DESIGN AND THERMAL MODELING OF A PORTABLE FUEL FIRED CYLINDRICAL TPV BATTERY REPLACEMENT

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ABSTRACT: A novel portable fuel fired cylindrical thermophotovoltaic battery charger is described. It uses an array of GaSb TPV cells along with a novel Omega recuperator design and a novel IR emitter design. Computational fluid dynamic (CFD) calculations are presented for this TPV cylinder design showing the potential for an overall fuel to electricity conversion efficiency of 10.9%. The estimated weight of the TPV cylinder is 200 gm and its volume is 900 cc. Fuel volume is arbitrary, but a comparable 900 cc of fuel will weigh 540 gm. The specific energy in a hydrocarbon fuel is 12,900 Wh/kg, resulting in 6970 W-hr of energy in the 900 cc tank. The weight of the TPV cylinder and the fuel cylinder combined is thus 740 gm. Given a TPV conversion efficiency of 10%, the converted energy available from the fuel will be 697 W-hr. The specific energy for this TPV system will then be 697 W-hr/0.74 kg = 942 W-hr/kg. A lithium ion rechargeable battery weighing 1.1 kg has a specific energy of 145 W-hr/kg, .. The TPV power system described here is lighter, has 6.5 times higher specific energy, operates 7 times longer, and is easily refueled.

Keywords: GaSb, Thermophotovoltaics, Batteries.

1 INTRODUCTION

The first high efficiency low bandgap infrared (IR) sensitive photovoltaic cell, the GaSb cell, was invented and demonstrated by Fraas and Avery in 1989 [1,2,3]. This cell responds out to wavelengths of 1.8 microns and enables the use of man made hydrocarbon fuel sourced IR radiators operating at temperatures up to 1700 C for the fabrication of thermophotovoltaic (TPV) DC electric generators. The invention of this cell inspired a renewed surge in TPV system development starting in 1990.

The work on TPV at JX Crystals (JXC) from 1990 up to 2007 is summarized in the TPV-7 conference proceedings [4]. The development of a complete TPV system has required more than just the IR cell. An important additional area of development has included spectral control [5]. It is important to tailor the IR spectrum from the radiant heat source such that the photon wavelengths arriving at the cell fall within the convertible wavelength band for the cell. Longer wavelength radiation falling outside the cell conversion band will simply heat the cell. For this purpose, JXC has developed and patented Cobalt and Nickel doped ceramic matched IR emitters [6,7].

The TPV work at JXC up until recently has focused primarily on hydrocarbon fired combined heat and power systems for the home. Two such examples are the TPV Midnight Sun Stove [8] and the integration of TPV into a standard heating furnace [9].

This paper and a companion paper describe a more immediate TPV application: a portable fuel fired cylindrical TPV battery charger or battery substitute. It uses an array of GaSb TPV cells along with a spectrally matched IR emitter and a novel Omega recuperator. Currently, the military carries heavy batteries. The portable cylindrical TPV unit described here is potentially lighter, runs longer, and is more easily recharged (refueled) when compared with a battery. This paper describes the overall TPV cylinder design along with the novel recuperator design and modeled thermal performance. The companion paper [10] will focus on the matched emitter design and the spectral control topic.

2 PORTABLE TPV BATTERY CONCEPT

2.1 Background

A lithium ion rechargeable battery weighing 1.1 kg has a specific energy of 145 Wh/kg. Meanwhile a hydrocarbon fuel such as Butane or Propane has a specific energy of 12,900 Wh/kg. Therefore, given a small, efficient and lightweight chemical to electrical converter, a much higher specific energy of approximately 1000 Wh/kg should be achievable.

More generally, there is a need for a lightweight compact electric generator that can replace the use of batteries in several potential applications. For example, refueling can be much faster than battery recharging.

2.2 Soda Can Sized TPV Battery Replacement

Figure 1 shows a perspective view of a portable cylindrical TPV battery charger. It is a cylinder 8 cm in diameter and 15 cm long. There is a cooling air fan on one end and a combustion air fan on the other end. The length from end to end including the two fans is 18 cm. Fuel enters this TPV cylinder and DC electricity is generated. In figure 1, a fuel cylinder is shown adjacent to this TPV cylindrical battery.

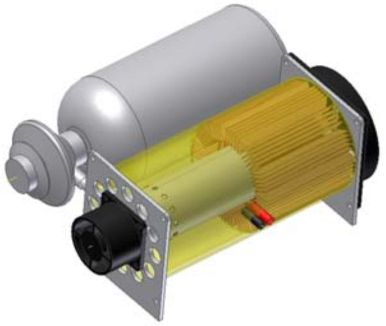

Figure 1: Small portable TPV battery with adjacent fuel cylinder.

2.3 Concepts

TPV generators are intrinsically lightweight. In a TPV generator, any fuel such as Butane or Propane can be used to heat a small solid element until it glows in the infrared (IR) and photovoltaic cells surrounding the IR emitter simply convert the IR radiation to DC electricity.

Figure 2 shows a cross section drawing of the TPV cylinder shown in Figure 1. The key components and subassemblies are labeled. Referring to Figure 2, one can see the IR emitter subassembly in the middle on the right hand side. It is surrounded by the GaSb TPV cells on a cylindrical circuit with fins for cooling. The power converter array subassembly is cooled via air flow around it from the cooling fan on the cylinder end at the right. The IR emitter is heated by combustion gases from its inside. Fuel and combustion air are provided through the recuperator as seen on the left hand side.

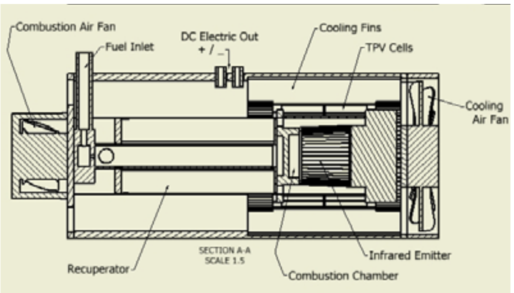

Figure 2: Portable TPV Generator cross section.

A more detailed description is provided in Section 3 on TPV Subassemblies. The basic principles of operation are described next. Fuel is injected through a metering valve orifice into a Bunsen burner like center coaxial tube. Combustion air is fed into a coaxial space around the fuel tube through a finned recuperator stage and into a fuel and air mixing chamber. A fuel/air swirling mixture is then injected into a combustion chamber and ignited. An IR emitter is located around the combustion chamber. The flame heats the IR emitter to the target temperature of 1200 C (1473 K). The combustion byproduct gases flowing initially in one direction are then turned around and then flow back. These hot exhaust gases are confined by an outer window tube. The exhaust gases now enter the recuperator flowing counter to the combustion air heating the combustion air. The cooled exhaust gases exit the recuperator at the left hand side and mix with the cooling air. TPV cells in circuits surround this combustion / emitter chamber forming the TPV converter section of this compact DC electric generator.

The challenge for TPV is conversion efficiency. However over the last several years, major improvements have been made in TPV converter components.

To first order, the conversion efficiency of a TPV system is given by the product of four terms: the chemical to radiation conversion efficiency, η_{CR} , the percent of radiation in the cell convertible band known as spectral efficiency, η_{SP} , the cell conversion efficiency, η_{PV} , and the cell to emitter view factor efficiency, VF. In recent years, JX Crystals Inc has been making major improvements in all four of these subsystem efficiency areas.

The chemical to radiation conversion efficiency is based on the adiabatic flame temperature of approximately 2000C (2273K) and our IR emitter target temperature of approximately 1200C (1473K). Without provisions to manage the waste exhaust heat, the exhaust temperature would be 1200C and the system chemical to radiation conversion efficiency would only be (2273-1473)/2273 or 35%. This problem is solved by the use of a recuperator where heat from the exhaust gases is extracted and fed back into the combustion air. The recuperator design in this portable cylindrical TPV generator is novel. The goal is to extract 70% of the chemical energy from the fuel and to convert it into radiation.

The goal is to achieve an overall TPV electric conversion efficiency of 10%. TPV cells are now reasonably developed and cell conversion efficiencies for in-band radiation are approximately 30%. In the companion paper on the emitter subassembly, spectral efficiency will be discussed with a goal of a spectral efficiency of 60%. Setting a goal for the VF of 80%, then the overall TPV goal efficiency, η_{TPV} , of 10% can be achieved: (The goal of a VF of 80% can be achieved by making the cell area larger than the emitter area in a future TPV circuit design.)

$$\eta_{TPV} = \eta_{CR}\ \ \eta_{SP}\ \ \eta_{PV}\ \mathrm{VF} = 0.7 \times 0.6 \times 0.3 \times 0.8 = 10\%$$

In the following section, the physical designs of the two primary subassemblies will be described. Then in the section after that, a computational fluid dynamic simulation model will be described. Results from this simulation model are consistent with a 10% overall efficiency prediction.

3 TPV SUBASSEMBLIES

The two primary subassemblies are the TPV Power Converter Array and the Burner / Emitter / Recuperator.

3.1 TPV Power Converter Array

The TPV Power Converter Array subassembly consists of a TPV circuit, cooling fins, and a cooling fan. The GaSb TPV cells and circuits are fabricated at JX Crystals Inc. GaSb cells [1, 10] respond to IR radiation out to 1.8 microns. GaSb TPV cells are mounted on a circuit as shown in Figure 3. The circuit substrate base can be copper are aluminum. This metal circuit base has an insulating layer on its front side coated with a metal layer with a gold reflecting top surface. The top metal layer is etched to create cell pads, circuit traces, and reflective regions as shown.

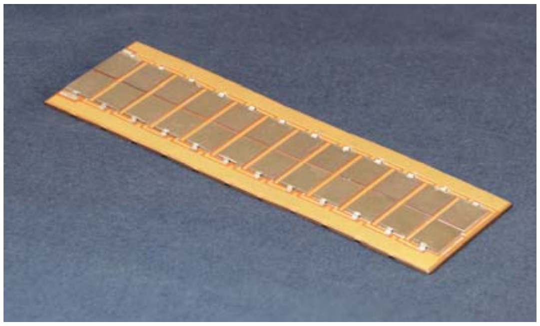

Figure 3: TPV circuit in flat form.

After circuit assembly, this circuit can be flash tested to verify its power conversion performance. Figure 4 shows the results of one such circuit performance measurement.

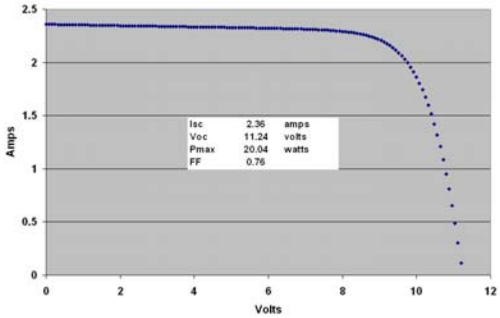

Figure 4: Sample GaSb TPV circuit power curve.

After circuit test, convoluted fin stock is then attached to the back side of the TPV circuit. There are machined grooves on the back side of this circuit allowing the circuit to be folded into a polygonal cylinder at shown in Figure 5.

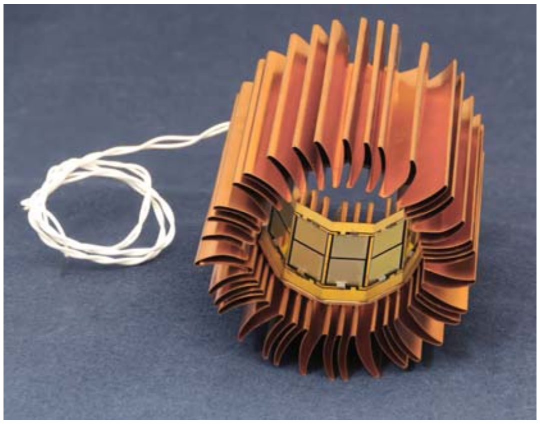

Figure 5: Cylindrical TPV power converter array.

3.2 Burner / Emitter / Recuperator

A perspective view of the burner / emitter /recuperator subassembly is shown in Figure 6. The IR emitter is shown at the top and the recuperator is shown at the bottom. It divides into a burner / emitter subassembly and a recuperator subassembly. The burner / emitter assembly is described in more detail in a companion paper [10]. The recuperator design is novel and critical to the operation of this TPV generator.

3.3 Recuperator

The purpose of the recuperator is to extract energy from the exhaust and to transfer that energy into the combustion air stream. Specifically, the goal is to reduce the exhaust temperature from 800 C to 300 C while increasing the combustion air temperature from 20 C to 600 C. The goal is to increase the chemical to radiation efficiency to 70%.through exhaust heat recuperation.

Figure 7 shows front, top, bottom, and cross section drawings of the novel Omega recuperator, and Figure 8 shows a perspective view of the recuperator partially assembled.

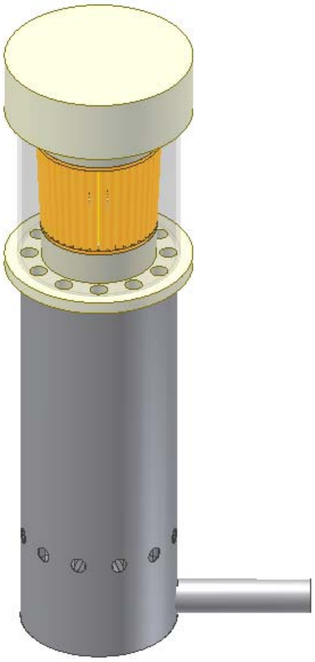

Figure 6: Perspective view of the burner / emitter / recuperator subassembly.

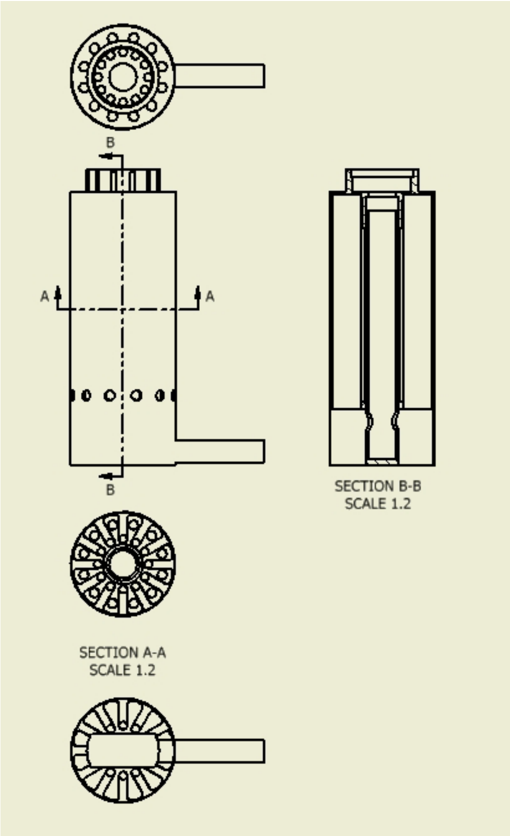

Figure 7: Front, top, and bottom drawings of the Omega recuperator along with horizontal (A-A) and vertical (B-B) cross sections.

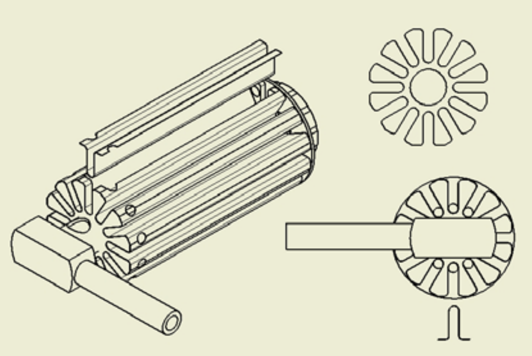

Figure 8: Omega recuperator partially assembled (left); separate drawing of flower disc (top right); bottom view of recuperator (middle right); Cross section through Omega heat transfer membrane (bottom right).

The recuperator section is novel in that it uses Omega (Ω) shaped sheet metal heat transfer membranes as shown in Figure 8. A horizontal cross section through this recuperator is shown in section A-A in Figure 7. As shown in this cross section, twelve Omega shaped sheet metal heat transfer elements create alternating flow cavities for the supply combustion air and for the exhaust. Heat transfers through the walls of the Omega shaped elements as air flows in one direction and the exhaust flows in the opposite direction.

Referring to Figure 8, there is a flower shaped disc shown in the upper right. This disc fits over the fuel supply tube and the base of the burner fits over the open end of the fuel supply tube. Figure 8 shows the recuperator partially assembled. As shown, the Omega shaped sheet metal heat transfer membranes slip into the openings between the petals in the flower shaped disc. One can now see the alternating air supply and exhaust channels. Referring to the top view drawing of the recuperator in Figure 7, one can see two circular hole-patterns. The inner hole-pattern mates with the air channels and allows for the combustion air to enter the combustion chamber. The outer hole-pattern allows for the exhaust to enter the recuperator exhaust channels. Recuperator assembly is completed by placing a cylindrical sleeve around the Omega elements. This sleeve extends down and mates to the combustion air fan. There is a radial hole-pattern in this sleeve shown in Figures 7 that allows the exhaust to exit and mix with the cooling air stream.

4 CFD Modeling

4.1 Overview

The design of the portable cylindrical TPV generator described in the previous section is the result of an internal research and development activity at JX Crystals Inc. During this internally funded activity, solid models were created for the cylindrical generator and its subassemblies using Solid Works. Given this ground work, JXC then received funding from the US Army Research Lab and from Sandia National Labs to perform computational fluid dynamic CFD) simulations for the model TPV generator using SolidWorks-cfd-flow-analysis-software [12].

4.2 Model Results

The CFD software allows one to integrate solid models with sources of air flow and sources of heat to calculate temperature profiles, flow velocities, and heat transfer rates. The calculations include conduction, convection, and radiation effects.

Several CFD simulations have now been run and the most relevant results are presented in Figures 9, 10, and 11 and Table 1. All of these runs used the same cooling air fan, combustion air fan, and heat input simulating a fuel burn rate of 225 W. The cooling air fan chosen has dimensions of 80 mm x 80 mm x 15 mm. It consumes 1.2 W and produces an air flow of up to 1 m^3/min and a pressure of up to 22 Pa. The combustion air fan chosen has dimensions of 40 mm x 40 mm x 20 mm, consumes 0.8 W and produces a pressure of up to 52 Pa. In the simulations, the combustion air flow was set at 0.1 g/s.

Figure 9 shows the temperature profile through the Power Converter Array. The color ranges from 38C for sky blue to 68C for orange. Temperatures over 80C are shown as red. Simulation runs were made for 6 and 8 fins per cell with results showing cell temperatures of 65C and 55C respectively.

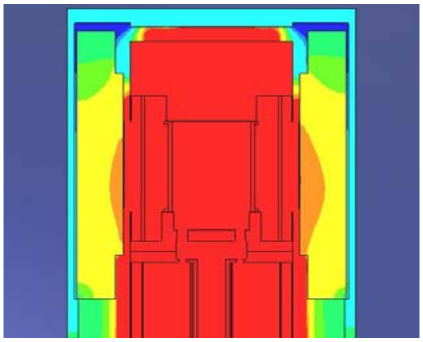

Figure 9: CFD calculation of power converter array temperature profile with 6 fins per cell.

Turning next to the recuperator, Figures 10 and 11 show temperature profiles through the recuperator. The colors now range from 20C for blue to red for temperatures above 400C.

Figure 10: Temperautre profile for recuperator.

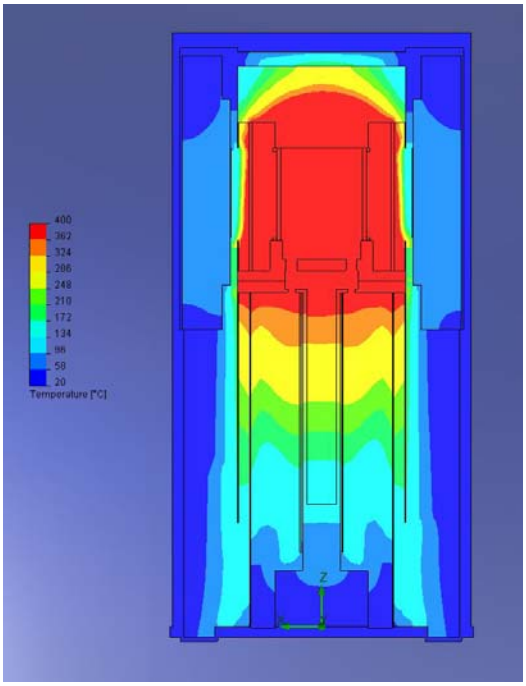

Figure 11: Temperature profile with range from 20 C (blue) to 400 C and above (red).

Referring to Table 1, the solid surface temperature for the recuperator ranged from 120 C to 412 C. The exhaust gas temperature is, of course, somewhat hotter and the inlet air temperature prior to combustion is somewhat cooler.

Turning next to the IR emitter, Figure 12 shows the temperature cross section profile through the emitter. In the case modeled here, the IR emitter consists of an array of ceramic 1 mm diameter rods with 0.1 mm slits between them. The plan is that these ceramic emitter rods in the TPV generator will be Ni or Co doped matched emitter rods that have wavelength dependent selective emissivity high in the cell converter band and low at wavelengths longer than 1.8 microns.

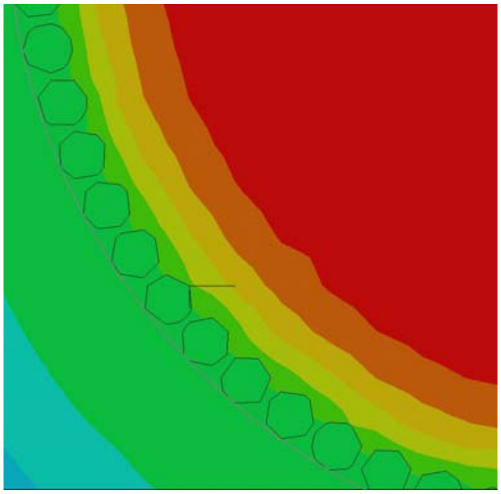

Figure 12: Temperature profile through post-array IR emitter. Red > 2200 C, Green = 1150 C, blue = 700 C.

However, the CFD software does not allow wavelength dependent emissivity. So, the emitter has been modeled as a gray body with an emissivity of 0.3. This 0.3 value was chosen to match the emitted power over the wavelength range from 0.5 microns to 6 microns for the gray body at 1200C to that projected for a matched emitter over the same wavelength interval at the same temperature. As will be discussed in the companion paper [10], the emitted power over this wavelength band at 1200C for the matched emitter should be 7.3 W/cm^2. Since the diameter of the cell array is 48 mm and the diameter of the emitter array is 26 mm, this will correspond to a cell incident power density of 4 W/cm^2. (As noted previously, this reduction in radiant energy flux can be compensated for by increasing the cell receiver area.)

Given the emitter gray body emissivity of 0.3, Figure 11 shows the resultant temperature profile from the CFD simulation. Assuming a combustion gas temperature of 2300C, resulting now from burning preheated air, the IR emitter temperature then reaches 1198C. On the outside of the emitter the gas temperature drops to 800 C.

The results of these portable cylindrical TPV generator CFD simulations are summarized in Table 1.

Table 1: TPV CFD Simulation Summary

Flow Simulation ID	**Jul23-2**	**Units**
Input power	**225 W emitter**	
emitter temp	**1035-1198**	**°C**
combustion air temp	**20-2300**	**°C**
combustion air pressure	**101325-101378**	**Pascal**
Combustion air mass flow	**1.0 x 10^{-4}**	**Kg/s**
combustion air velocity	**0-5.4**	**m/s**
cooling air temp	**20-55**	**°C**
cooling air pressure	**101325-101350**	**Pascal**
cooling air velocity	**0-7.5**	**m/s**
cells net radiant flux	**148 W**	
Estimated electric with 18% efficiency	**26.6 W**	
cells net radiant flux density	**1.1-5.5, 4.05avg**	**W/cm^2**
cells temperature with 6 fins per cell	**65-75, 71avg**	**°C**
cells temperature with 8 fins per cell	**55-65, 61avg**	**°C**
recuperator temperature	**120-412, 226avg**	**°C**
recuperator sleeve temperature	**166-395, 226avg**	**°C**
sapphire temperature	**446-581, 527avg**	**°C**
flame temp	**501-2339**	**°C**

5 SUMMARY AND CONCLUSIONS

TPV cell device efficiencies of 30% have been demonstrated at JXC with GaSb cells [4]. The argument for 60% spectral control efficiency for a matched IR emitter will be presented in a companion paper [10]. Given a 30% cell efficiency and a 60% spectral control efficiency, then 18% of the radiation arriving at the cell circuit should be converted into DC electricity. The CFD simulation results presented in Table 1 suggest that 148 W of radiant energy will arrive at the cell plane given a 225 W fuel burn rate. This means that 0.18 x 148 W = 26.6 W of DC electric power will be produced. Subtracting the combined electric power consumed by the combustion air and cooling air fans of 1.2+0.8=2 W gives a net produced electric power of 24.6 W for a net energy conversion efficiency of 24.6/225 = 10.9%. This is a very exciting result but at present, it is a model prediction. The next step is a funded effort to produce a physical prototype.

The estimated weight of the TPV cylinder described here is about 200 g. The size of the cylinder is 8 cm in diameter x 18 cm long. Its volume then is 900 cc or 900 ml. If a parallel fuel cylinder of equal size and volume is used, the fuel cylinder will contain about 900 ml of fuel and weigh about 540 g. The specific energy in a hydrocarbon fuel is 12,900 Wh/kg. So the energy in the 900 ml fuel cylinder above will be 6970 Wh. The weight of the TPV cylinder and the fuel cylinder combined will be 740 g. Given a TPV conversion efficiency of 10%, the converted energy available from the fuel will be 697 Wh. The specific energy for this TPV system will then be 697 Wh/0.74 kg = 942 Wh/kg. The TPV system described here is lighter than a Li-ion battery, has 6.5 times higher specific energy, operates 7 times longer, and is much more rapidly refueled.

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