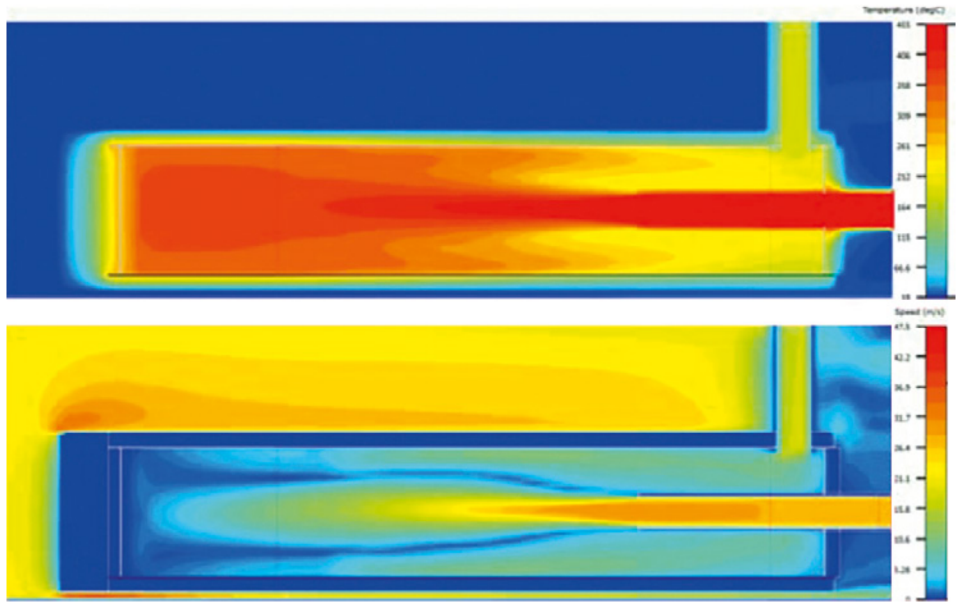

Figure 5. Thermal simulation shows the exhaust gas flow pattern with fins placed in a semicircle in the center

Mechanical Design

The mechanical design of the EHTEG had two main requirements:

- Able to support the thermal components and allow adequate flow of cold air around the external heatsinks, and
- Be lightweight with minimal frontal area to reduce aerodynamic drag.

The heatsinks were fastened from the outer (cold side) to the inner (hot side) forgings. The TEG modules were sandwiched between the outer heatsinks and the EHTEG sidewalls. They used a high-temperature thermal interface material at each interface in the thermal path to maximize heat transfer from the inner heatsinks through the thermoelectric generator modules and the outer heatsinks. Figure 8 shows an exploded view of the EHTEG.

Converting to Usable Electricity

The thermal environment of each thermoelectric module was slightly different because of its location on the EHTEG, so each module's output was also different from its neighbors. The input interface modules received the output from a pair of

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modules and converted the input voltage to 12 V. The input module also automatically adjusted its input impedance to match the source impedance, thus operating at the maximum power transfer point.

The outputs of the input modules were combined and fed to a single 12-V bus regulator that provided a regulated 12-V output to external loads. An electronic load was included in the power conditioning electronics for testing purposes. The electronic load automatically adjusts its resistance to extract the maximum power available from the EHTEG system. The data I/O board provided voltage levels proportional to selected voltage and current levels for input to the onboard data-logging system.

In Summary

The team used FloTHERM to create virtual models of the exhaust system, analyzing various design configurations quickly before building any physical prototypes. And the results of the CFD models correlated well with those obtained on the engineering test bed. Since the TEGs are actually thermoelectric coolers run in reverse, their efficiency is only around 5%; that is, 5% of the heat energy flowing through is turned into electricity. If this efficiency rate can be doubled, the technology could be used in many practical and profitable applications. New commercial opportunities are spurring interest in thermoelectric power generation. The design techniques described here could be used to develop much higher power output thermal energy harvesting power systems.

References

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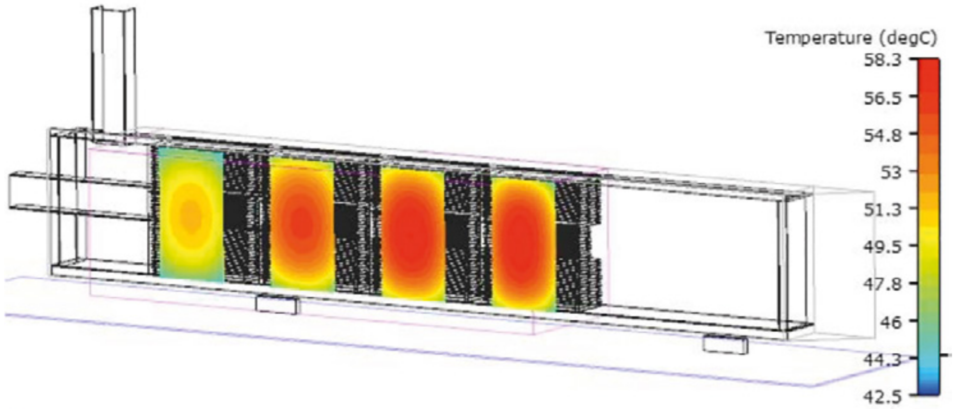

Figure 6. Cool-side temperatures of the outside TEGs.

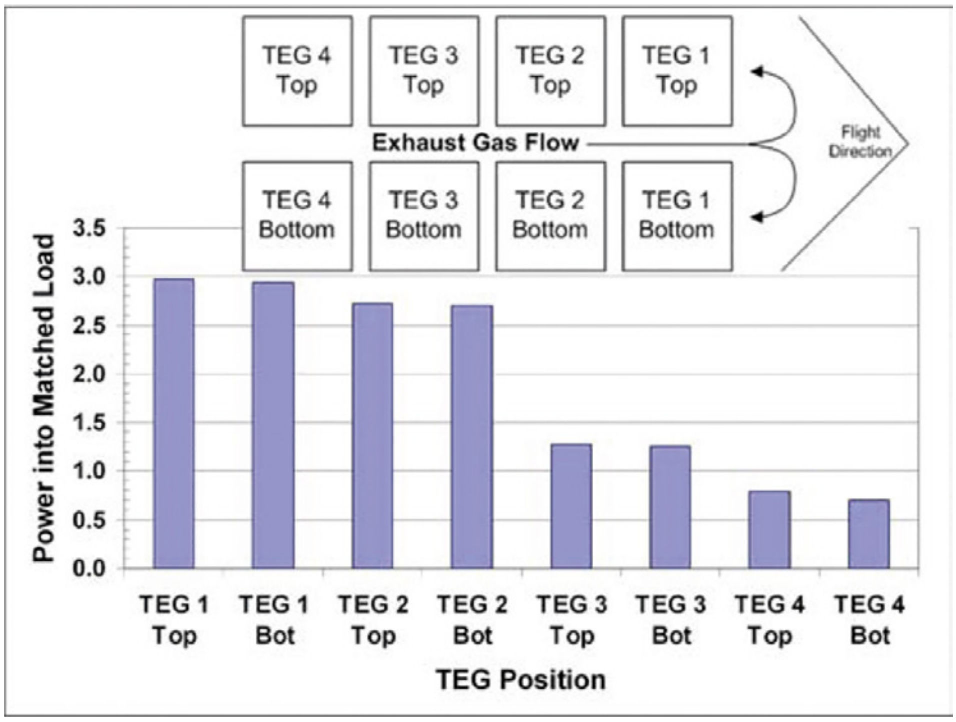

Figure 7. Single-side power output (W) for the flight configuration

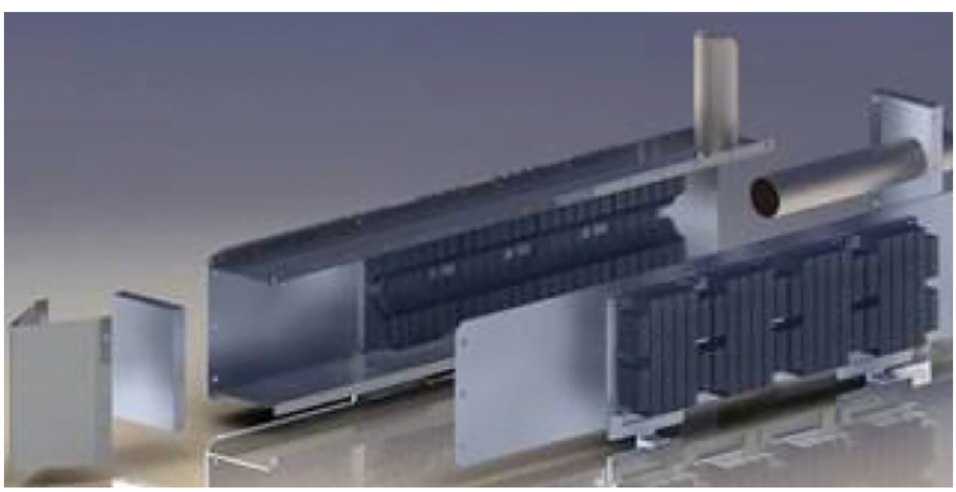

Figure 8. The inside and outside of the EHTEG

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