ABSTRACT

Three new developments have now occurred making economical TPV systems possible. The first development is the diffused junction GaSb cell that responds out to 1.8 microns producing over 1 W/cm² electric given an IR emitter temperature of 1200 °C. This high power density along with a simple diffused junction cell makes an array cost of $0.5 per Watt possible. The second development is new IR emitters and filters that put 75% of the radiant energy in the cell convertible band. The third development is a set of commercially available ceramic radiant tube burners that operate at up to 1250 °C. Herein, we describe a 1.5 kW TPV generator / furnace incorporating these new features. This TPV generator / furnace is designed to replace the residential furnace for combined heat and power (CHP) for the home.

KEY COMPONENTS

After inventing the required IR sensitive cells, JX Crystals began to develop complete TPV systems. This effort then required us to invent and integrate several key components into a practical generator that can be manufactured economically.

While the TPV idea was first proposed in 1960, three new developments have taken place in the last 10 years that now make economical TPV systems possible. The first new development is the diffused junction GaSb cell [1,2,3,4], that responds out to 1.8 microns producing over 1 W/cm² electric given an IR emitter temperature of 1500 K (1225 °C). Two TPV circuits incorporating these new cells are shown in figure 1a along with a power curve in figure 1b showing 2 Watts per cell. The power density is approximately 100 times more than the traditional planar solar cell making cost of $0.5 per Watt possible.

INTRODUCTION

Solar cells can produce electric power from sunlight without burning a fuel. If very low cost solar cells can be made, a homeowner can generate his own electricity at rates below the electric utility rate. However, while this can be true during summer months, there is a problem in winter months when the sun doesn’t shine. Low Bandgap photovoltaic or “Solar” cells can solve this problem. A homeowner can put solar cells on his roof for electric power in the summer months and “solar” cells in his furnace for electric power during the winter months. The idea of “solar” cells in a heating furnace is called ThermoPhotoVoltaics or ThermoPV or TPV. The idea is that a ceramic element is placed in the flame in the furnace and this element then glows like the coals in a fireplace. “Solar” cells near by then convert the glow into electricity. Using TPV, the homeowner generates electricity whenever he needs heat. Therefore, it is not necessary to burn additional fuel.

While this TPV concept is simple, the problem has been that the two types of solar cells (or more accurately photovoltaic cells) are not the same. While the solar cells on the roof convert visible light into electricity, the TPV cells in the furnace need to convert infrared radiation into electricity. JX Crystals has invented and developed the required GaSb TPV cells.
Figure 2 shows a projection for the GaSb cell cost from ABB given input from JX Crystals and the Ioffe Physico-Tech Institute. The cost is a function of volume. Note that the GaSb cell fabrication process closely parallels the conventional Si cell process where both cells are made with simple diffusions without toxic gases. Therefore, the GaSb cell cost curve is expected to parallel the Si cell cost curve. However, when expressed in $ per Watt, the GaSb cell is almost 100 times less expensive than the Si cell at a given production volume because of its higher operating power density.

The second new development is new IR emitters and filters that put 75% of the radiant energy in the cell convertible band. These spectral control elements [5,6,7] along with the TPV cells and circuits have been described in more detail previously [1-7].

The third new development is the commercial availability of low NOx SiC radiant-tube burners that operate at up to 1250 C. Figure 3a shows a schematic of a radiant-tube burner from WS Inc and figure 3b shows a photograph of several of these burner tubes in operation in an industrial furnace. According to the WS Inc literature, "In over a decade of practical experience with ceramic radiant tubes, material failure due to thermal wear has not yet occurred."

In the next section, we will describe a TPV generator / furnace built around these three key components. This unit is designed for combined heat and power for the home.

### 1.5 KW TPV GENERATOR / FURNACE DESIGN AND PERFORMANCE

We have previously described the design, fabrication, and testing of a 500 W cylindrical TPV generator [7] in which a TPV array surrounds a custom radiant tube burner. All of the parts for this 500 W TPV generator were built at JX Crystals. We have now adapted this earlier design to use a small WS Inc radiant tube burner. ABB Ricerca in Italy funded this detailed design of a larger 1.5 kW TPV generator / furnace. Figure 4 shows an overview of this design. This unit is designed around the WS Inc C100 / 950 radiant tube burner which means that the SiC radiant tube is 100 mm in diameter and 950 mm long.

Figure 3: (a) Schematic of a low NOx radiant tube burner as manufactured by WS Inc. (b) Photograph of several of these burners in operation in an industrial furnace.

Figure 4. Design of TPV 1.5 kW electric generator / 12.2 kW thermal furnace for home combined heat and power.
Referring to figure 4, note that there are three SiC ceramic parts. They are the large SiC radiant tube, the inner SiC recuperator, and an inner SiC tube. These parts are in the standard WS radiant tube design. However, we are incorporating five important modifications.

The first is a ceramic insulator stand-off at the bottom inside the outer SiC tube supporting the inner SiC tube. This stand-off both supports the inner SiC but also inside the outer SiC tube supporting the inner SiC tube. This is unlike the standard WS design where the end glows (see figure 3b).

The second important recommended change relates to the inner SiC tube. In the standard WS design, all three SiC tubes are made using Si bonded SiC. This material has an upper temperature limit of 1350°C. Here, we recommend using a higher quality SiC for the inner tube with a higher temperature capability.

The third important change is the addition of the fold-back section in the outer SiC tube. This allows the addition of the secondary stainless steel recuperator coaxial with the first higher temperature SiC recuperator.

The fourth important feature in our design is the use of the AR coated refractory metal foil IR emitter wrapped around the outer SiC tube as a means of controlling the IR spectra for maximum conversion efficiency. There are also refractory metal foil heat shield wrappings.

The fifth and final important feature in our design is the use of o-ring seals at the top and bottom PCA flanges. These seals are required so that the space between the PCA and the radiant tube can be evacuated and back filled with a noble gas such as krypton. This is done for two reasons. First, it is necessary to protect the emitter foil against oxidation and second, krypton is used to reduce heat transfer losses to the PV array via thermal conduction through the gas. This noble gas fill feature appears daunting but is really no different than the conventional incandescent tungsten filament light bulb.

We have projected the performance of this TPV generator design based on data from WS Inc and our own experience with burners and based on modeling of the emitter and PV array performance using TracePro. TracePro is a Monte Carlo based software package by Lambda Research that has been used for TPV modeling by Richard Thomas at Bechtel Bettis [8]. Table 1 summarizes the resultant predicted system performance.

Modeled with:
- Emitter Temp = 1260°C
- Cell Temp = 50°C
- 16 circuit array with 63 cell (21x3) circuits

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pmax</td>
<td>1.5 kW</td>
</tr>
<tr>
<td>Ptotal-Precycle</td>
<td>9729 W</td>
</tr>
<tr>
<td>Pwater</td>
<td>8229 W</td>
</tr>
<tr>
<td>Pmax/(Ptotal-Precycle)</td>
<td>15.40%</td>
</tr>
<tr>
<td>Burner/Recup Efficiency</td>
<td>80%</td>
</tr>
<tr>
<td>System Electric Efficiency</td>
<td>12.30%</td>
</tr>
<tr>
<td>Fuel Burn Rate</td>
<td>12.2 kW</td>
</tr>
</tbody>
</table>

Table 1: Predicted TPV generator/furnace performance.

ECONOMICS

From the point of view of the homeowner and the country, our strategy is to conserve fuel and save money by combining an energy efficient TPV furnace (winter) with a renewable energy source, solar cells (summer). While the TPV furnace does burn fuel, it utilizes the fuel energy with over 90% efficiency (referred to the fuel lower heating value, 100% efficiency is possible). Our distributed combined heat and power residential system saves on the need for additional central power plants and additional transmission lines. While fuel energy utilization efficiency in a central power plant might be 40%, the other 60% will be thrown away as waste heat. Co-generating electricity and heat in the home with TPV avoids burning fuel in the central power plant.

Figure 5 shows a comparison created by a utility showing the advantage in fuel saving for a TPV cogeneration system versus separate boiler heating and central utility electric power to the home. For our TPV generator/furnace in which eighty-eight percent of the fuel energy is used for home heating and 12% is used for electric power production, the separate supply of heat and electricity consumes 140 units of fuel versus the 100 units of fuel required by TPV CHP.

TPV cells and solar cells are natural allies. They both produce electricity without the need for additional fuel. The bar graph shown in figure 6 is for the electricity use in a typical residence in NY. It illustrates how TPV and solar can work together to produce home electric power. This bar graph is typical for Mid Atlantic & New England states as well as states around the Great Lakes, Alaska and Canada.

The economics for photovoltaics is now very exciting as the following calculation shows. Given investment for manufacturing and marketing, we expect our Residential TPV Furnaces (figure 3) to be selling for $1500 on top of the standard heating equipment cost. At what price will a Residential TPV Furnace begin to be cost effective? Referring to the bar graph in figure 5, the annual savings in a home-owner’s electric bill will be $376 per year at 10 cents per kWh. At this savings rate, the payback time will be 4 years (4x$376=$1505).
A very interesting advantage for our TPV generator / furnace is that it is both a generator and a furnace. Therefore, for a new home purchase, one gets a credit for the furnace. In other words, a new home owner can chose to buy a furnace for $2700 for example or a TPV generator / furnace for $2700+$1500 = $4200.

We can now close the loop for our economics discussion by noting that ABB has estimated the cost of the TPV unit in Figure 4 to be $3200 which, given a target price for a home owner of $4200, gives a margin of $1000 for installation and profit.

CONCLUSIONS

From the point of view of technical design and market potential for this technology, the conclusions in this paper are very positive. We present a design capable of producing 1.5 kW electric with an array efficiency of 15.4%, a burner / recuperator efficiency of 80%, an overall electrical efficiency of 12.3% and a combined heat and power efficiency of over 90%. The cost analysis of this design suggests a total cost of approximately $3200. JX Crystals’ analysis for the US market suggests an installed cost to a homeowner of $4200, gives a margin of $1000 for installation and profit.

REFERENCES


[2] See US Patents # 5,217,539, # 5,389,158, # 6,057,507, # 6,232,545 B1, and PCTs assigned to JX Crystals Inc.


