Silent lightweight battlefield power source: Scalable from Soldier wearable power to platform power

Dr. Walker Chan
wrchan@mit.edu
Postdoctoral Associate
Institute for Soldier Nanotechnologies
Massachusetts Institute of Technology

Dr. Ivan Celanovic
ivanc@mit.edu
Principal Research Scientist
Institute for Soldier Nanotechnologies
Massachusetts Institute of Technology

Prof. John D Joannopoulos
joannop@mit.edu
Francis Wright Davis Chair Professor of Physics
Director, Institute for Soldier Nanotechnologies
Massachusetts Institute of Technology

Overview

We have developed a generator that fits in the palm of the hand: based on a high-temperature nanophotonics enabled thermophotovoltaic conversion process, it has no moving parts, can operate on almost any fuel (liquid or gaseous), and exceeds ten times the energy density of lithium batteries. The nanophotonics enabled thermophotovoltaic (TPV) generator comprises a microcombustor that heats a photonic crystal emitter to incandescence and the resulting tailored thermal radiation drives low-bandgap photovoltaic (PV) cells to generate electricity. This portable power generation platform is a result of years of research and development in four areas: design, fabrication, and packaging of high-temperature nanophotonic crystals as selective thermal radiation emitters; design of advanced super-alloy high-T microcombustors that are easy to manufacture and low-cost; low-bandpag III-V photovoltaic diodes; advanced system level design and optimization.

The primary benefits of our approach are:

- **Small form factor:** with gravimetric and volumetric high power density, resulting from both the T^4 scaling of thermal radiation, and simple auxiliary systems (control, air/fuel delivery, cooling).
- **Ultra-high energy density** of 800-1500 Wh/kg (including the generator), resulting from the high energy density of conventional hydrocarbon fuels combined with the high conversion efficiency enabled by the photonic crystal emitter. This number far surpasses even state-of-the-art batteries.

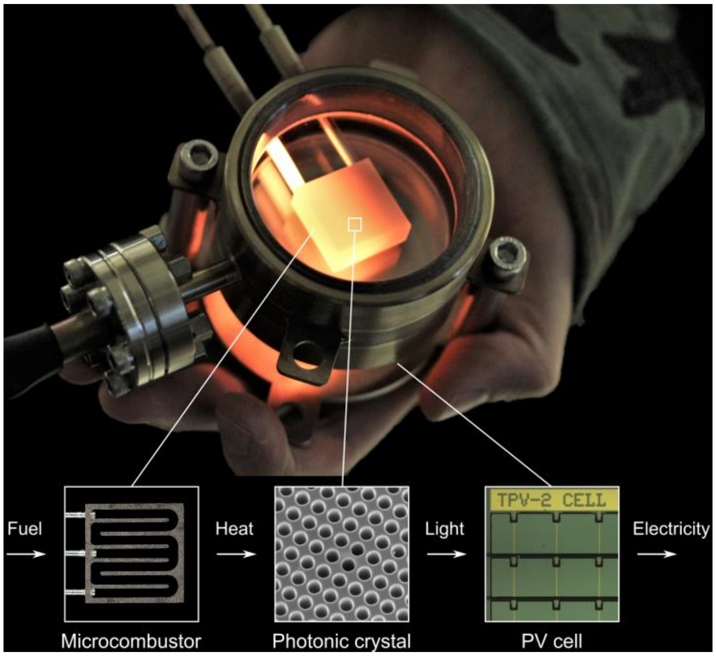

Figure 1. A prototype 5 W system being held in the palm of the hand (top PV cells were removed). Inset: the fuel to electricity conversion process using heat and light as intermediaries.

- **Scalability:** in the 10-1000 W range where batteries become cumbersome due to their low energy density, yet internal combustion engines cannot scale down effectively into this range due to losses driven by surface to volume ratio.
- **Multifuel operation:** unlike fuel cell, our generator requires no special fuels, and it is possible to use even JP-8 and local resources. Also, fuel impurities are not critical (e.g. sulfur etc.) since the conversion of chemical energy into heat doesn't require catalyst or complex electrochemical steps.
- **Silent and static conversion process:** has virtually no moving parts, unlike conventional generators which are loud and heavy.
- **Ready-to-go operation** means no downtime, long shelf life, and no sunlight needed.

Potential for impact

Army applications

Based on our research of high-temperature nanophotonics and small scale super-alloy burner, and fueled by our development of palm sized portable generator system we are now developing a platform technology to silently harness the high energy density of hydrocarbon fuels that is applicable for 10–1000 W scale. This has multiple applications to support Army MDO operations:

1. **Unburdening dismounted Soldiers.** We can reduce the battery load carried by 75%, or 10–15 pounds—freeing capacity for up to nearly two gallons of water or over 100 rounds of 5.56 ammunition.
2. **Increasing small UAV range and endurance.** We can significantly extend the range and endurance of small UAVs (e.g. AeroVironment Puma, Lockheed Stalker, Insitu Scan Eagle) by more than ten times. We also enable in-air refueling.
3. **Extending silent watch missions.** We can silently power computers and radios, eliminating the need to idle the main engine—reducing fuel consumption and signature.
4. **Sensors**. We can silently power unattended sensors or instrumentation stations for months or years.
5. **Countering IEDs.** Our generators can power jammer (e.g. Thor III) and UGVs (e.g. PackBot) reducing Soldier load in dismounted missions and extending runtime.

Technology performance estimates

- **Specific energy.** We predict upwards of 1500 Wh/kg specific energy for UAV larger power sources to 800 Wh/kg for small Soldier wearable power sources. These figures include both the generator and fuel mass for typical missions.
- **Specific power.** We predict upwards of 200 W/kg for larger UAV power sources to 40 W/kg for smaller Soldier wearable power sources.

- **Power output.** This technology performs best at the 10-1000 W power level.
- **Endurance.** We expect refueling to be nearly instantaneous, using either bulk liquid fuel or fuel cartridges.
- **Durability.** With proper ruggedization, the generator can withstand shock, water, dirt, and dust. We expect one of the challenges to be the need for combustion air; exhaust makes the system vulnerable to water and dirt.
- **Vulnerability to attack.** There is no particular vulnerability to attack or disruption.
- **Portability/mobility.** This technology is highly portable because of its small size and high energy density, as well as low acoustic and thermal signature.
- **Supply and maintenance.** Our solution can operate on any fuel, greatly simplifying logistics. The generator will have long lifetime and require little maintenance: there are no moving parts aside from a small combustion air fan and cooling fan and the core of the generator is hermetically sealed.
- **Investment and unit cost.** At a scale of 10000 units, we estimate a bill of material cost of about $100 per watt for small Soldier wearable systems, and less for larger systems. The cost is dominated by the photonic crystal and PV cells.
- **Safety.** Using a small quantity of low flammability fuel such as JP-8 reduces the risk of fire. On vehicles and UAVs, there is no safety risk.
- **Personnel training requirements.** Only minor changes to existing CONOPS will need to be made. We expect the generator to be easy and intuitive to use and to be compatible with the future Soldier power management system.
- **Policy and regulatory concerns.** None.

Technology

In our system, a propane-fueled microcombustor heats a photonic crystal emitter to incandescence and the resulting tailored thermal radiation drives low-bandgap photovoltaic (PV) cells to generate electricity. In the sections below, we detail the photonic crystal, microcombustor, and system integration work.

Photonic crystal

Two-dimensional metalo-dielectric photonic crystal as thermal emitters, based on refractory metals, are the only viable candidates to achieve the high spectral selectivity crucial for high efficiency thermal radiation conversion. Not only does the photonic crystal need good optical performance (high emission in the wavelength range that is convertible by the PV cell and low elsewhere) but it also needs to be stable at high temperatures and readily fabricated in large areas and integrated into the rest of the system:

- **Optical performance.** The introduction of photonic crystal resonances selectively enhances in-band thermal emission while the low loss polished tantalum substrate suppresses emission elsewhere. In terms of conversion of fuel into useful in-band radiation, this photonic crystal reaches 67% of the performance of an ideal emitter, compared to 15% for a blackbody and 30% for natural materials. Furthermore, addition of the photonic crystal increased the electricity output of a test system from 1.5 W to 4.4 W, both for 100 W of propane burnt, and new designs promise to increase fuel-to-electricity efficiencies past 10% at the 5 W scale and upwards of 20% at the 100 W scale.
- **Thermal stability.** This photonic crystal design resists thermo-physical degradation because atomic mobility is limited by the large radius of curvature of its simple geometry and the high melting point and low vapor pressure of its refractory metal substrate. It resists thermo- chemical degradation, such as tantalum carbide formation, because of a conformal hafnium dioxide passivation layer. In initial work by Mesodyne's founders, there was no degradation of the photonic crystal even after a 300 hour anneal at 1000°C.

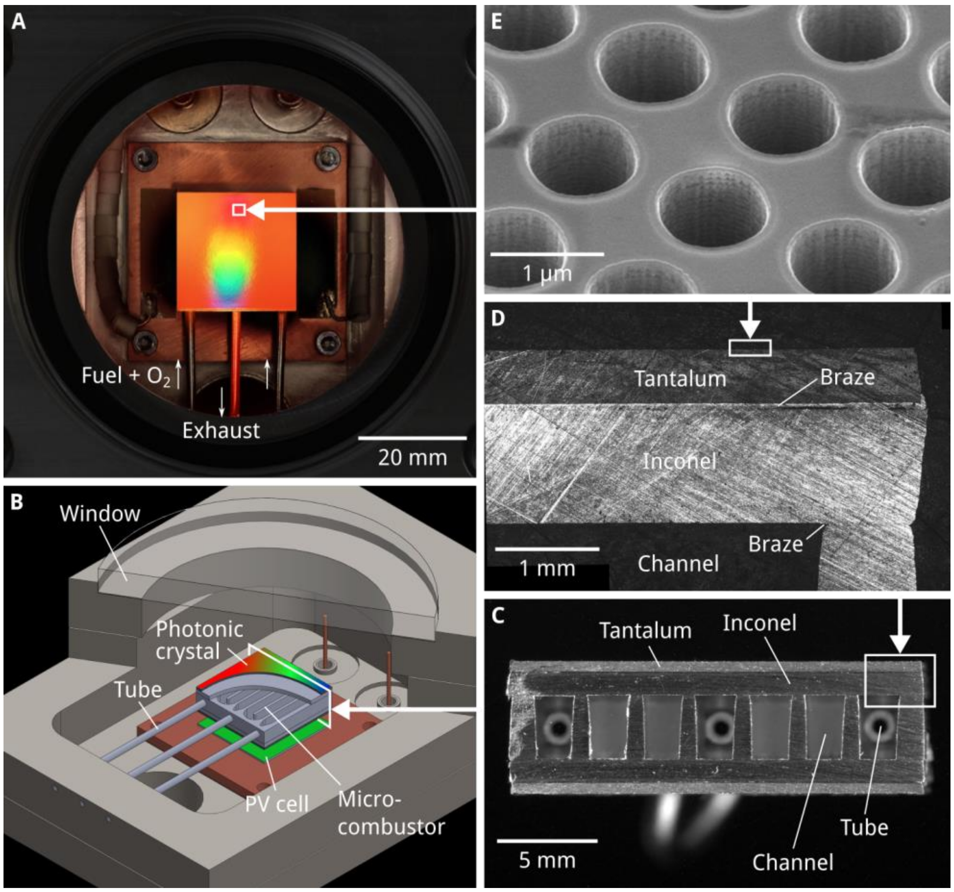

Figure 2. Benchtop demonstration of the 5 W system. (A) A photograph of the experimental setup during operation, where a diffraction pattern is visible on the photonic crystal from the ambient light. (B) A cutaway drawing of the experimental setup with labeled compo- nents. (C) A cross section of the microcombustor with unstructured tantalum substituted for the photonic crystal. (D) An optical micrograph of the corner of the Inconel microcombustor, with the diffusion brazed joint between the Inconel and tantalum visible. (E) A scanning electron micrograph of the surface of the photonic crystal.

This level of thermal stability is orders of magnitude greater than that seen in other engineered emitters.

- **Large area fabrication.** Even though the emitter is nanofabricated, it can be produced in large areas because the simple design requires a minimum number of steps. We have previously demonstrated 2×2 cm photonic crystal fabrication in rigid tantalum substrates. By using the proposed process, we will fabricate 6 cm diameter photonic crystals in flexible tantalum substrates and can easily scale to >20x20 cm at relatively low costs.
- **System integration.** We demonstrated that the photonic crystal can be integrated with metallic super-alloy combustors by diffusion brazing. A fully metallic combustor-emitter assembly is more robust than a silicon or ceramic system because stress can be relieved by deformation rather than fracture. Furthermore, the flexible foil substrate allows the emitter to be integrated with cylindrical combustors, which are favored for power levels over about 50–100 W.

We have fabricated selective emitters on single crystal tungsten bulk substrates as well as polycrystalline tantalum bulk substrates. Our photonic crystal structure consists of a square array of cylindrical cavities etched into the refractory metal substrate to selectively enhance the spectral emissivity in a certain spectral range. The cutoff wavelength is tuned by selecting the appropriate geometric parameters by numerical simulations and optimization. The photonic crystal fabrication process involves interference lithography and reactive ion etching (RIE) of an SiO2 hard mask and a subsequent deep RIE (DRIE) of the tantalum. A passivating layer of

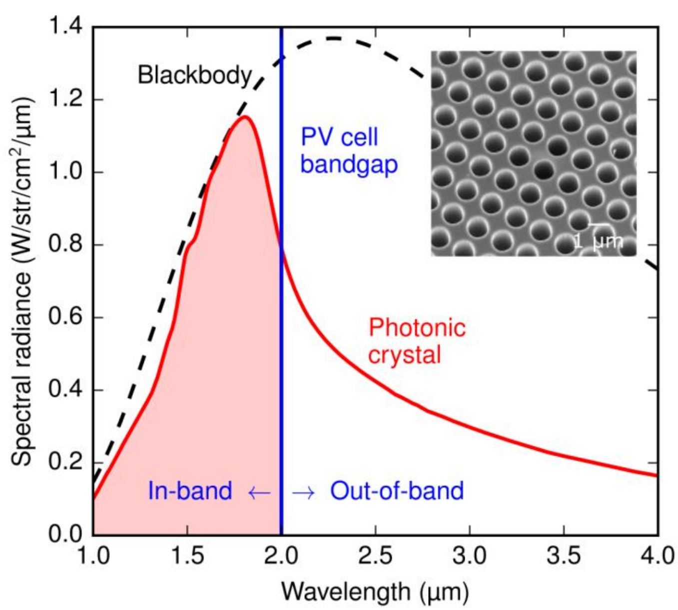

Figure 3. Simulated spectral radiance at 1000 C normal to the surface of the photonic crystal and a blackbody are plotted. The photonic crystal's emission spectrum is engineered to primarily fall below the bandgap of the PV cell, and this in-band radiation, highlighted in red, is converted to electricity. Inset: The photonic crystal is composed of a square array of cylindrical cavities, and its cutoff wavelength can be tuned by varying the radius, period, and depth.

hafnium oxide is deposited via atomic layer deposition (ALD) to prevent degradation of the photonic crystal at high temperatures.

Currently, we are developing a next-generator metalo-dielectric 2D photonic crystal. Our motivation for the dielectric in photonic crystal is to increase the in-band emission (as oposed to metal-air 2D photonic crystal). The overall system efficiency of a TPV system is estimated to increase from demonstrated 4.3% to above 12% when a filled 2D PhC is used as the TPV emitter in a 5 W system. A filled PhC enables this increase in system efficiency because it enables greater spectral control (tailoring of thermal radiation) compared to previous-generation conformal PhCs. The main principle of a PhC emitter is that in a PhC each cavity enhances emission of light with wavelengths below a certain cutoff wavelength (this region is called in-band). The cutoff wavelength is designed to match the bandgap of the photovoltaic cells.

Compared to previous-generation conformal PhCs, a filled PhC has increased in-band emittance at off-normal angles, which leads to an increased overall (hemispherical) emittance. A higher in-band emittance leads to increased convertible radiated power and thus system efficiency. By filling the cavity with a high index dielectric material, we are able to decouple the physical and optical diameters—allowing us to suppress diffraction losses at off-normal incidence. The end result is that the filled cavity photonic crystal offers much higher in-band emission by radiating into all possible channels (not just around normal incidence), leading to higher system efficiency by shifting the heat balance.

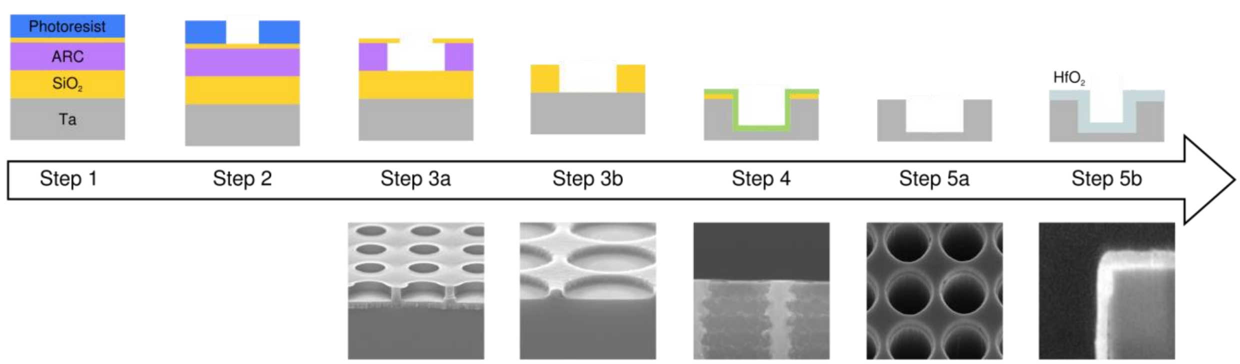

Figure 4.. The fabrication process of our photonic crystal involves (1) layer deposition, (2) pattern generation, (3) pattern transfer into the hard mask, (4) pattern transfer into the metallic substrate, and (5) passivation of PhC.

Microcombustor

We developed a new swirl-stabilized microcombustor. We chose a swirl-stabilized design because it allows for a highly stable flame over a wide range of fuel flow rates and equivalence (fuel to air) ratios and doesn't require any precious metal based catalyst (catalyst was used in our previous generation microcombustor). While our 20 W_e microcombustor is designed for 400 W_{th} it can operate from 100 W_{th} up to 1000 Wth with a stable flame and low pressure drop. The microcombustor design is scalable up to 1000 W_e. The advantages of the swirl stabilized approach are

- Ultra-low pressure drop. Reduced pressure drop is needed to reduce power consumption of the blower used to move air through the microcombustor. The previous design relied on a serpentine channel, while this design relies on parallel channels to transfer heat from the combustion process to the photonic crystal emitters. Parallel channels reduce pressure drop while providing the same surface area.
- Rapid ignition that can be accomplished with minimal energy usage. In the previous catalytic design, the entire microcombustor needed to be heated to 350 C before the combustion process would become self-sustaining. With the swirl-stabilized design, a single spark is sufficient.
- Long lifetime. The previous catalytic system would become difficult to ignite after about a week of operation because the prolonged time spent at high temperature would sinter the catalyst particles. The new design does not suffer from this degradation mechanism.

Below, we summarize how the new microcombustor works by walking through the flow path:

1. Air mixes with propane and flows over the swirler (a static set of pitched vanes placed in the inlet tube, Fig. 2A) where it acquires a tangential velocity. The purpose of the swirler is to create a stable flame at a defined location. We chose a swirl-stabilized design because it allows for a highly stable flame over a wide range of fuel flow rates and equivalence (fuel to air) ratios. While our 20 W_e microcombustor is designed for 400 W_{th} it can operate from 100 W_{th} up to 1000 Wth with a stable flame and low pressure drop. The microcombustor design is scalable up to 1000 W_e.
2. The fuel/air mixture enters the combustion chamber (Fig 1B) where it is ignited by a spark. The mixture is fed into the combustion chamber at a velocity much exceeding the flame velocity (1–2 m/s vs 40 cm/s) and would instantly blow out if no flame stabilization is used. We rely on the flow pattern to carry part of the flame back upstream in order to ignite the incoming stream of unreacted fuel/air mixture—this process is known a recirculation. The flame bends upstream on the inside of the conical flame (the inner recirculation zone) to fill the stagnation zone along the axis of the swirler (similar to the eye of a hurricane), shown in Fig. 2B. The flame also bends upstream on the outside of the cone (outer recirculation zone) to fill the stagnation zone created by the rapid transition between the inlet tube and combustion chamber.
3. The hot combustor products pass over an array of fins to transfer the heat into the photonic crystal emitters on the top and bottom surfaces. We are engineering the geometry to maximize heat extraction while minimizing pressure drop.

Additionally, we are developing a recuperator to recover exhaust heat from the exhaust in order to preheat incoming air and improve system efficiency. We designed, fabricated, and tested a counterflow recuperator built around a piece of corrugated Inconel foil. Although the recuperator was able to transfer heat between the two gas streams with about 75% effectiveness, the current challenge is preserving the exhaust heat for small systems.

System design

We have demonstrated full fuel to electricity generators on the benchtop at the 5 and 20 W scale and are working on the 100 W scale. We are working on a self contained demonstration:

- We have also demonstrated auxiliary systems such as the fuel and air delivery to the microcombustor and PV cell cooling. We developed a feedback system to control an off-the-shelf blower to maintain the proper air flow to the burner.
- We have demonstrated hermetic vacuum packaging (Figure 1) of the microcombustor and photonic crystal. Vacuum packaging is needed to suppress convective heat loss from the microcombustor and prevent degradation of the photonic crystal.

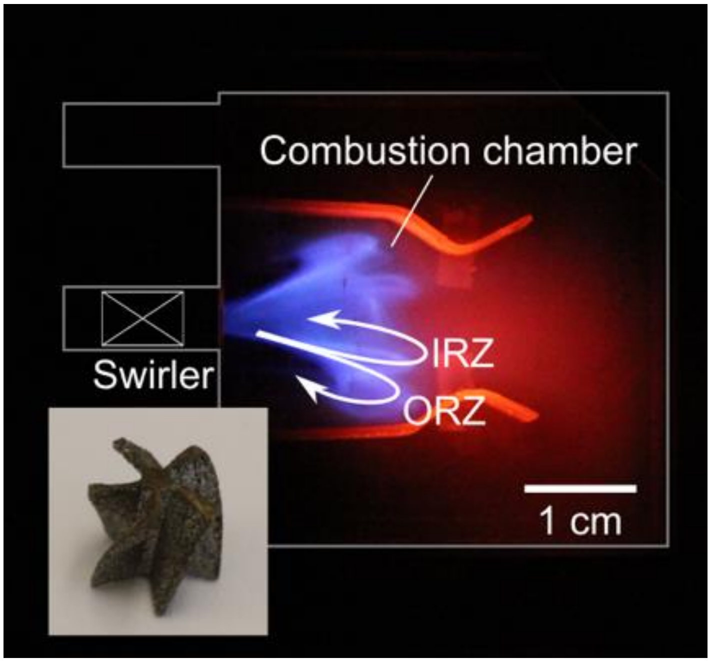

Figure 5. Photograph of the swirl stabilized flame in a microcombustor with a transparent lid. The inner and outer recirculation zones are labeled. Inset: the 3D printed swirler.

Development timeline

We have demonstrated the core conversion technology (microcombustor, photonic crystal, and PV cell working together; TRL 3) at the 5 W scale in 2017. Since then, we have scaled up to 20 W in order to better align with the current power demands of dismounted warfighters. We have also developed the necessary auxiliary systems and plan to have a first standalone prototype by the end of this year (TRL 4-5). Afterwards, expect to develop and field test a series of prototypes (TRL 6-7) over the next few years, and have an operational system acquirable by 2035.

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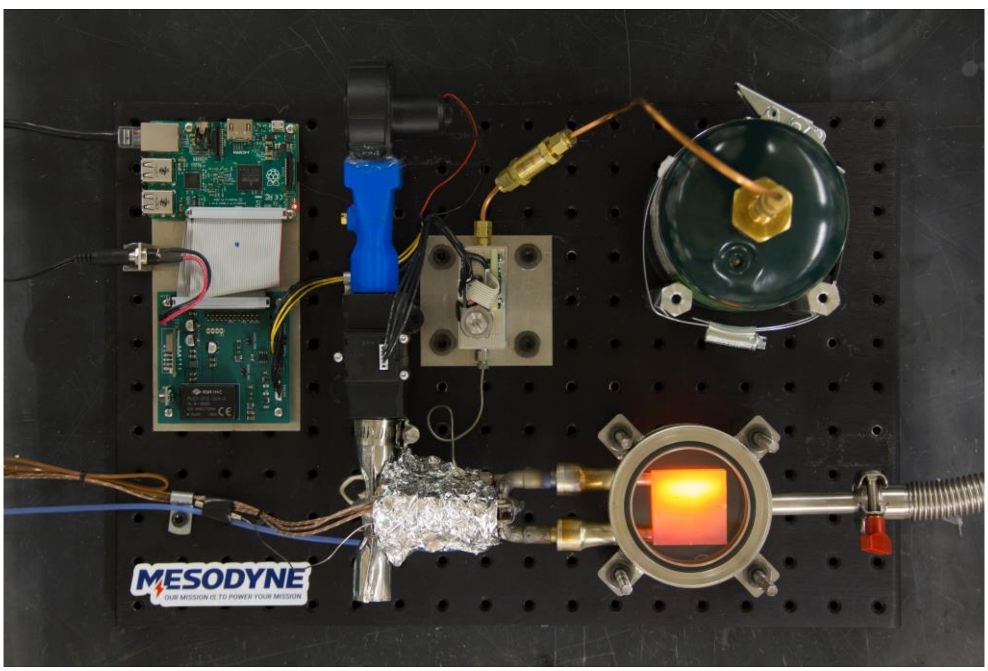

Figure 6. 20 W generator testbed with swirl-stabilized microcombustor with fuel and air systems and recuperator.

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