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Performance assessment of thermophotovoltaic application in steel industry

Ehsan Shoaei

Sharif Energy Research Institute, Department of Energy Engineering, Sharif University of Technology, Tehran, Iran

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ABSTRACT

The potential for using Thermophotovoltaic (TPV) generators as an alternative for recovering energy losses in steel production industry is assessed. A mathematical model for the assessment of the performance of TPV application in the iron and steel industry has been developed. In order to support the mathematical model, a sample TPV apparatus in laboratory scale based on an IR emitter has been designed and assembled. The key modeling parameters of TPV generator include: the open circuit voltage, the short circuit current density and fill factor of the TPV cell. These parameters have been considered in the model as functions of several variables such as: the emitter (hot steel slab) temperature, the cell temperature, the distance between the cells and emitter, the spectral response and the cell energy gap. The External Quantum Efficiency (EQE) as an important indicator of the cell's spectral response is included in the model. Moreover, the variation of the emitter temperature has been considered. Several tests have been carried out for different values of the cell-emitter gap. It has been found that when the GaSb cells are used for energy recovery, a minimum temperature of 873 °C is required. The upper limit of the emitter temperature is usually determined in steel production process associated with hot rolling process which has a temperature around 1250 °C. Finally, the total efficiency of the system was obtained to 4.12%, when GaSb cell with temperature of 27 °C and slab emitters with temperature of 1257 °C are used. The results of the simulation of the model in a casting process at the Mobarakeh Steel Complex have shown a potential of energy recovery of 26.987 MJ per year.

1. Introduction

Similar to all the energy conversion concepts, Thermophotovoltaic (TPV) is a method for converting thermal energy (heat radiation) into electrical energy [1]. Since TPV is a technology which requires a heat source with sufficiently high temperature, it can be used in industries where a process is operated under such a condition. A straightforward application of TPV would be waste heat recovery in high temperature industries such as the glass or steel industry. An example of waste heat recovery via TPV cell is the case of the continuous casting of hot rolled steel plates in steel industry. These plates have an initial temperature around 1200 °C and are cooled down to less than 1000 °C. If TPV cells are to be placed above the hot plates during the cooling process, an electric current can be generated via the emission process. It is estimated that the potential power generation of a hot steel slab with a surface area of 50 m^2 would be around 440 kW [2].

Application of TPV generators goes back to the early 1990s when the low band gap infrared (IR) sensitive III-V cells were introduced. The first TPV was the GaSb cell invented in 1989 and then described in 1990 [3]. The function of a TPV was then demonstrated by using the commercially available SiC radiant tube burner. It was then possible to monitor and control the emitted spectrum [4]. Qiu et al. used a TPV system in a combustion chamber where GaSb cells were used [5]. Subsequently, the effect of combined usage of TPV and thermoelectric (TE) on enhanced power generation was investigated [6].

The combustion of fuels also provides appropriate heat sources for emitters and part of the heat loss in a combustion chamber may be recovered via a TPV system. Yang et al. studied possible heat recovery based on laboratory tests [7]. The emitted spectrum of a flame in a combustion chamber was also investigated by Li et al. [8,9]. Pascale et al. examined the integration of TPV and generator of Organic Rankine Cycle and were able to reduce the intensity of the input energy [10]. Cockeram and Hollenbeck used an emitter surface that was coated with substances of high emissivity which led to the development of efficient systems [11]. They showed that an alternative approach would be to use cells that have an energy band gap proportional to the spectrum of the emitter resulting in the enhanced efficiency of a TPV system. As an example, an emitter of Yb_2O_3 may be used together with

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E-mail address: eshoaei@alum.sharif.edu

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Cu(In, Ga)Se_2 (CIGS) cells that show an energy band gap proportioned to the emitted spectrum [12].

Regulation of the thermal radiation spectrum is an essential element of TPV system. Mostafa et al. used Si/SiO_2 and Ag/SiO_2 photonic crystals to control the spectrum [13].

In three subsequent works, Badescu [14–16] analyzed a particular type of TPV device and used a theory integrating the main components of TPV devices. Various combinations of spherical and (disk) plane absorbers and solar cells are analyzed. The components include the primary lens (or mirror), the absorber, the PV cell, and a photon recuperator system. He maximized the TPV efficiency by using three optimization parameters, namely absorber, PV cell temperatures, and cell voltage. As the main results of these works, the thermal design has a significant influence on the optimum PV cell band gap. He concluded that in the case of a normal thermal design, the cell temperature is usually high and depends strongly on the band gap. When accurate thermal design is considered, the optimum cell temperature is less than 30 degrees higher than the ambient temperature and decreases with an increase in the band gap.

Bitnar et al. [17] explained another application of a TPV system in a residential central gas heating system. They designed a TPV to supply the electrical power in order to drive the gas heating system truly independent from the electrical grid. This has not yet been commercialized while it can successfully work.

Butcher et al. [18] reported the successful demonstration of a self-powered oil-fired hydronic heating system using TPV technology to provide grid independent operation by producing 119 W of electrical power.

Bitnar et al. [19] reviewed some related developments of TPV system components such as radiation emitters, filters and photocells and compared theoretical system simulations to experimental results regarding system efficiency and the electrical output power. They suggested novel applications of TPV and discussed the commercial potential of this technology.

Following the trend of research on technical features of TPV systems, industrial application of TPV has been studied by Utlu and Parali [20]. They concluded that the iron and steel industry provides considerable potential of energy recovery via TPV systems. They pointed out that further works is required to demonstrate the performance of a TPV system for a range of slab radiation temperatures in steel industry.

Regarding this application, Johansson et al. [21] proposed the application of TPV in steel and iron production units and presented some opportunities for both integrated and scrap-based steel plants. They evaluated several options from a system perspective and reported more specific measures for two Swedish case companies.

Hence, a model of a TPV system could be developed which would avail itself to further investigation of the potential of energy recovery and the parameters that may affect its realization in industry. The development and application of a mathematical model of a TPV system and its verification constitutes the core content of the present paper.

2. Conceptual model

The mathematical model of a TPV is founded on the conceptual model of a TPV system as shown in Fig. 1. The conceptual model is deducted as a reference energy system which depicts the flow of energy from primary sources through processing and conversion systems.

Line number (1) in Fig. 1 indicates the transmission of radiated heat from the emitter to the optical filter. Line number (3) shows the heat that is lost to the ambient surrounding area. Since the emitter is placed in free environment, the heat is partially released to the environment via convection and radiation. Line number (2) represents the reflected radiation of the filter toward the emitter. Possible outcomes of incident electromagnetic waves are: transition, reflection and absorption. All the Outcomes are subjected to the type and thickness of the filter. Line number (4) shows the radiation which passes through the filter. The radiation on the cell is segregated into two parts, one part which can be converted into electrical power and the other part includes the absorbed and reflected radiation. The reflected radiation is depicted via line number (5) and the absorbed radiation heats up the cell itself. Consequently, the cell temperature rises and considerably exceeds the ambient temperature which leads to heat loss and is denoted by line number (6). If a filter failure occurs, the cell temperature rises more rapidly. Therefore, a cooling system is required to avoid overheating and dysfunction of the TPV system. Overheating and cooling are singularly represented by line number (9). Line number (8) shows the required power for the cooling system. Line number (11) represents the heat loss through the cooling system. Finally, the power generated by the TPV system flows to the end user is indicated by line number (7). Both the cooling system and filter prevent overheating of the cell and their function is shown by line number (10).

3. Mathematical model

3.1. Governing equation

As an analytical tool, a mathematical model is conceived to study the interrelationships between the various flows as explained in the conceptual model. It could then be applied for parametric analysis and technical evaluation of the performance of the system. Some important functions and equations required for representing the flows in the reference energy system are described here and complementary set of equations included in

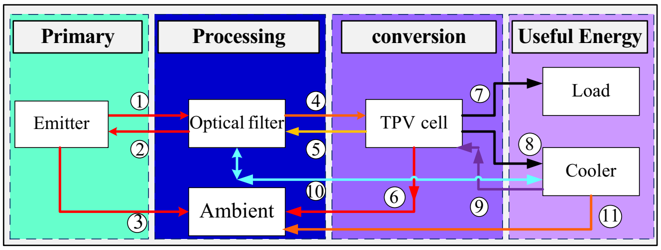

Fig. 1. Conceptual model of a typical TPV system.

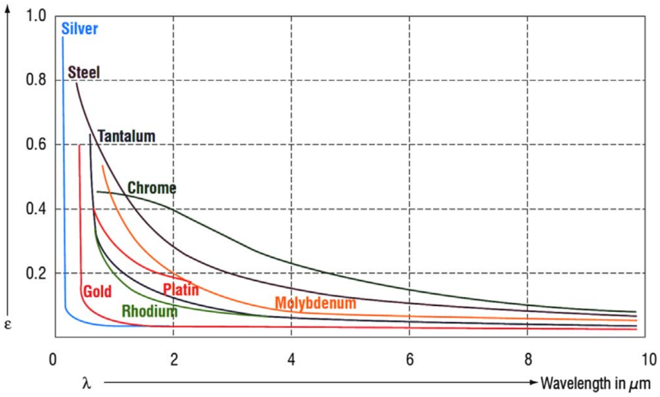

Fig. 2. Variation of the amount of emissivity for different metals [22].