MINIATURE POWER SOURCE WITH CATALYTIC COMBUSTOR AND HYBRID THERMOELECTRIC GENERATOR

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ABSTRACT: A miniature fueled power source using a catalytic combustor and thermoelectric generator (TEG) has been demonstrated. The combustor is designed to produce a nominal thermal power of 100 W using butane fuel and to conduct 75W to a hybrid (BiTe/PbTe) TEG designed to deliver 6 W of with 8% conversion efficiency. The fabricated combustor showed self-sustained combustion using butane, with combustion efficiencies of 85% to 99% and thermal efficiencies (fuel to thermal enthalpy into the TEG) of 41% to 56%, for thermal power outputs in the range of 40 to 140 W. Testing of the hybrid TEG yielded an average electrical power output of 5.2 W with 7.5% conversion efficiency when operating at 475 ºC and 75 ºC hot and cold side temperatures respectively. When a pair of hybrid TEGs is integrated with the combustor, the system produced a maximum electrical power output of 9.4 W, corresponding to a thermal efficiency of 41%, and net system efficiency (fuel to electrical) of 2.85%, corresponding to an energy density of 362 Watt-hr per kg of butane.

KEY WORDS: miniature, power source, catalytic combustion, thermoelectric generator, efficiency

INTRODUCTION

The U.S. Air Force seeks miniature electrical power sources with significantly higher energy density than electro-chemical batteries for applications in the next generation Small Unmanned Aerial Systems (SUAS). A power source based on hydrocarbon fuel offers the potential to achieve several times higher energy density than Li-ion batteries that are commonly used in today's SUAS. Several types of fueled power sources have been developed [1], including gas engines with electric generator, fuel cells, photovoltaic generators and thermoelectric generators. Power generation using a combination of catalytic combustion and thermoelectric generation offers the advantage of a system with few moving parts, flameless combustion, and well-controlled heating sources. In a combustion-thermoelectric generation (CTEG) power source the electricity is produced through a two-step conversion process: fuel is converted into thermal energy by using a combustor (or burner) and this energy is converted to electricity using a TEG. A number of early studies investigated the development of small combustors and reactors using liquid fuel [2, 3]; later studies demonstrated the integration of miniature combustor and TEG [4, 5]. These studies generally targeted low-power generation (less than 1 W electrical) using chip-scale or meso-scale structures. For SUAS applications, while small size is important, significantly higher power is required, typically in the range of 10 to 20 W electrical. This study reports on the development of the critical components required for a miniature CTEG power source, namely the combustor and TEG, and integration testing of these components.

MICROCOMBUSTOR^{TM} DESIGN

The design of the Microcombustor is driven by several key objectives:

1. Maximize combustion efficiency. To achieve this objective, the burner needs a large surface area for catalytic reactions and long flow paths to enable sufficient residence time for complete combustion of fuel. The design of the burner must trade off size, combustion efficiency, and pressure drop.
2. Optimize heat recovery versus pressure drop and heat loss. Adding heat exchangers recovers some heat from the exhaust but also increases system pressure drop and system volume.
3. Maximize burner thermal isolation. The burner operates at temperatures from 350 °C to 600° C. At these temperatures, heat losses can significantly reduce system's thermal efficiency.
4. Minimize parasitic heat loss. Heat loss due to wires, fuel tubing, and support brackets can significantly reduce system efficiency.

Figure 1 illustrates the final design of the Microcombustor. This system consists of two parallel gas flow channels, each with a miniature burner and a pair of heat exchangers located on two sides of the burner. Opposing flow directions in each channel results in a counter-flow heat exchanger, allowing the exhaust heat from one channel to pre-heat the incoming gas mixture of the second channel. For high thermal isolation, the burner and heat exchangers are attached to an inner housing that is thermally isolated from the outer housing. Both housings are made of high temperature polyimide thermoplastic (Vespel^{TM}).

Catalytic combustion was selected for its stability (i.e., the ability to ensure combustion at specified locations) and ease of heat transfer to the TEGs. The burner is formed using an array of flat stainless steel fins that are coated with Platinum catalyst and the ends of the fins are attached to a copper base plate. One TEG (not shown in Figure 1) is attached to each burner base plate. The heat exchangers are formed by an array of copper pins (0.65 mm diameter, 0.65 mm pitch) that bridge the two flow channels.

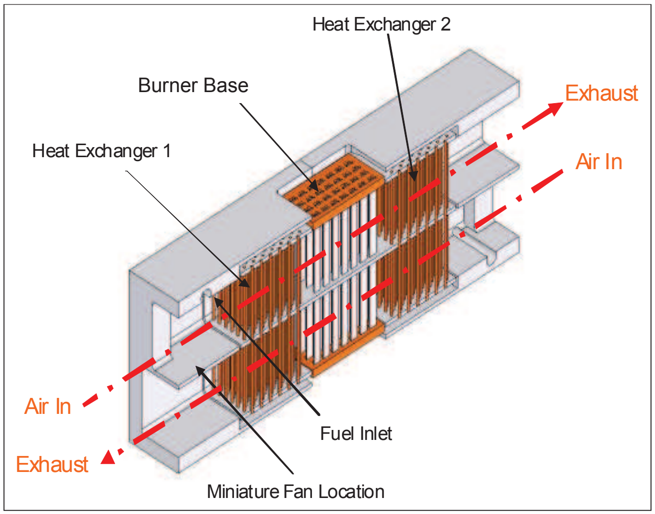
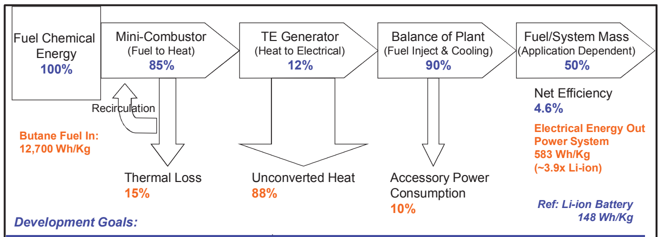


Figure 1: Cross-section view of the Microcombustor. The dual-channel combustor uses a counter-flow heat exchanger to achieve high thermal efficiency (Patent Pending).

ANALYSIS AND MODELING

Fueled power sources are attractive because hydrocarbons such as propane, butane, gasoline, and others have energy densities of 80 to 100 times higher than lithium-ion batteries, hence, even with relatively low conversion efficiency, the resulting system can still achieve several times the energy density of lithium-ion batteries. To determine the achievable system energy density, the critical parameters are conversion efficiencies of the combustor and TEG. Additionally, the energy required to operate the power source (referred to as balance of plant) must also be considered. Lastly, to yield a figure of merit in terms of system energy density, the ratio of the fuel mass to system mass must also be included. The fuel to system mass ratio is dependent on the applications and system design. Figure 2 shows a diagram that illustrates an example of CTEG energy conversion process and design goals for several development programs that were conducted at ISC8.



Development Programs	Fuel to Heat Conversion	Heat to Electrical Conversion	Balance of Plant Power Consumption	Fuel Mass/ System Mass	Net Power Conversion Efficiency (60%	System Energy Density (Wh/Kg)
Program 1 (12 W)	85%	4%	25%	30%	.8%	97
Program 2 (12 W)	85%	8%	25%	30%	1.5%	194
Program 3 (20 W)	85%	8%	10%	40%	2.4%	310

Figure 2: Example of the energy conversion process in CTEG power source and different project goals.

To guide the design development, our team developed several models using analytical expressions from textbooks for all modes of heat transfer, including conduction, convection, and radiation. Three separate models were built, including:

- Combustion and heat-exchanger model
- Thermal loss model
- TEG system model

A combustion model was developed to evaluate the combustion efficiency and temperature profile along the gas flow path. The combustion model used the smaller of the kinetically-limited or mass-transport-limited enthalpy release rates. Kinetically-limited rates were taken from experimental data for varying temperatures for platinum coated samples. Transport-limited rates were estimated from textbook formulas. The heat-exchanger model also used textbook values for heat transfer rates to/from the copper pins. The thermal loss model accounted for the effects of the dual wall construction, thermal radiation shielding, and conduction through assembled parts. The TEG model characterizes key interaction mechanisms between the combustor and the TEG. This simplified system model provided a top-level view of the system, and enabled prediction of key system characteristics such as burner temperature, combustor power, external wall temperature, TEG hot side temperature, and system thermal efficiency. Figure 3 shows the predicted temperature profile along the gas flow path. The combustor temperature is low at the inlet, then rises due to due to heat transfer from the combustor pins, then decreases due to heat transfer to the TEGs exceeding combustion-generated enthalpy. The heat exchanger provides a temperature rise of about 100˚C in this case, reducing fuel consumption by about 5%. The catalyst coverage is critical; too low and there is substantial remaining unburned fuel, too high and the temperatures and heat losses become unacceptable.

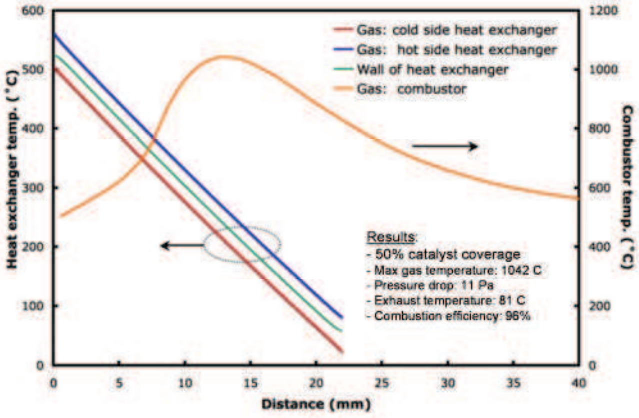


Figure 3: Predicted integrated combustor and heat exchangers temperature profile for 50% catalyst coverage.

BURNER TESTING

A prototype Microcombustor model was built for testing and evaluation to determine concept feasibility and performance. Figure 4 shows the assembled microcombustor with several key features highlighted. For the initial testing, the miniature fan as shown in the figure was not used for air injection; instead, butane fuel and air were individually metered using mass flow controllers and mixed prior to feeding into the Microcombustor. Figure 4 also shows the burner with an array of Platinum catalyst coated fins.

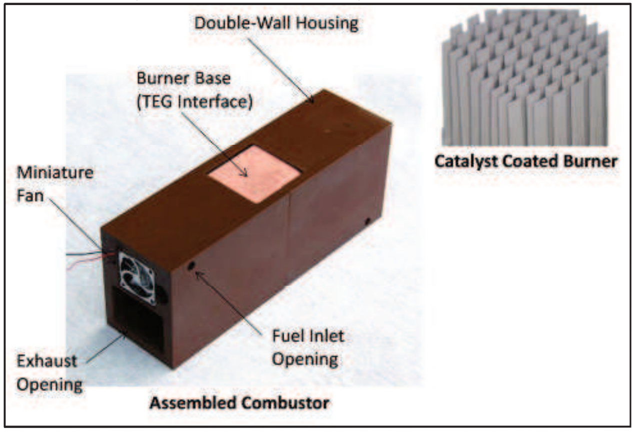


Figure 4: Assembled Microcombustor (11.1 cm x 4.3 cm x 3.2 cm) and catalyst coated burner (inset photo).

A series of tests were conducted to evaluate the performance of the Microcombustor. These tests included testing for combustion stability (2.5 hours self-sustained combustion), equivalence ratios, and extended temperature exposure (4 hrs, 500 °C). The pressure drop across the flow channel was measured using a differential pressure meter. Figure 5 shows measured temperatures at different equivalence ratios. As expected, the maximum power obtained occurred at a slightly rich equivalence ratio of about 1.25.

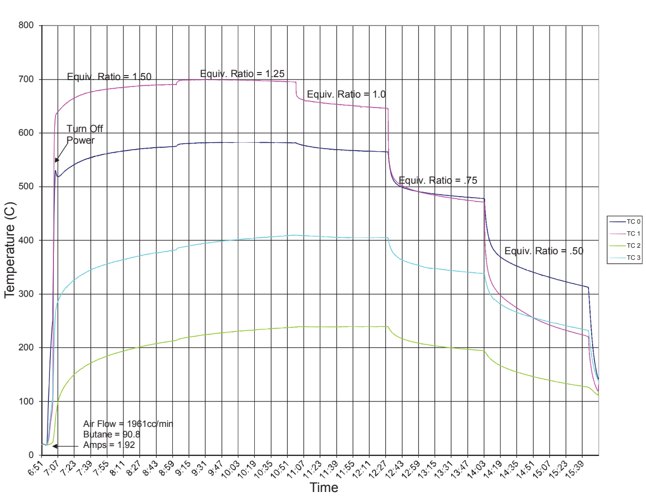


Figure 5: Microcombustor equivalence ratio tests. The maximum power was obtained at the ratio of 1.25.

HYBRID TEG

A companion hybrid TEG has been developed for the Microcombustor by Marlow Industries (Dallas, Texas) under another project in support of this program. The development goals were to achieve 8% conversion efficiency and an electrical power density of 1.5 W/cm^2. To achieve these objectives, a two-stage, hybrid TEG was developed using Bismuth-Telluride (Bi_2Te_3) for the low temperature stage and Lead-Telluride (PbTe) for the high temperatures stage. The fabricated hybrid TEG is shown Figure 6 and measured performance is listed in Table 1. The average conversion efficiency achieved was 7.5%, with each TEG producing an average of 5.2 Watts when connected to 475 °C and 75 °C hot and cold sides, respectively.

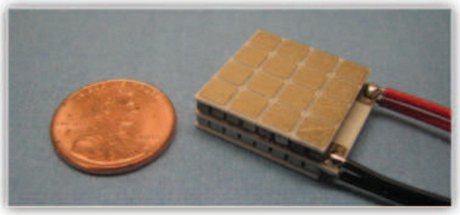


Figure 6: Fabricated hybrid TEG (2cm x 2cm x .7cm).

Table 1: Measured results of the hybrid TEG

	Thot [°C]	Tcold [°C]	Vocv [V]	Rload [Ω]	Pteg [W]	η_{teg} [%]
Device 1	475.04	74.51	1.48	0.12	5.18	7.26
Device 2	475.01	74.63	1.52	0.12	5.27	7.74
Device 3	474.94	75.21	1.52	0.12	5.31	7.63
Device 6	475.1	75.36	1.5	0.14	5.05	7.58
Device 7	475.05	75.09	1.47	0.14	5.04	7.31
Average			1.50		5.17	7.50

SYSTEM TESTING

The catalytic combustor and TEGs were integrated for final testing. Figure 7 shows the assembled system, with external cooling connected to the cold side of the TEG. Table 2 shows measured performance and design targets. In this table it should be noted that the thermal efficiency is defined as the amount of thermal power that passed through the TEG divided by fuel mixture enthalpy. To estimate combustion efficiency, two methods were used. The first is based on the chemical analysis of the product gases using gas chromatography. The second method is based on estimated calculated heat losses compared to the enthalpy in the fuel mixture.

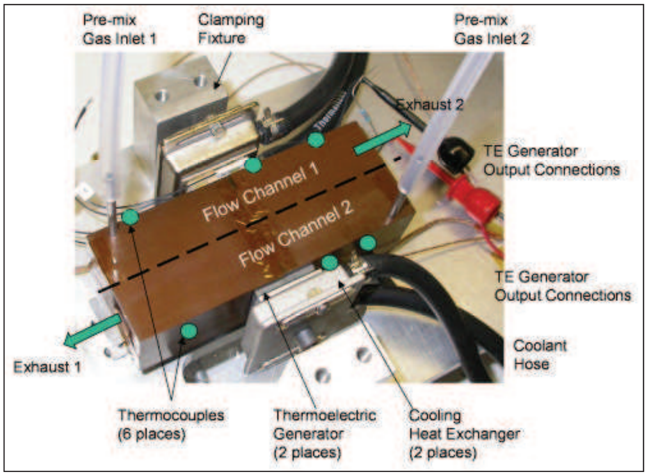


Figure 7: Test assembly with the combustor, TEG and reference cooler.

The microcombustor produced 9.4 W of electrical power slightly below the target of 10 W. A range of efficiencies were found based on the range of burner temperatures that were tested. The burner temperature range (230 °C to 580 °C) corresponds to a thermal power range of 40 to 140 W. The measured combustion efficiencies are close to the target of 95%. On the other hand, the average thermal efficiency (48.5%) is significantly lower than the target value of 85%. A detailed analysis of the heat losses for a typical condition showed a total loss of 132.5 W, consisting of the following: surface heat loss 53.8 W (40.6%), exhaust loss 8.3 W (6.2%), parasitic loss 4.1 W (3.1%), and 66.3 W (50.1%) passed through the TEG. The high surface heat loss is a result of insufficient thermal isolation between the inner combustion chamber and the outer housing. We believe that additional design optimization with improved thermal isolation and reduced system volume will enable the next generation design to approach the target efficiency of 85%.

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Table 2: Microcombustor performance summary.

Microcombustor	**Performance**	**Design Target**	**Comments**
Combustion Efficiency (%) [CE = Thermal Power/Fuel Power]	85 – 99(1)	95	Based on Gas Chromatography measurements of the combustion products and/or estimated heat losses.
Thermal Throughput (%) [TT = Heat Passed Thru TEG/Thermal Power]	48 -55(1)	90	The surface heat losses account for about 40% of the total loss.
Thermal Efficiency (%) [TE = Heat Passed Thru TEG/ Fuel Power]	41 - 56(1)	85	Need to reduce combustor volume and improve thermal insulation.
Pressure Drop (Pa)	5	25	Low pressure reduces air injector power.
Note: (1) Burner temperatures ranged from 230C to 580C.			

CONCLUSION

A miniature power source using catalytic combustion and thermoelectric conversion has been demonstrated. The prototype model produced 9.4 W of electrical power with a net fuel-to-electricity conversion efficiency of 2.85%.

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