Purdue University
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International Refrigeration and Air Conditioning Conference

School of Mechanical Engineering

2012

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SOLID STATE MICROCHP BASED ON THERMOPHOTOVOLTAIC AND THERMOELECTRIC CONVERSION

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ABSTRACT

MicroCHP involves the coproduction of both heat and electric power in (typically) residential heating systems. A range of different energy conversion technologies are currently receiving attention for this application including Stirling engines, internal combustion engines, fuel cells, and Rankine cycles with steam or organic compounds as working fluids. In this work the use of ThermoPhotoVoltaic (TPV) and ThermoElectric (TE) conversion devices either alone or in combination for power production in an oil-fired heating system have been explored. The focus of this work to date has been on sufficient electric power output to achieve self-powering of the appliance with the consideration that reliability of the heating system during power outages may provide the greatest value to the consumer. Also explored is the potential for producing larger power output levels, to 1 kW.

Low cost, currently available TE devices, based on bismuth telluride, have very low thermal to electric power conversion efficiencies. The use of these in self-powered heating appliances for other applications is established art. Further for simply self-powering, a low conversion efficiency is all that is required to produce the 100 watts needed to power the system. Advanced TE materials under development offer strong potential for increased efficiency in the future. TPV, while currently at an earlier state of development offers the potential for higher conversion efficiencies.

This work will report the production of power with both TE and TPV integrated with a residential boiler. A hydronic system was selected relative to a forced air system because of the lower electric power requirements. Using a novel pressure atomized oil burner in combination with very low power circulating pumps, the total running power demand has been reduced to 72 watts. In consideration of cycling, it is estimated that a minimum steady state power output level of 120 watts is required. Experimental results on power production with both TE and TPV in this system are presented. The potential for integration of both TE and TPV devices in a hybrid system are discussed.

1. INTRODUCTION

MicroCHP (micro- Combined Heat and Power) refers to the coproduction of heat and electric power in systems on the scale typically used for the heating of single family residential buildings and small commercial buildings. The basic motivation for this technology is the thermodynamic efficiency gains and the potential for reduction in primary energy use. Currently there is strong interest in the commercial development of microCHP systems and a wide range of technologies for the electical power production are considered to be viable (Kuhn et al., 2007; Berndt, 2008). This includes, for example: Stirling engines, reciprocating internal combustion engines, Rankine cycle engines with a range of working fluids, steam reciprocating engines, and high and low temperature fuel cells.

For many of these small scale systems, electric power output is in the 1 kW range and they are "heat led" - i.e. operate only when a heat demand exists. These systems typically operate in parallel with the electrical power grid, feeding power back into the grid when the building power demand is lower than the output of the engine. Generally these systems cannot operate independently from the electric power grid. There are of course many variants to this typical system – a few concepts have been developed which will operate during power outage situations and there are larger systems available. For the building owner, the primary benefit which drives a purchase decision is the reduction in annual energy costs and reported savings range from 15 to 25%. These systems are typically expensive and in many cases market potential is constrained by payback potential and the capital cost requirements.

In the work reported here, the focus has been on solid-state power production using thermophotovoltaic (TPV) power production and thermoelectric power production. Relative to many of the microCHP concepts this offers a key advantage of simplicity and a lack of moving parts. Further the focus is on the development of lower power output levels, no grid integration, and total self-powering of a heating system. One part of the rationale for this approach is that the reliability of heat supply, the ability to operate without the presence of the power grid, and avoidance of the need for emergency power generators may provide a more significant benefit to the building owner than a reduction in primary energy use. Also, this would enable such a system to be used in a remote location.

Residential heating systems in North America include a mix of forced air and hydronic systems with the forced air dominating. Hydronic systems are most common in the Northeast U.S. In contrast the market in Europe is strongly dominated by hydronic systems. This work is focused only on hydronic systems simply because of much lower electric power requirements. Further the work has been focused on oil-fired systems. The basic system concept is illustrated in Figure 1. When a heat demand is initiated, the burner fires from battery power. After the system has heated to operating temperature power generation both meets system demand and recharges the battery.

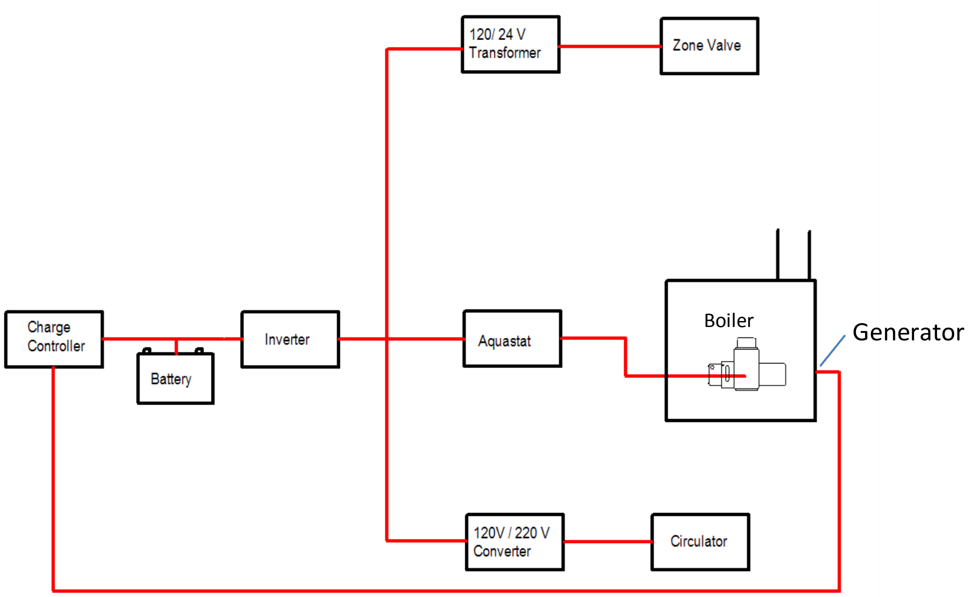

Figure 1: Basic System Concept Sketch

TPV power production involves the generation of electrical power through the interaction between a heated body and photocells. Over the past two decades there has been a great deal of research and development work done on TPV cells and systems. Relative to solar photovoltaic power production, TPV emitter sources are lower in temperature and so have less energy in the visible part of the spectrum and more in the near infrared range. Much of the work, then has been focused on low bandpass photocells and the present work uses gallium antimonide (GaSb) cells. For the heated light emitter, different approaches have been used in fuel-fired TPV systems including solid "blackbody" emitters heated by a flame, porous media with natural gas combustion in the media, selective emitters with high emissivities in a range suitable for the cells used, and to a much lesser degree direct flame radiation. For the present work, which focuses on an oil flame, the choice of an emitter approch was constrained by the practical aspects of the flame. Considerable effort was place on evaluation of direct flame radiation and this approach offers the potential advantage of the highest emitter temperature. After evaluating options an optimal approach of a porous media emitter, downstream of the flame was selected (Butcher et al., 2008; Butcher et al., 2011). Details are provided in the following section.

Another important design decision in a TPV system is the use of optical filters and/or selective emitters. These selective emitters are ceramic oxide coatings which can be added to porous substrates. The key reason why these were not considered in this work was concern about long term durability based on prior studies. This group has had considerable involvement with high performance narrow bandpass filters (Horne et al., 1996). These offer the potential of high overall system efficiency (fuel to electric power - potentially to 15% with regeneration and air preheat) in dedicated systems. These filters, however, reduce cell power density and can significantly increase system cost. The approach taken here was the use of "unfiltered" cells. This approach leads to higher cell power output but creates a very significant cell cooling challenge. For the goal of self-powering, the level of fuel to electric efficiency required is very low – on the order of 1%. Also, all heat from the cells is used in the heating system in any case and is not lost. The term "unfiltered" is not fully accurate, however, as the cells still require a separation from direct exposure to combustion products.When a GaSb cell array is placed in the furnace, its delicate metallization grids and junction surfaces need to be protected from soot and other contaminants. The cells also need to be prevented from overheating. The solders used in fabricating the array melt at temperatures on the order of 150 C and the PV junctions degrade at sustained temperatures above 250 C. The glass separating the cells participates strongly in the exchange process through filtering, reflection, absorption, and reradiation.

Thermoelectric (TE) power generators use the Seebeck effect to produce electric power with assemblies of dissimilar materials. The most widely available, and lowest cost conversion modules now are bismuth telluride (Bi_2Te_3) based (http://hi-z.com). A wide range of advanced thermoelectic materials have been developed or are in development which offer the potential for much better future performance (Sootsman et al., 2009). In the present work on the the common bismuth telluride modules have been explored, primarily to allow evaluation of such a very low cost option. Both TE and TPV conversion with a plan for a potential hybrid approach have been considered in this work.

2. Experimental

The boiler used for this work is a modified version of a conventional, oil-fired home heating boiler with a nominal maximum input (firing rate) of 35 kW. Figure 2, provides an illustration of this boiler, as modified. The combustion chamber, into which the oil burner fires, is a horizontal, refractory-lined cylinder. On the right side of the chamber the exhaust gas passes through a ceramic foam emitter. This is a silicon carbide/alumina (SiC/Al_2O_3) material, with a thickness of 1 inch and a pore density of 10 pores-per-inch. This very open pore structure was selected to provide a negligible pressure drop. As indicated in Figure 2, some tests were done without the emitter in place to evaluate the potential for direct use of the flame as the emitter. The results were similar; however the performance was not as good as with the emitter foam in place. Further, without the emitter in place the TPV system performance was found to be strongly dependent on excess air level which can lead to operational problems. This figure shows a triple layer of quartz used to separate the combustion products from the TPV cells although testing was done with 1 to 3 layers.

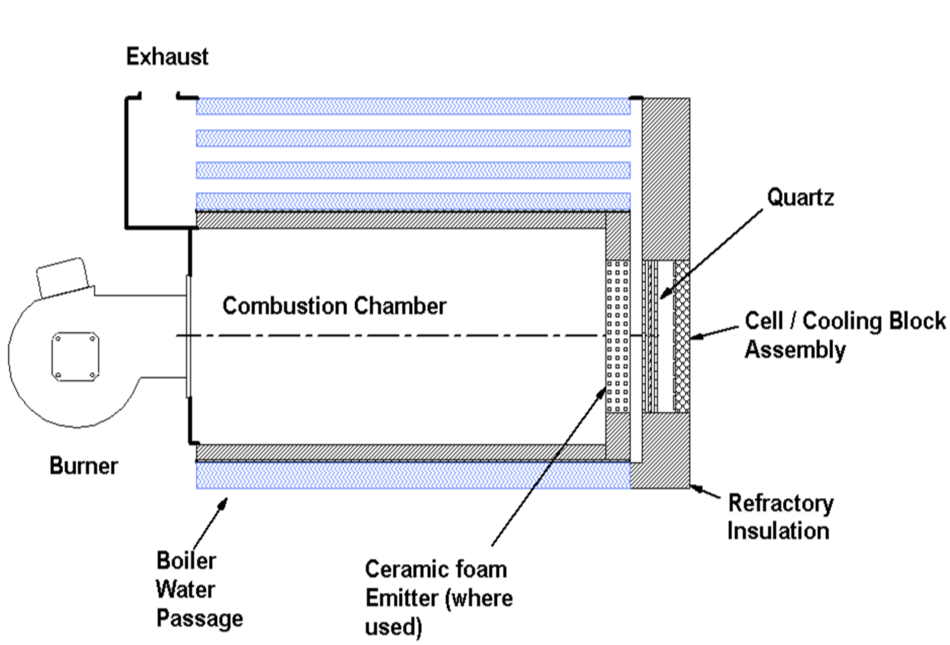

Figure 2: Sketch of the boiler as modified for testing

After passing through the ceramic foam the combustion products travel upward and then enter the tubes which comprise the convective heat transfer section of the boiler. In the hybrid approach under consideration, the TE modules are installed above the TPV cell array, where the gas is cooler and there is a much lower level of direct radiation.

Figure 3 provides a photo of the back end of this modified boiler with the rear cover removed to illustrate the ceramic foam and tubular convective heat exchanger.

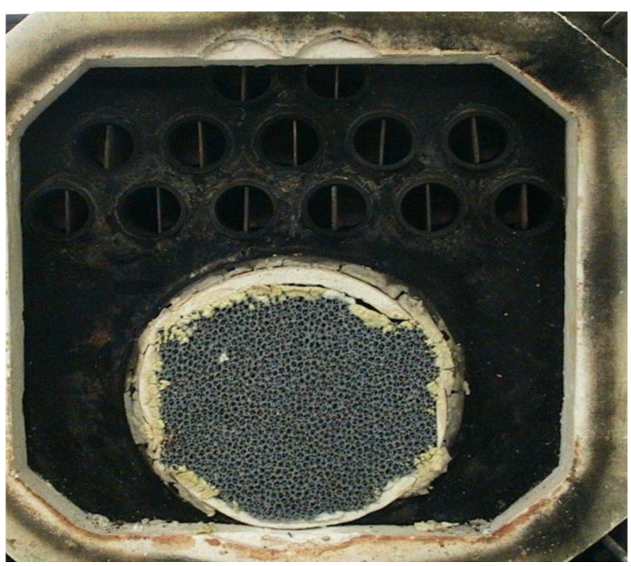

Figure 3: Photo of rear end of the boiler with cover removed to show ceramic foam and heat exchanger tubes.

As discussed above GaSb photocells were used in this project. These convert light with wavelength's shorter than 1.7 microns (near infrared) to electric power. There have been serveral other studies which have used lower cost silicon “solar” cells. The advantage of the silicon cells is wide availability in addition to the low cost and a wide range of options are available. The disadvantage is that the silicon cells only convert light with wavelengths shorter than 1 micron. For a typical TPV emitter with a temperature of 1400 C, the blackbody emissive power integrated between 0 and 1 micron is 1.2 W/m^2, but the emissive power between 0 and 1.7 microns is 10.6 W/m^2 – 8.8 times higher.

The TPV converter module was designed as a rectangular array of 100 GaSb cells, each with 1 cm^2 of active surface area. The entire array, with interconnects and void space is approximately 15 cm X 20 cm. In our first prototype converter module, the array was built as a single module with its back board mounted to a water cooled copper block using a thermal epoxy. Tests with this system in the boiler were promising but it was clear, from measurements of the open circuit voltage that the cell temperature was rising too quickly following the burner start, leading to expected thermal damage. The problem was likely due to air in the epoxy layer and the large size of this array made it difficult to ensure that this air would be removed during assembly. To address this issue, a second design approach was taken in which smaller arrays, with two rows of 10 cells each were built on independent water-cooled copper blocks. In this design the interconnects and bonding pads for the PV cells are etched into the top surface of a copper clad SiN_3 ceramic circuit board. The copper cladding is left intact on the back surface of the ceramic board. The epoxy bonding is replaced with a low-temperature solder whose liquid state during bonding enables any air pockets to be easily purged during the bonding process.

The heat sinks were machined from solid copper. The coolant channel was machined to form the back of the heat sink to within 0.1 inch of the front surface so that coolant fluid flows in a thin sheet underneath the entire active area of the PV cells with the thermal conduction path being only 0.1 inch from the back of the PV cells. Four fins that run the length of the channel extend 0.1 inch into the fluid channel to maximize the heat transfer surface area. A channel cap plug is then machined to fit snugly into the channel opening in the back of the heat sink and provide fittings for pipe nipples into each end of the coolant channel. Figure 4 provides an illustration of the cooling block.

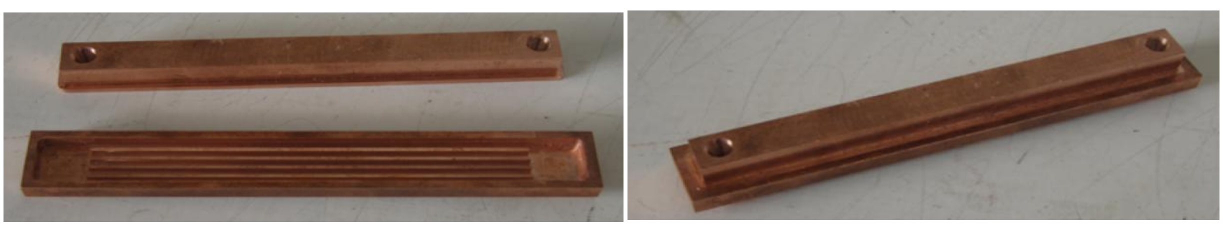

Figure 4: Illustration of the TPV cell cooling block, before (left) and after (right) assembly

For the TE tests a standard bismuth telluride module was evaluated, Model HZ-20 from Hi-Z Co. (http://hi-z.com). Relevant specifications for this module are provided in Table 1, below.

Table 1: Properties of the Thermoelectric Module Tested

Size	7.5 X 7.5 cm
Design Hot Side Temperature	230 ºC
Maximum Hot Side Temperature	250 ºC
Maximum Intermittent Hot Side Temperature	400 ºC
Heat Flux	19 watts
Efficiency	4.50%
Electric Power Output	19 W

The nominal power output shown in Table 1 is based on a cold side temperature of 40 ºC. In the boiler application the heating system return water temperature, and so TE module cold side temperature, depends on the system it is used in. With conventional radiator heating with an outdoor reset control, the temperature can vary from 43 to 66 ºC. With a radiant floor heating system the return water temperature may be as low as 32 ºC. At 66 ºC the nominal output is reduced to 14 Watts. The electrical power output density then of the TE module can nominally vary from 0.34 to 0.25 W/cm^2.

The performance of a TE module is strongly affected by the thermal connection to both the cold and hot sinks. For these tests a water cooled block, manufactured by Hi-Z was used for the cold sink. A stainless steel hot face plate was included in the assembly. The bismuth telluride module was sandwiched between the hot face plate and water cooled block using four corner bolts. A thin layer of thermally conductive grease was used on all faces. Testing of the performance on a hot plate with careful measurement of the hot face temperature confirmed that the module achieved the manufacturer's nominal performance.

3. RESULTS

To date one of the planned TPV converter modules has been built and tested. With a burner firing rate of 35 kW and using just a single quartz window Figure 5 shows the cell temperature, calculated from measured open circuit voltage (Voc) and published relationships between Voc and temperature. Similar tests were done under lower firing rates with the same results. This essentially confirms that the cooling system is capable of transferring the large amount of heat flux from the emitter and keeping the cell temperature within a reasonable range.

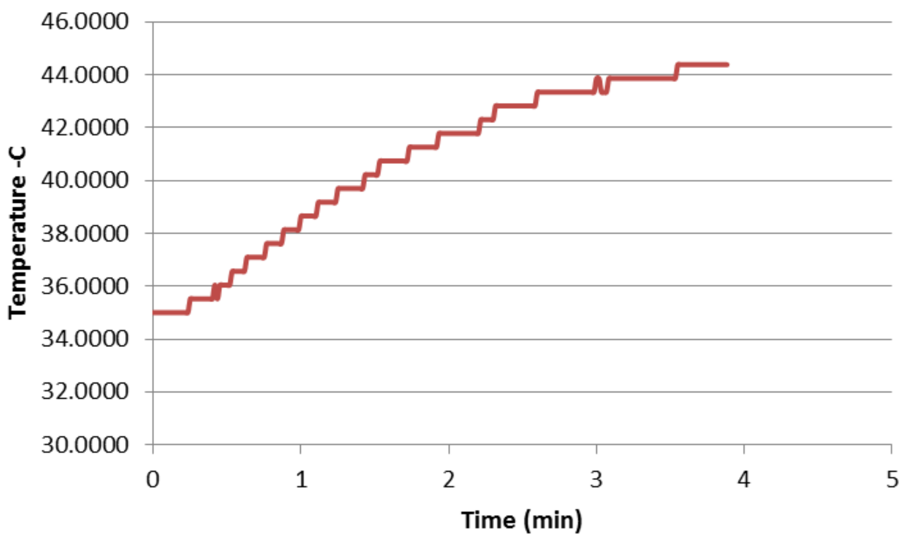

Figure 5: Trend in TPV cell temperature following startup.

For the 35 kW burner firing rate, Figure 6 shows the trend in Voc and short circuit current (Isc) as a function of time from cold start. These parameters were measured simultaneously on separate 10 cell strings in the two row array. These results show that, for this configuration, approximately four minutes are required for the system to reach full electrical output. Assuming a representative cell fill factor of 0.7, each string in steady state has an output of 9 Watts. The full 100 cell array is projected to have an output of 90 Watts.

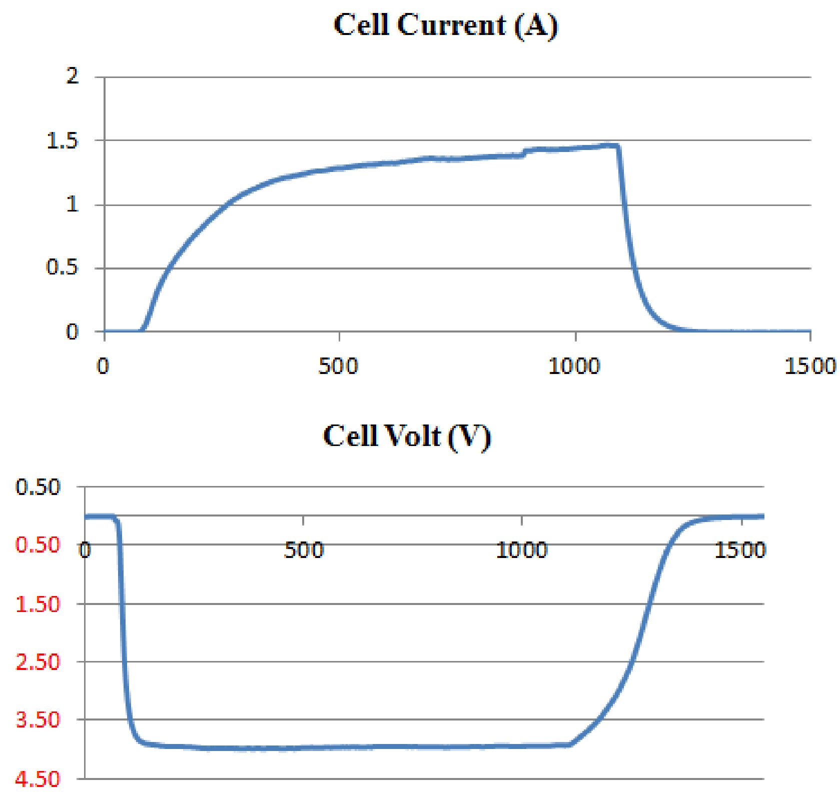

Figure 6: Trend in Voc and Isc following startup (x axis is time in seconds)

For testing of the TE module in the boiler, it was located in the boiler back cover, above the top edge of the combustion chamber and emitter. A small hole was drilled through the edge of the 3.2 mm thick hot face plate and a thermocouple was installed to provide a direct measurement of the hot face temperature. Following startup the hot surface temperature and maximum power output was measured as a function of time. The maximum power was determined by varying the load resistance to find the max power point. It should be noted that the hot surface of the TE module was simply a flat plate and did not have fins to improve convective heat transfer. These results indicate that, at least at this condition, such fins are not required. Figure 7 shows the results on the form of max power output vs temperature. Based on these results we conclude that a power output level of 12 Watts is a reasonable design basis for these TE modules. If the entire back cover of the boiler were covered with TE modules – we estimate 12 could reasonably fit and the total power output would be 160 W.

4. INTEGRATED HYDRONIC SYSTEM

A conventional hydronic heating system has an electric power draw on the order of 300 W. Considering the power production capability of the TPV and/or TE modules discussed above this power level is not achievable. For a reasonable system there is a need to reduce the system power demand. This was accomplished in this project through a combination of unique features including use of:

- DC electronically commutated burner air blower;
- Solenoid pulsed piston fuel pump in place of a conventional gear-type pump;
- DC electronically commutated water circulator.

With the integration of all of these components, including solenoid valves and system controls the power consumption in steady state was measured at 72 Watts. While this power level is smaller than the expected power level from the TPV system, it is not sufficient to recharge the battery following startup and warmup (i.e. during no power production) periods. For this reason a higher level of nominal full load output is required. The magnitude of additional power required depends on the burner cycling pattern. A burner which only runs for 4 minutes, for example, at every firing will barely reach its steady state power output point before shutting off. To extend the burner run time a 30 gallon water storage tank has been integrated with the system. The burner then will primarily operate to recharge this storage tank and have longer run times.

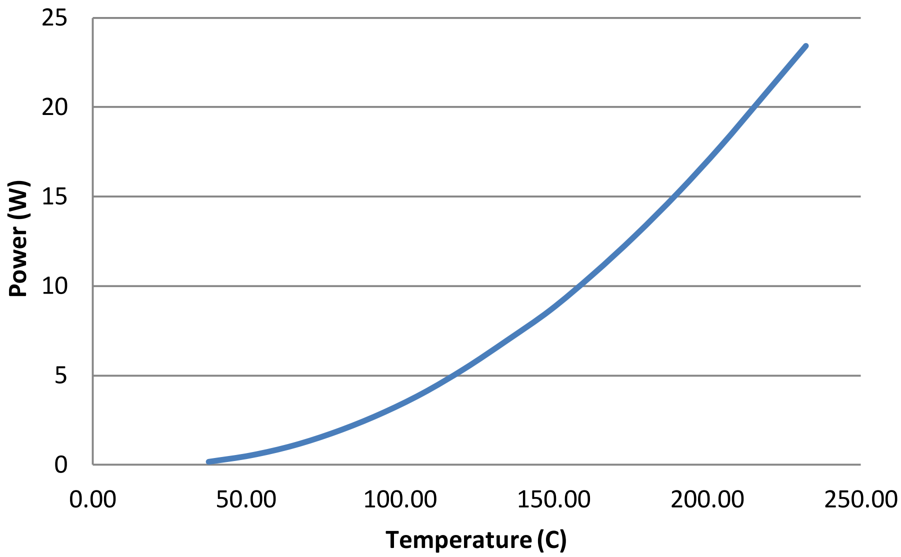

Figure 7. Power produced by thermoelectric module vs hot face temperature during startup.

5. DISCUSSION

The TPV system test results which have been achieved indicate the potential for a power density of 0.9 W/cm^2 of active cell area or 0.3 W/cm^2 of total array board area. It is the opinion of the authors that this power density figure can be increased and it is planned to explore this in continuing work. The methods to achieve this involve optimized selection of the quartz glass separating the cell array from the combustion products and decreasing the length and diameter of the combustion chamber. Regarding the first point, as part of this project available data on the optical properties of different high temperature glasses was explored. The transmission over the range relevant for this work varies considerably, however tests with different materials have not yet been conducted. Regarding the combustion chamber geometry, a shorter chamber with a smaller diameter will offer the potential to increase the emitter temperature and, in turn, power output. Using a smaller chamber, through installation of refractory sections would also yield more rapid heatup of the emitter.

Based on the test results reported here, the power density of the TE modules is similar to what has been achieved to date with the TPV cells. However, the TE cells cannot be used with direct exposure of flame radiation simply because they would overheat. Using TE cells in the highest temperature region would require thermal shielding to avoid excessive hot face temperatures. In a similar way, use of the TPV arrangement in cooler regions of the boiler beyond the emitter area is not practical because the power density would fall to unacceptable levels. Based on these considerations the plan for future development work in this area is in the direction of a hybrid system, with TPV cells in the high temperature region and TE modules in the lower temperature region. The target power output of the hybrid system is 120 W, which is expected to “cover” the warmup power draw for typical cycling patterns. Qiu and Hayden (2012) also used a hybrid TPV / TE approach with a gas-fired boiler but in a rather different configuration.

6. CONCLUSIONS

This work has served to demonstrate the technical feasibility of integrating unfiltered TPV converters as well as TE modules within an oil-fired boiler system. The power production potential is easily greater than the steady state system power demand but additional power must be produced to compensate for warmup periods before the system reaches full power output potential. The steady state power demand of an oil-fired hydronic heating system has been shown to be under 80 watts if low power components are used as demonstrated in this paper. The use of thermal storage with the system reduces burner cycling and leads to reduced steady state power demand.

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