Adapting TPV for Use in a Standard Home Heating Furnace

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Abstract. A novel TPV configuration will be presented that can fit into a standard home furnace cabinet. This system incorporates an externally faceted glass cylinder with a dichroic filter deposited on its outer surface and a GaSb IR cell array bonded to the outer surface on top of the filter. This cylindrical array is then surrounded with an envelope containing a low boiling point liquid for evaporative cooling. The liquid is in direct contact with the backside of the cell array. An air-cooled condenser is then mounted above the photovoltaic converter array. Evaporative cooling potentially allows a heat removal rate of 20 W/cm^2. Additional novel features of this design are described. The goal is to design a cost-effective retrofit forced-air warm air furnace that can work either as a self-powered furnace or as a Combined Heat and Power appliance. In order to achieve low cost, the design point for the GaSb cell electric power density is 2.5 W/cm^2.

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FURNACE COMPANY PERSPECTIVE

In a companion paper [1], two hydrocarbon-fired TPV generator configurations using GaSb IR sensitive PV cells were described. The Midnight Sun TPV stove is a simple combined heat and power unit providing heat and electricity for small off-grid homes. As summarized in table 1 (Case 1), its primary advantage is simplicity and its primary disadvantage is low electrical conversion efficiency.

A second cylindrical TPV generator has been designed for the US Army as a quiet battery charger. As also summarized in table 1 (Case 2), the primary advantage of this unit is high electrical conversion efficiency but its primary disadvantage is complexity. This unit uses exhaust gas recuperation but its complexity and efficiency both come from its efficient spectral control. It incorporates an anti-reflection coated tungsten foil emitter for improved TPV spectral efficiency but this then requires the complexity of a vacuum emitter thermos.

These efficient cylindrical TPV generators are designed around a family of commercially available SiC radiant tube burners. We have previously noted [2] that one of these efficient cylindrical TPV generators could be adapted as a Combined Heat and Power (CHP) furnace-generator for use in a home. Its size would be a 40,000 BTU/h (12 kW) furnace with a 1.2 kW TPV electric generator.

However, after discussions with furnace companies, it is now clear that they have a different perspective. The US heating market demands furnaces with higher heating capacity, e.g. 85,000 BTU/h or 28 kW. They argue that this higher heating capacity is required to heat a home on the coldest day and that customers want to heat a cold home rapidly when returning home. Further, the bulk of US furnace sales are for replacement of old furnaces that are naturally found in older, less well insulated homes. There also appear to be competitive reasons for favoring higher “numerical” furnace ratings.

The US furnace market also favors relatively low power generation for two interesting reasons. First, there is a significant demand for self-powered furnaces that will operate during power outages, particularly those due to ice-storms. These self-powered furnaces require only 600W of generator output and within this segment there is essentially no demand for excess generation. Second, the demand for CHP furnaces – that is furnaces that generate more electricity than they use and return the excess to the grid – favors a furnace generator configuration that can be attached to existing house wiring as this simplifies and minimizes the cost of retrofit installations. Existing US electrical codes require a dedicated 15A, 120V circuit for furnaces and a retrofit furnace connected to such a circuit can deliver no more than 1.4 kW to the grid. Rewiring existing homes would be necessary to accept retrofit CHP furnaces with greater generating capacity, and this would make the sale of such furnaces difficult and the rewiring costs would adversely impact the economics.

There are other requirements as well. Ideally, the TPV generator should fit entirely within existing furnace dimensions, function properly under on-off operation in forced-air furnaces, operate quietly, and of course be low cost.

Our initial TPV generator design for the US furnace market has 1.2 kW electric output with 28 kW fuel input, and 4.3% conversion efficiency. To achieve the desired size, cost and operating characteristics, it operates at very high power density, reducing overall size and the quantity of IR cells.

Table 1: Features of prior art hydrocarbon TPV generators.

Case 1: Midnight Sun TPV Stove	**Case 2: Efficient Cylindrical TPV Generator**
<u>Advantage</u> • Simplicity	<u>Advantage</u> • High electrical conversion efficiency
<u>Key Features</u> • Flow through SiC emitter operating at 1250 C • Planar geometry with poor radiation feedback • No exhaust gas heat recuperation • Forced air cooling	<u>Key Features</u> • SiC radiant tube burner operating at 1250 C • Good spectral control with AR tungsten IR emitter • Vacuum thermos for low convection heat transfer • Integral exhaust gas heat recuperation • Water cooling
<u>Disadvantage</u> • 2% electrical conversion efficiency	<u>Disadvantage</u> • Complexity

NOVEL TPV GENERATOR UTILIZING BOILING COOLANT

Figure 1 is a view of the Simplified Cylindrical TPV Generator in cross-section taken along the axis of the generator and Figure 2 is a cross-section view of the generator taken perpendicular to the axis of the generator body. This unit does not have exhaust gas recuperation or a tungsten emitter with its associated vacuum thermos. It uses a SiC emitter and a mid wavelength IR filter. As shown in figure 2, the SiC emitter is a flow through cylinder. A glass cylinder surrounds the IR emitter cylinder with the IR filter deposited on its outer surface and the IR cells bonded on outer surface, on top of the filter. The IR cell array is then immersed in a boiling organic liquid for cooling. The coolant vapor circulates through a air cooled condenser as shown in Figure 1 where it condenses to a liquid that returns to the generator by gravity flow. Table 2 is a summary of the key features for this novel device.

Table 2: Simplified Cylindrical TPV Generator using boiling coolant

Key Features

- SiC flow through IR emitter
- Cylindrical geometry for better radiation feedback
- Higher emitter operating temperature of 1425 C
- Boiling coolant for enhanced cell cooling rate
- Higher cell electric power output

Advantage

- Lower cost TPV electric power
- Small size suitable for mounting internal to the furnace
- Fast on-off response time

Disadvantage

- Development of PV array using boiling coolant required

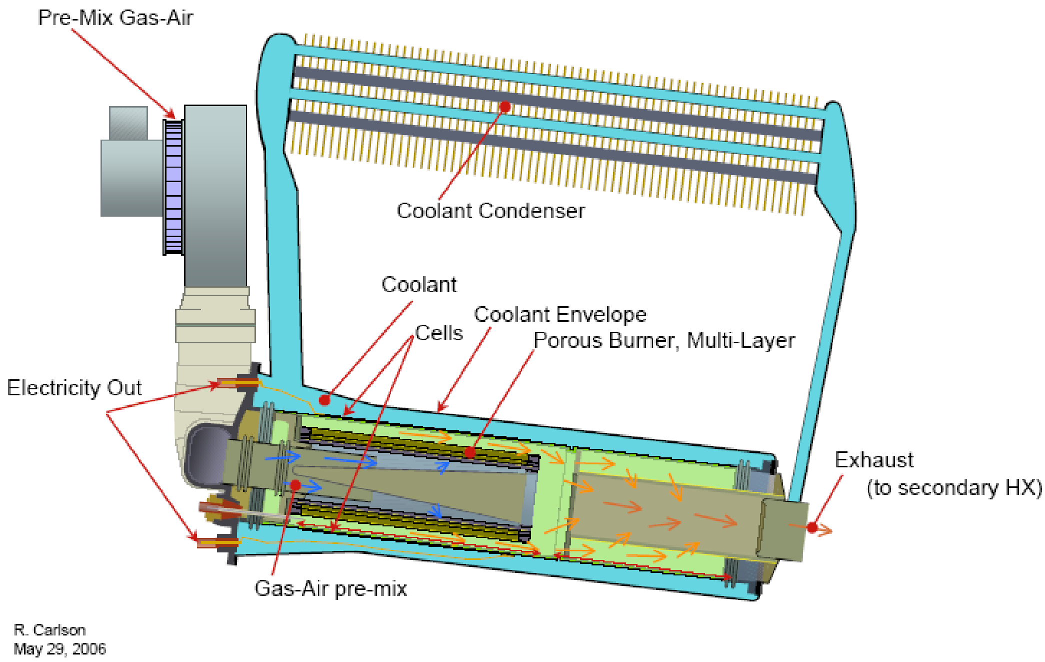

FIGURE 1. Cross section of Simplified Cylindrical TPV Generator showing flow through SiC emitter surrounded by an IR cell array immersed in a boiling coolant. The coolant condenses in an air heat exchanger and is returned to the TPV generator by gravity.

This generator has not yet been built. However, it can be considered in some ways as evolutionary from our Midnight Sun TPV stove. Neither this novel configuration nor the stove use exhaust gas recuperation and both use SiC black body IR emitters and mid wavelength filters for spectral control. However, the Midnight Sun stove used a SiC flow through emitter in a planar configuration heated to approximately 1250 C by a premixed fuel and air mixture whereas our new generator uses these elements in a cylindrical configuration. Since the view factor from the cells back to the emitter was poor in the planar geometry, radiation losses were high. By going to a cylindrical configuration, the feedback from the filter in the new configuration of figure 2 will be much higher allowing a higher emitter temperature of 1425 C to be achieved.

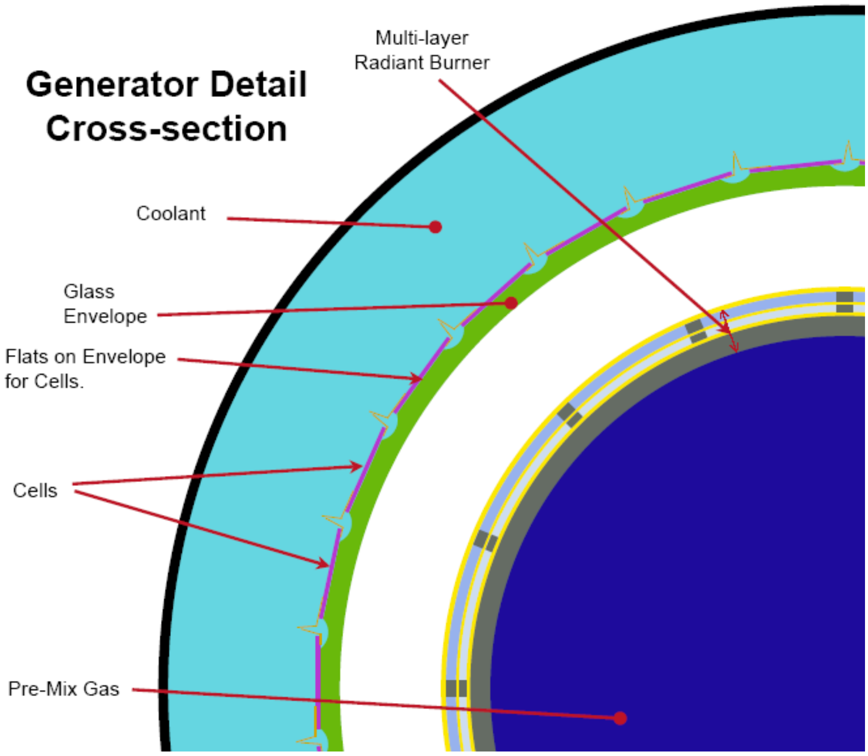

FIGURE 2. The IR cell array is bonded onto a glass cylinder and cooled from its backside. There is an IR filter coating on the outer surface of the glass cylinder that reflects mid-wavelength radiation back to the SiC fibrous emitter.

Operating without exhaust gas recuperation and without the tungsten emitter is expected to reduce conversion efficiency. However, increasing the emitter temperature will shift the emitted IR radiation energy peak toward the visible increasing the system electrical conversion efficiency for the new generator relative to the stove's poor efficiency. This improvement can be calculated as is summarized in table 3.

Referring to Table 3, note that increasing the emitter temperature to 1425 C has now increased the heat load on the cells to 17.6 W / cm2. This is where the novelty of this new design appears. Boiling a liquid involves a phase change and this then can remove large amounts of excess heat. Possible coolants include NOVEC® 7100 segregated hydrofluroether manufactured by 3M Corporation or R-134a refrigerant or similar compound capable of operating as a coolant and compatible with the materials and having high electrical resistance. Cell cooling rates of 22W/cm^2 are possible per 3M data on NOVEC 7100.

Again referring to table 3, the most important numbers are highlighted in bold print. The cell electrical power density has now risen to 2.4 W/cm2 for a lower cost TPV array. The electrical conversion efficiency is now at 4.3%, providing 1.2 kW of electrical output which is appropriate, as explained earlier, for a retrofit combined heat and power furnace for the US market. A lower cost TPV generator to meet the self-powered furnace requirement is obtained by simply reducing the number of PV cells and thus the electrical output.

Table 3: Performance comparison for 3 alternative hydrocarbon TPV generator designs.

	Case 1: TPV Stove "Midnight Sun™"		**Case 2 : Cylindrical TPV Battery Charger**		**Case 3: Simpler TPV CHP Furnace**	
Fuel burn rate	**7.5 kW**		**5.2 kW**		**28 kW**	
Emitter Temperature	**1227 C (1500 K)**		**1227 C (1500 K)**		**1427 C (1700 K)**	
Electric Power	**150 W**		**700 W**		**1.2 kW**	
	W / cm2	%	W / cm2	%	W / cm2	%
Black Body Radiation per emitter area	28.7		28.7		47.3	
Cell in-band IR flux per emitter area	4.9	17	4.9	17	11.8	25
Filter flux per IR emitter area	13.5	47	13.5	47	22.2	47
Long wavelength flux	10.3	36	10.3	36	13.2	28
View Factor (VF)		50		80		80
W_{elec} per cell area	**0.6 W/cm2**		**1.0 W/cm2**		**2.4 W/cm2**	
Heat Load per cell area	**7**		**4.8**		**17.6**	
Cell Cooling	**Forced Air**		**Water Cooling**		**Boiling Coolant**	
W_{elec} / Heat Load (E / H)		8.6		21		13.4
Fuel to Radiation (F / R)		48		80		40
System Elec Efficiency = VF x (E / H) x (F / R)		**2 %**		**13.4 %**		**4.3 %**

CONCLUSIONS

A simple TPV CHP furnace / generator design has been presented. It is compatible with the specifications for a typical 85,000 BTU/h home-heating furnace. The TPV section should be capable of generating 1.2 kW of electricity with only 450 cm2 of active cell area for a low cost TPV electricity generating section. Challenges will be the demonstration of the cylindrical flow through SiC emitter and the PV array with boiling coolant.

CHALLENGE

While it is unlikely that a furnace company will commit the R&D funds to explore boiling liquid cooling for TPV furnaces, a small scale compact and powerful TPV demonstrator could be built using a simple Bunsen burner as shown in figure 3. The demonstrator shown could be an interesting tool in a University Ph.D. thesis project.

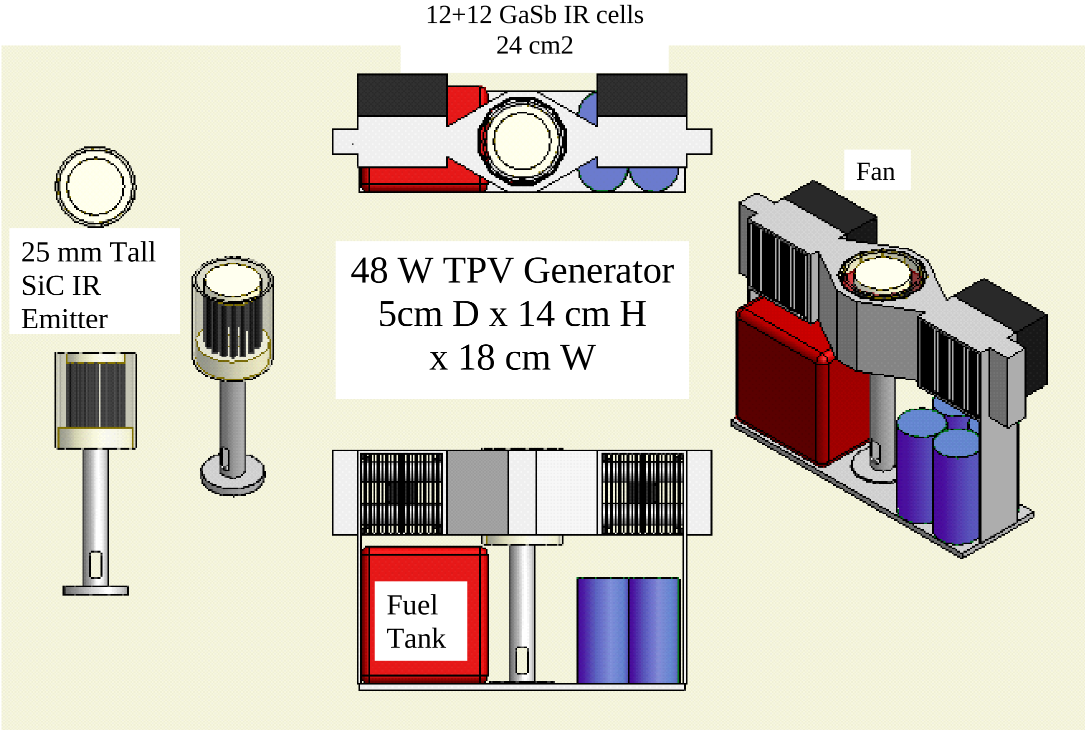

FIGURE 3: Compact and powerful TPV demonstrator using boiling liquid cooling built around a Bunsen burnr.

A simple Bunsen burner can operate at a combustion rate of up to 3 kW, more than enough power than required as our calculation below will indicate. From the data in the right column in table 3, imagine fabricating a GaSb IR circuit using top and bottom symmetric rows of 12 cells each with 24 cells total. Imagine 1 cm2 cells operating at 2 W per cm2. The demonstrator shown in figure 3 would then produce 48 W of electricity (approximately 7 V and 7 Amps). The heat load per cell might then be 15 W/cm2. With a boiling coolant this heat could be transferred to 2 compact fan-cooled heat exchanger with 20 times more surface area as shown. Given the 4.3% electrical conversion efficiency calculated in table 3, a fuel burn rate of 1120 W would be required. As figure 3 shows, this would be an amazingly compact and powerful little TPV generator.

REFERENCES

1. Lewis M. Fraas and Leonid Minkin, these proceedings.
2. L. M. Fraas et al, “Thermophotovoltaic Furnace-Generator for the Home Using Low Bandgap GaSb Cells”, Semiconductor Science & Technology. **18**, p. S247 (2003).