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Implementation of a TPV integrated boiler for micro-CHP in residential buildings

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HIGHLIGHTS

- A TPV integrated boiler for micro-CHP application is designed, tested and demonstrated.
- Thermal radiation was emitted by a porous emitter in the TPV unit.
- The electric output of four TPV cell modules connected in series is measured and characterized under various conditions.
- 246.4 Electricity is generated at the emitter temperature of 1265 °C.
- This study shows that TPV generation in boilers/furnaces is feasible for micro-CHP application in residential buildings.

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ABSTRACT

There is a growing interest in direct thermal-to-electric energy conversion using solid state devices such as thermophotovoltaic (TPV) generators. TPV devices convert thermal radiation from heat sources into electricity without involving any moving parts. TPV opens up possibility for efficient and stand-alone power generation in boilers and furnaces. In this paper, a TPV integrated boiler was designed, built and investigated for micro combined heat and power (micro-CHP) application in residential buildings. A full size gas fired residential boiler was used as a precursor for integration with TPV devices. Experiments were conducted with the prototype TPV boiler so as to evaluate various issues related to this new technology. The electric output of TPV modules installed in the boiler was characterized under different operating conditions. The TPV cell modules generated 246.4 W at an emitter temperature of 1265 °C, which would be enough to power the electrical components of the whole heating system. Moreover, such a TPV integrated boiler could be employed to form a micro-CHP system in residential homes, providing an effective means for primary energy savings, on-site power and energy security.

1. Introduction

Thermophotovoltaic (TPV) generators convert radiant energy from heat sources such as combustion into electricity (Fig. 1). This energy conversion is achieved by means of photovoltaic (PV) cells. Low bandgap PV cells are preferred for TPV generators since the photons emitted from heat sources at temperatures of practical interest are distributed at lower energies in comparison to solar radiation. Low bandgap PV cells are referred to as TPV cells. The advantages of TPV systems include: (a) a high fuel utilization efficiency is achievable due to that the fact that the heat dissipated can be recovered on-site for space conditioning and water heating needs, (b) no moving parts are involved in the power generation, and (c) this is a relatively low maintenance technology. Based the above features, the TPV generator is well suited for micro combined heat and power (micro-CHP) applications in residential buildings. A combustion driven TPV generator usually consists of a heat source, a thermal emitter, a spectral control filter and TPV cell modules. The thermal emitter converts the combustion heat into radiation energy (photons) at appropriate wavelengths. The emitter could be a solid surface heated by flame impingememt, or a porous medium burner with combustion taking placing inside the porous medium. The TPV cells play a pivotal role in the heat energy to electricity energy conversion process. Cells made of low bandgap semiconductor materials, such as GaSb, are favored because these cells can convert more infrared radiation (low energy photons) from the emitter to electricity. To maximize thermal to electric energy conversion efficiency, a spectral control filter should be used. The filter is capable of passing the desired portion of broadband thermal radiation and reflects the non-convertible

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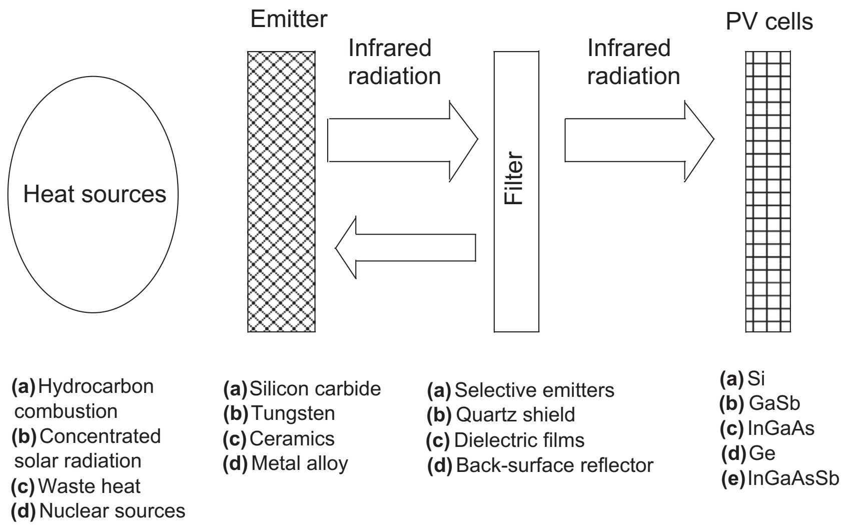

Fig. 1. Illustration of TPV energy conversion.

radiation back to the emitter to increase the overall system efficiency.

A number of research groups have been developing cogeneration systems based on TPV devices [1–4]. Schubnell et al. [1] have analyzed the influence of various parameters including cell bandgap and flue gas temperature on the electricity conversion efficiency of a TPV central heating unit, however, they did not provide their experimental results. Horne et al. [2] presented a liquid fuel-fired TPV system for portable power applications where a resonant metal mesh infrared band pass filter was used, yet a TPV system with such a filter would be difficult to implement in practical applications. The investigators at JX Crystals Inc. reported on the development of a prototypical propane-fueled TPV stove, generating up to 100 W of electric power [3]. In a study by Nelson [4], a self-powered, gas-fired, warm air furnace was evaluated as a candidate for the autonomous generation of electric power. In addition to the above work, TPV systems were shown to have the potential for application in high temperature industries [5,6]. There have been other investigations that have examined the combination of TPV with other power generation approaches such as thermoelectrics [7] and low temperature Rankine cycles [8,9]. The reviews of TPV research [10–12] have shown that TPV systems have many advantages, including no moving parts, high reliability and the capability of converting radiation from a variety of heat sources directly into electricity. The same reviews have also shown that TPV systems have certain limitations, for example, the electrical efficiency of combustion-driven TPV systems developed to-date has been relatively low [3,12–14]. The major energy losses in combustion-driven TPV systems arise from the limited conversion of fuel to radiation energy and low fraction of in-band radiation. It has been suggested that heat recovery or recuperation from the flue gas exhaust could be an effective means of increasing TPV system efficiency [15–20].

TPV devices can suitably be integrated with heating equipment to form micro-CHP systems for use in residential buildings. Residential combined space/water heating equipment, such as fuel fired boilers, use both fuel for heat production and electric power to drive its electrical components. If a boiler utilises a TPV generator to convert part of the combustion heat energy to electricity that then operates its electrical components including a combustion fan/blower, pumps, valves, and controls, it becomes a so-called self-powered heating system. Any surplus electricity generated can be provided to other electrical loads within the home, realizing the CHP concept in a residential setting. This provides a possible means for power supply, energy security for the home, and overall primary energy savings as well. Although a number of TPV systems were investigated [3,7,13–28], no work on practical or full-size TPV systems has been reported in the literature and little attention has been paid to an integrated system in the earlier investigations. In this paper, a TPV integrated boiler was designed, built and investigated for micro-CHP application in residential buildings. A full size gas fired residential boiler was used as a precursor to integrate with TPV. Recently-developed GaSb TPV cell modules were employed in the direct thermal-to-electric energy conversion system. Experiments were conducted with the prototype TPV boiler in order to address certain issues related to this technology, which must be resolved, before TPV can be applied in practice. While the development of a self-powered boiler was considered as a first target, upgrading the equipment to a micro-CHP system was also addressed.

2. TPV integrated boiler for micro-CHP in residential buildings

2.1. Concept description

Fig. 2 shows the schematic diagram of the TPV power generation process in a gas-fired boiler. Natural gas is converted by a radiant burner into thermal radiation and the sensible heat of flue

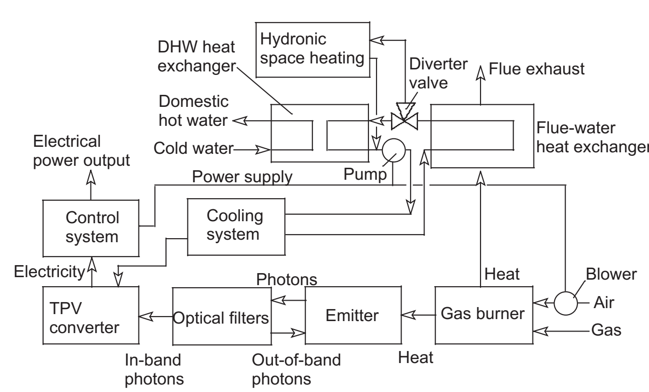

Fig. 2. Schematic diagram of the TPV power generation process in gas-fired residential boiler.