DESIGN OF A MATCHED IR EMITTER FOR A PORTABLE PROPANE FIRED TPV POWER SYSTEM

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ABSTRACT: The design of an IR emitter is described for use with a small portable cylindrical ThermoPhotoVoltaic (TPV) generator. The IR emitter consists of a cylindrical array of 1 to 2 mm diameter ceramic rods. The spacing between these rods is chosen such that slits are formed between the rods with a slit width equal to about 1/10th of the rod diameter. Computational Fluid Dynamic (CFD) modeling shows that these slits promote very efficient heat transfer from the hot exhaust gases to the IR emitter. These rods are formed from Ni or Co doped Alumina, Sapphire, or Magnesia. These materials produce an emission spectrum that is selective and matched to the sensitive response band for the GaSb TPV cells. The IR emitter described both efficiently collects energy from the combustion gases and efficiently radiates it to the TPV cells. In one possible configuration, the side of the rods facing inward toward the combustion zone is coated with Pt to promote efficient combustion and energy transfer to the emitter.

Keywords: GaSb, Thermophotovoltaics, Batteries.

1 INTRODUCTION

The portable cylindrical TPV battery replacement shown conceptually in figure 1 is described in a companion paper at this conference [1]. This small 8 cm diameter unit is designed to consume fuel at a rate of approximately 200 W and to produce 20 W of DC power. In [1], it is noted that given a TPV conversion efficiency of 10%, the lightweight TPV cylinder shown in figure 1 along with a fuel cylinder can have a much higher specific energy of approximately 1000 Wh/kg, i.e. 6.5 times higher than the specific energy for a Li-ion battery with a similar power rating.

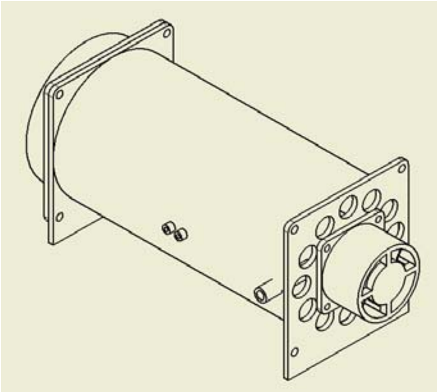

Figure 1: Perspective view of small portable TPV generator.

The TPV cylinder shown in Figure 1 has combustion and cooling air fans at each end. Fuel enters the cylinder and DC electric power is produced and exits the cylinder. There are two subassemblies inside the cylinder: the TPV converter section and the recuperator section. The companion paper [1] describes the overall design and operation of this unit including the details of the recuperator section. The TPV converter section consists of a photovoltaic converter section surrounding an infrared emitter. This paper is focused on the infrared emitter subassembly.

Figure 2 shows a cross section through the TPV cylinder shown in figure 1. As shown in figure 2, the emitter subassembly sits on top of the recuperator subassembly and it is surrounded by the air cooled TPV array.

The design of the IR emitter in a TPV system is critical to the efficient operation of a TPV generator. Both its physical dimensions and its chemical composition are important. Its physical geometry and chemical composition are important for the efficient coupling of energy to it from the combustion process and its chemical composition is important for tailoring the spectrum of the radiation emitted by it.

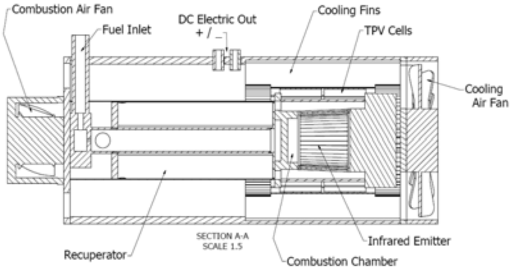

Figure 2: Labeled section view of TPV generator.

2 IR EMITTER REQUIREMENTS

There are three requirements for a good IR emitter design in the context of a fuel fired TPV generator. These requirements are as follows:

1.) It needs to have the appropriate chemical composition such that it emits infrared radiation with wavelengths matched to the response band of the TPV cells.
2.) Its geometry must be such that it efficiently extracts energy from the combustion gases passing through and around it.

3.) It needs to be easily fabricated.

3 SPECIFIC IR EMITTER DESIGN

3.1 Physical Geometry

Figure 3 shows the side view of the infrared emitter design specifically for the cylindrical TPV generator shown in figures 1 and 2. Figures 4 and 5 show horizontal and vertical cross sections through this burner and IR emitter subassembly.

As shown in figures 4 and 5, the burner and IR emitter subassembly consists of a lower insulating plate with fuel and air injection holes and exhaust gas exit holes. There is an array of emitter posts on top of this insulating plate with a combustion chamber inside this array. These emitter posts are cylindrical with a diameter of approximately 1 to 2 mm. The hot exhaust gases exit through small slits between these IR emitter posts. The slit widths are approximately 0.1 to 0.2 mm. There is an insulating lid on top of this post array. A sapphire transparent window also surrounds this IR emitter post array. Because entry and exit holes for both the fuel and air and the exhaust are in the bottom plate, there is a tendency for the lower end of the emitter array to run hotter than the upper end of the emitter array unless the post array is tilted as shown. This tilt increases the slit widths between the emitter posts toward the top end enhancing the heat transfer rate at the top to promote more emitter temperature uniformity from top to bottom.

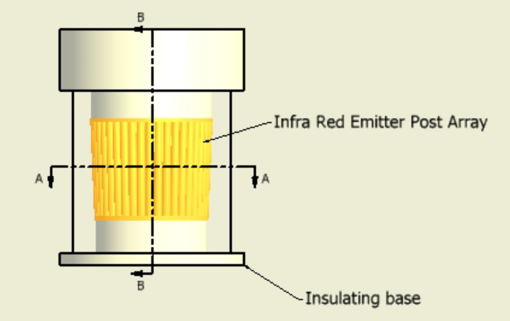

Figure 3: Side view of the Infrared emitter assembly showing the cylindrical array of tilted IR emitter posts and locations of section cuts for figures 4 and 5. The IR emitter rods are shown here as yellow hot.

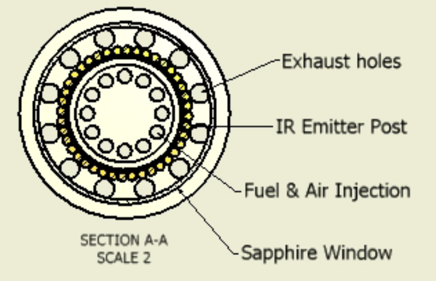

Figure 4: Section A-A through emitter assembly.

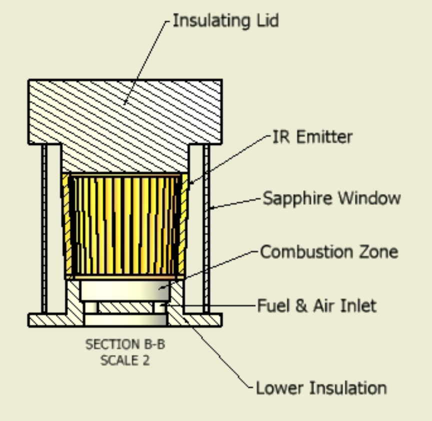

Figure 5: Section B-B through emitter assembly.

3.2 Chemical Composition

The chemical composition of the IR emitter rods is important for spectral control. The emitter rods needs to have the appropriate chemical composition such that they emit infrared radiation with wavelengths matched to the response band of the TPV cells.

The appropriate TPV cells are either GaSb or InGaAs/InP or Ge cells that convert radiation with wavelengths less than approximately 1.8 microns into electricity. The infrared emitter ideally should only emit radiation with wavelengths less than 1.8 microns. If infrared wavelengths longer than this wavelength are emitted, this radiation will only produce unwanted heat in the TPV cells. It has been shown that Ni or Co ions in an oxide matrix emit radiation in the 1 to 1.8 micron wavelength range [2, 3]. Appropriate IR emitter post for this invention consists of these ions incorporated as impurities in oxide ceramics such as alumina (Al_2O_3, including sapphire), magnesia (MgO), or Spinel ($MgAl_2O_4$),

4 MEETING THE DESIGN REQUIREMENTS

4.1 Spectral Control

In the companion cylindrical TPV generator paper [1], it was noted that a target spectral efficiency for the IR emitter of 60% would allow a overall TPV efficiency of 10% to be achieved.

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Ferguson and Dogan [3] have fabricated NiO doped magnesia ribbons for use in TPV generators and measured their spectral emissivity as shown in figure 6.

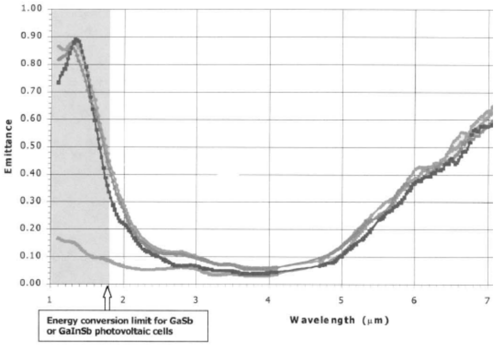

Figure 6: Spectral emittance measurements for a 2 wt.% NiO-doped MgO tape cast ribbon at 1268, 1341, and 1404°C. The emissivity of the 2 wt.% NiO-doped MgO emitter appears nearly constant within this temperature range. The emittance of an 'undoped' MgO ribbon is also included for comparison. The emissivity of the NiO-doped MgO is much greater than it is for the 'undoped' MgO at wavelengths less than about 1.9 μm where radiant energy is efficiently converted by photovoltaic cells, however, NiO doping has little or no effect on the emittance at longer wavelengths.This spectral selectivity' is explained in terms of ligand field theory and interactions between dopant ions and coordinating host atoms [3].

From the emittance data presented in figure 6, the spectral efficiency can be calculated as shown in Table 1. The radiance numbers presented in this table assume an emitter temperature of 1500 K surrounded by a sapphire window shield at 1000 K. These temperatures are consistent with the values assumed in the overall cylindrical TPV generator model presented in [1]. The resultant spectral efficiency is found to be 61% consistent with the target value.

Table 1: NiO doped ceramic emitter Spectral Efficiency

Wavelength	Emissivity	Radiance W/cm2	Comment
0.5 to 1.8 μ	0.9	5.3	1500 K
1.8 to 6 μ	0.1	2	1500 K
6 to 20 μ	1	1.4	Shield at 1000 K
Spectral Efficiency = 5.3/8.7 = 61%			

4.2 Combustion Energy Transfer

The result presented in table 1 shows that once the emitter reaches the target temperature, its spectral efficiency will be approximately 60%. However, the emitter geometry must be such that it efficiently extracts energy from the combustion gases passing through and around it so that it reaches the target temperature.

The porosity of the post array emitter geometry is important. We have now performed computational fluid dynamics (CFD) calculations using flow-analysis software from Solid Works [4] on the emitter geometry shown in figures 3, 4, and 5. These calculations are summarized in table 2 and figure 7. These calculations show that the rod diameter and rod spacing are important for heat transfer. Furthermore, they show that catalytic reactions are not required for efficient heat transfer. This data shows that the gas temperature drops from 2400 C to 1180 C as it passes through the emitter post array leaving the emitter solid temperature at approximately 1180 C suggesting that over 50% of the energy in the gas is extracted as radiation.

Table 2: CFD calculation results for emitter post arrays.

	1mm rods	2mm rods	
Temp Solid	1195 avg	1177 avg	°C
Net Radiation	214	219	W
Area	55.76	59.56	cm^2
Pressure	101328-101338	101327-101337	Pa
Radiation Flux	3.95 avg	3.72 avg	W/cm^2
Mass Flow	1.40E-04	1.40E-04	kg/s
Flow Source Temp	2400	2400	°C
Rod spacing	0.1 mm	0.2 mm	
Emitter OD/ID	26/24	28/24	mm
Emitter height	23mm	23mm	

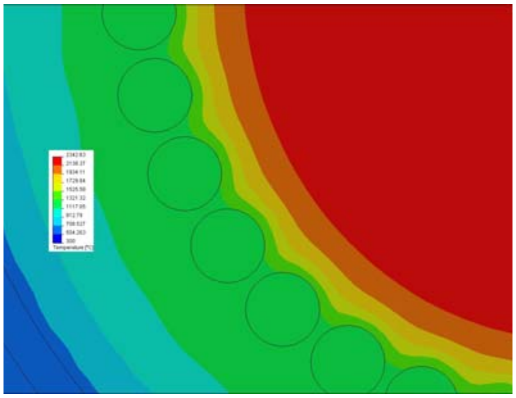

Figure 7: Temperature profile through the 2 mm diameter post array emitter. The color changes occur at 2138, 1934, 1729, 1525, 1321, 1117, 912, and 708 C. Red represents 2138 C temperatures and higher.

4.3 Ease of Fabrication

The emitter should be easy to fabricate. Sapphire or alumina ceramic rods are commercially available in the 1 to 2 mm diameter range. These rods can be cut to length and the appropriate number can be placed in grooves with the appropriate diameter in the top and bottom insulator discs. A spacing can be set between the rods by interweaving a wire of the appropriate diameter between the rods in the array with one wire weave at the top of the array and a second wire weave at the bottom of the array. . For example, if a 0.1 mm spacing is required, a 0.1 mm wire can be used.

Eventually, it may be most desirable to have the rods doped with the appropriate impurity ions when the rods are fabricated. However, it is also possible to coat the ceramic rods as received with, for example, a Nickel film and then to fire the rods to create a doped surface emitter layer of, for example, $NiAl_2O_4$.

A potential fabrication sequence is shown conceptually in figure 8. In the sequence shown in this figure, the rods are first tied together in a flat form with a wire weave and then the flat form is coated on one side with Ni and on the other side with Pt. The flat form is then shaped into a cylinder. The Ni film can be fired to form the doped ceramic oxide layer either after the coating in the flat form or in operation in the TPV configuration. The Pt film on the inside of the emitter cylinder can potentially serve as a catalyst to promote more efficient combustion.

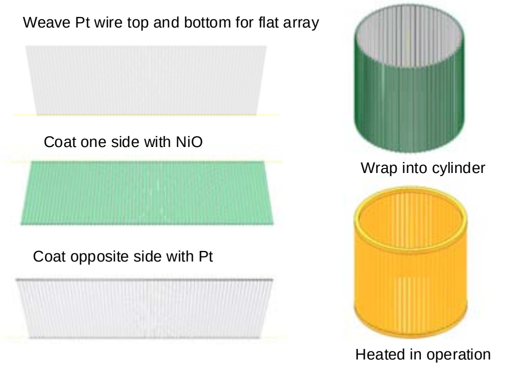

Figure 8: A potential emitter array fabrication sequence.

While the emitter fabrication concept described in figure 8 has not yet been demonstrated, sapphire samples have been coated with Ni and heat treated to form a Ni doped surface layer. Samples were then coated with silver and a reflection measurement was then made at room temperature with the results shown in figure 9. There are absorption bands at wavelengths starting at 1.5 microns and less. It is anticipated that these bands will broaden and shift to longer wavelengths at higher temperatures.

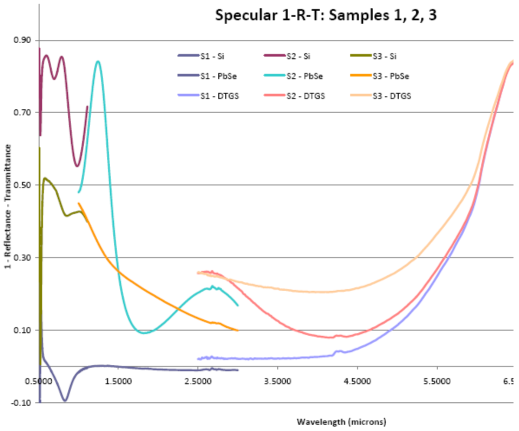

Figure 9: 1-R-T spectra derived from reflection measurements on three samples. S1 is a control sample with silver on sapphire. S2 and S3 have sintered Ni doped layers on sapphire coated with silver. The Ni doped layer in S2 is twice as thick as the sintered layer in S3.

5 SUMMARY AND CONCLUSIONS

A very promising application for TPV is for quiet lightweight compact portable fuel fired DC electric generators that can replace batteries in some applications. Given an overall fuel to electricity conversion efficiency of 10%, the small cylindrical TPV generator described here and in [1] can potentially operate with 6.5 times higher specific energy, 7 times longer, and be much more rapidly refueled. However, several elements will be required in order to achieve this 10% system level efficiency goal. These elements include:

1. 30% efficient TPV cells,
2. Recuperation to achieve 70% chemical to radiation conversion efficiency,
3. 60% emitter spectral efficiency, and
4. A TPV system integrated design with good thermal management.

TPV cells are now reasonably developed. A compact cylindrical TPV system integrated design has been briefly described here and more completely described in [1]. A novel recuperator design has also been described in [1] with CFD calculations indicating that a 70% chemical to radiation efficiency is achievable. The specific emitter design presented here is compatible with the proposed 10% efficient cylindrical TPV battery replacement. CFD calculations indicate that it can efficiently capture energy from the combustion gases and spectral measurements presented in [3] show that a 60% spectral efficiency is achievable.

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