Waste Energy Collection and Conversion using Advanced Thermophotovoltaics systems.

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ABSTRACT

Thermophotovoltaic (TPV) technology can harness the waste energy dissipated by heavy industrial processes to generate clean electricity. The efficiency of TPV systems depends on several factors, including the temperature of the thermal emitter, the bandgap of the photovoltaic cell, and the spectral matching between the emitter and the cell. Currently, state-of-the-art TPV devices can achieve efficiencies up to 50%, while most TPV systems typically have efficiencies in the range of 5-20%. Nonetheless, improving the efficiency of TPV devices remains an active area of research and development. The tandem configuration within the TPV device utilizes multiple solar cells stacked on top of each other, with each cell designed to absorb different portions of the solar spectrum. This configuration not only increases the overall efficiency of the TPV device but also enables better energy conversion and utilization. In our study, we evaluate the performance of TPV solar cell configurations. Using the finite element method, we have numerically studied the performance of these solar cells when used to harness waste energy within the range of 1500-2500K. We observe a maximum power density of 0.8 W/cm^2 is obtained with TPV cell when using a TPV having a maximum of 20% efficiency. Further, we evaluate the performance of these devices when used alongside non-uniform heat sources and explore pathways for their efficiency improvement.

KEYWORDS

Thermophotovoltaics, waste energy, heat-to-electricity, clean energy

INTRODUCTION

Many of the foundation industries like iron and steel making, cement, glass and oil refining across the world discharge a huge amount of energy in the form of heat. This waste heat is essentially excess heat generated during the manufacturing processes that is not effectively captured or utilized for productive purposes. Efforts to address waste heat include improving the energy efficiency of industrial processes, implementing heat recovery systems, and exploring ways to repurpose waste heat for other industrial or residential purposes. These measures can help industries reduce their energy consumption and environmental impact by making better use of the heat generated during their operations. According to a recent report [1]

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around 20 – 50% of the energy used for the production and manufacturing by the industries is lost as heat radiation. Globally, the iron and steel industries alone discharge energy approximately 1 quadrillion BTUs annually which is lost as heat [2]. Several countries such as EU, US and India have estimated their industrial waste heat and are actively seeking efficient ways to harness it. The European countries have estimated their waste heat recovery potential as 300 TWh/year of which more than 40% is of high temperature heat radiation in the range of 1000 K – 1300 K [3]. The U.S has an estimated waste heat recovery potential of 450 TWh/year and some of the process has an exhaust gas temperature of as high as 1500 K – 1600 K. India has an estimated waste heat recovery potential of 160 TWh/year which is equivalent to 20000 MW of coal-based power generation capacity [4]. Therefore, converting this waste heat into useful energy can cater up to 20- 40% of the power consumption by the industries.

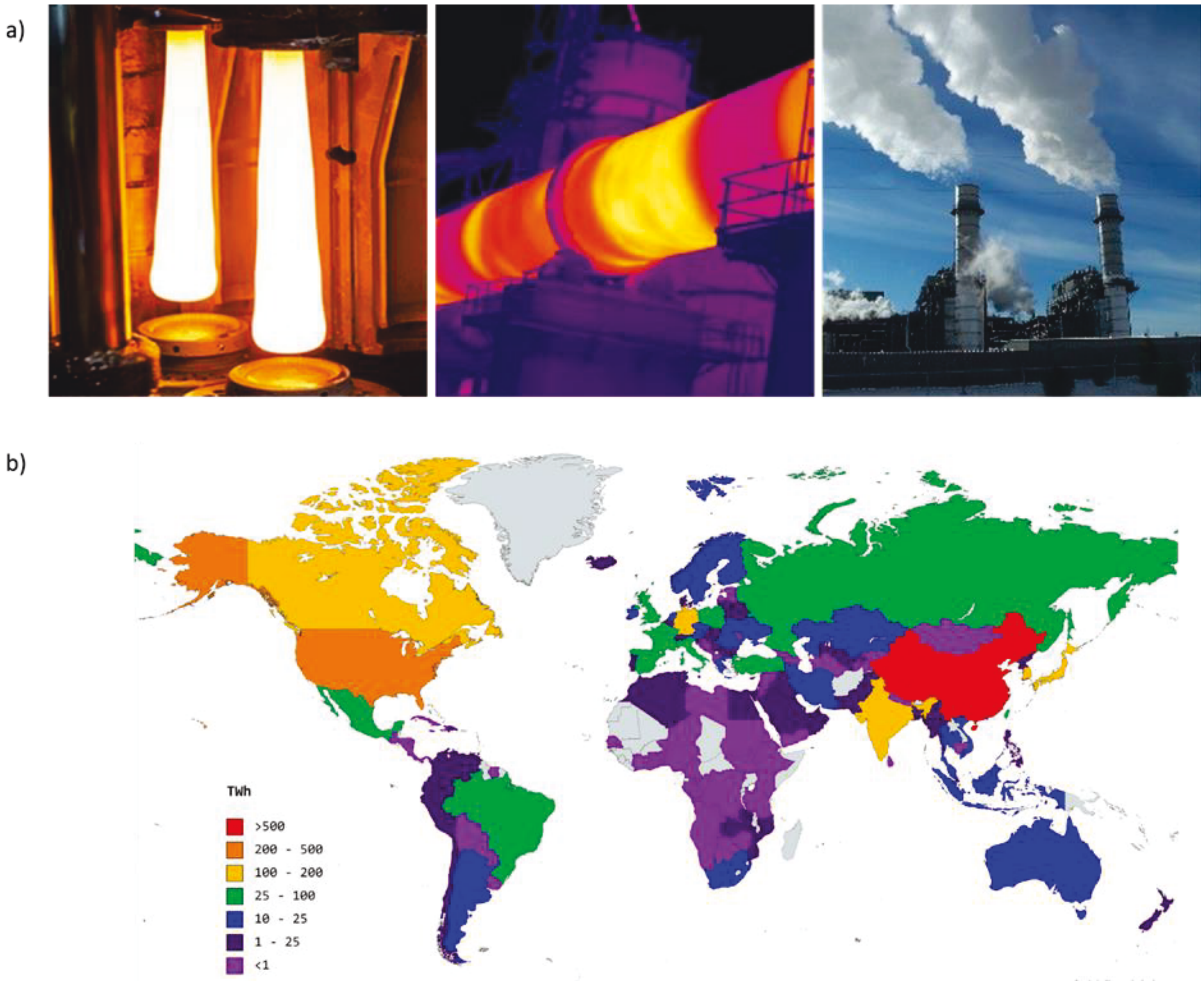

Figure 1a) Potential industries to recover waste heat dissipated into outside environment b) Industrial waste heat potential across the globe in TWh.

Figure 1a shows the large amount of thermal radiation that is being lost in the form of waste heat from major industries like glass, cement, iron, and steel industries. Figure 1b showcases the industrial waste heat potential across the world by various countries. For most of the European countries the data is available from ref [5] and for the remaining countries, the potential is estimated based on the industrial power consumed by the respective country. A minimum of at least 20% of energy supplied to industries is released in the form waste heat [1], so estimated potential is shown in TWh on the world map. Therefore, the major countries with over 100 TWh potential is China, USA, India, Japan, Germany, Canada, and South Korea which are the leading countries in terms of production and manufacturing. The grey colour regions in the world map indicates that the data is not available.

While waste heat recovery systems exist, there's a need for research into innovative technologies that can efficiently capture and convert waste heat into usable energy. This could include exploring new materials for heat exchangers, thermoelectric materials for direct heat-to-electricity conversion and other novel methods for heat storage. Depending on the type of industry, several technologies have been developed for the waste heat recovery and state of the art technologies include recuperators, economizers, passive air heaters and heat exchangers [6-7] which are further connected to turbines completing the waste heat recovery using Rankine and Brayton cycles. Nonetheless all these necessitate moving components, leading to specific criteria for the elevated-temperature mechanical attributes of the construction materials. Furthermore, these cycles are also being coupled to produce fuels like methane or propane which can be stored and reused at another rime.

Thermophotovoltaics (TPV) on the other hand offer a promising avenue for efficient heat recovery, especially at elevated temperatures. This technology involves converting heat radiation directly into electricity using photovoltaic cells optimized for capturing thermal radiation. By harnessing the emitted photons from hot surfaces, TPV systems can potentially convert waste heat into usable energy, addressing some of the limitations of traditional heat recovery methods. TPV technology is currently finding its use in industrial [8], automotive [6] and residential [9] sectors.

The emitted waste heat radiation has a wide range of temperatures and for efficient conversion by TPV systems, the radiation spectrum should be matched to the bandgap of the PV cell. For low temperature emissions, lower bandgap PV cells can harvest more photons and generate electron-hole pairs and vice versa which is mainly dependent on the Wien’s displacement law and Planck’s radiation law. For temperatures above 1300K, PV cells having wider bandgap like silicon [10], InGaAs [11], GaSb [12] and for temperatures less than 1300K, InGaAsSb alloy lattice matched on GaSb [13] and InAs [14] have been explored making them more suitable to convert into useful electricity. Further new types of TPV solar cells [15] have been developed for higher temperatures.

In this study, we have explored the use of thermophotovoltaic cell that are optimized for the high temperature sources. We have carried out steady-state 3D modeling of a parallel plate micro combustor that uses a thermal radiation source wall at a very high temperature. The thermal radiation emitted by the combustor is further enhanced through the integration of high contrast grating structures made of silicon onto the walls of the combustor. These structures serve as selective filters, effectively optimizing the emitted radiation. This filtering mechanism redirects the radiation below the sub-bandgap wavelength back to the combustion source, resulting in a notable increase in combustion efficiency. Owing to its high emissivity, silicon carbide (SiC) porous foam is further placed between the combustor walls to improve radiant energy. Further, one of the quartz walls is replaced with a reflector element so that radiation is emitted only on one side of the combustor, which reduces the effective PV cell material needed for TPV conversion.

NUMERICAL MODELLING

The numerical modelling details are provided in our previous work [16] which is steady-state model to analyse the performance of a parallel plate micro combustor system as shown in Figure 2.

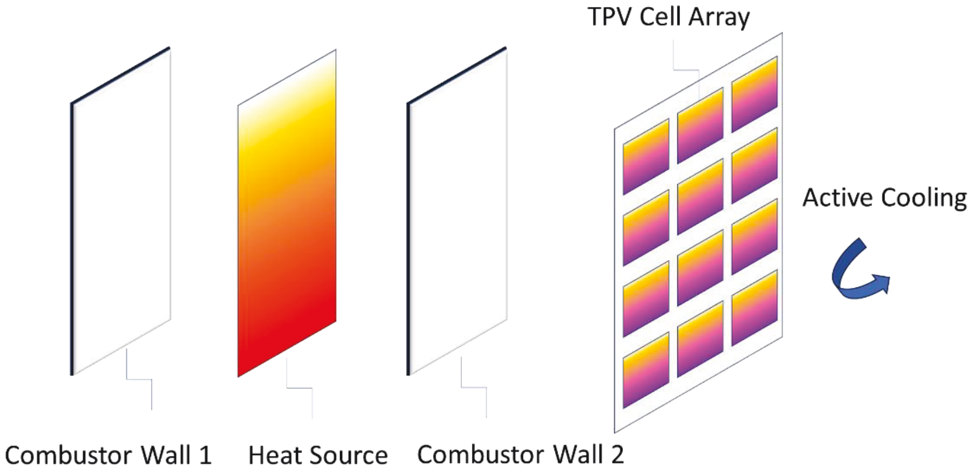

Figure 2 Geometric model of parallel plate micro combustor.

It consists of two combustor walls separated by gap. To convert the heat radiated from the combustor walls, a photovoltaic (PV) cell is placed, as shown in Figure 2. The governing equation for the heat transfer in solid interface for stationary conditions is given by Eq. 1

$$\nabla . q + \rho C_p (u_{trans} . \nabla T) = Q \quad (1)$$

where ρ is the density, C_p is the specific heat capacity at constant pressure, T is the absolute temperature, u is the velocity vector of translational motion, q is the heat flux by conduction, Q is the volumetric heat source.

The convective heat flux coefficient is governed by Eq. 2 and Eq. 3 for the stationary conditions.

$$-n . q = q_o \quad (2)$$

$$q_o = h\,(T_{ext} - T) \quad (3)$$

The surface-to-surface radiation physics is used to model the heat transfer between the combustor walls and the PV cell boundary surfaces, and the corresponding equation is given by Eq. 4.

$$J = \varepsilon e_b(T) + \rho_d G \quad (4)$$

The ray shooting method of surface-to-surface radiation physics is used with a wavelength dependent radiative property. A semi-transparent surface with a multiple spectral band is considered to account for the combustor walls reflection, transmission, and emission. The governing equation is given by Eq. 5.

$$\varepsilon_i + \rho_{d,i} + \rho_{s,i} + \tau_i = 1 \quad (5)$$

For the PV cell front surface, the diffuse surface properties are chosen with a boundary heat source. The PV cells converts a fraction of irradiation to electricity instead of heat. Heat sinks on the inner boundaries simulate this effect by accounting for a boundary heat source, q, defined by Eq. 6

$$q = -G\eta_{PV} \tag{6}$$

where η_{PV} is the efficiency of photovoltaic cell and is given by Eq. 7. For simplification purposes we assume a low efficiency of 20% maximum that can be achieved by our TPV cell. This value can be adjusted to higher numbers based on the type of TPV cell used.

$$\eta_{PV} = \begin{cases} 0.2\left[1-\left(\frac{T}{800\ K}-1\right)^{2}\right], & T \leq 1600\ K \\ 0 \qquad\qquad , & T > 1600\ K \end{cases} \tag{7}$$

For cooling purposes, the back surface of the PV cell is given a boundary heat source condition to dissipate the heat at a rate provided by Eq. 8.

$$Q_b = h_{cool} * (T_{cool} - T) \tag{8}$$

POWER ENHANCEMENT TECHNIQUES

High Contrast gratings

The latest research is focused on improving the efficiency of the TPV systems by tailoring the spectral shape of the radiation using selective emitters and filters. Figure 3 shows the schematic of the High Contrast Grating (HCG) based filter using amorphous silicon as a grating material on a quartz substrate. Simulations are optimized using Rigorous Coupled Wave Analysis technique in Grating Solver Development Co. software (Gsolver V5.2) to inhibit the transmission of the sub-bandgap photons by optimizing the grating parameters. For the blackbody temperature >2000 K, the majority of the radiation lies below 1.8 µm, therefore HCG structures are explored to filter radiation above 1.8 µm. Quartz because of its inherent nature does not allow the transmission above 4.5 µm, while gratings parameters (period (Λ) = 2.4 µm, duty cycle (a/Λ) = 0.4 and thickness (tg) = 600 nm) are optimized to further inhibit the transmission above 1.8 µm. Therefore, the filter reflects the radiation above 1.8 µm and contributes to the increase in source temperature due to photon recycling. These grating can be placed between the combustor walls and the TPV cells. Figure 4 shows the schematic of the operating principle of TPV with the integration of spectrally selective components.

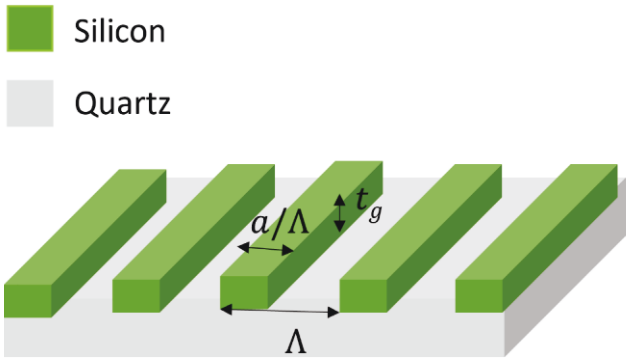

Figure 3 One-dimensional high contrast amorphous silicon gratings on quartz substrate

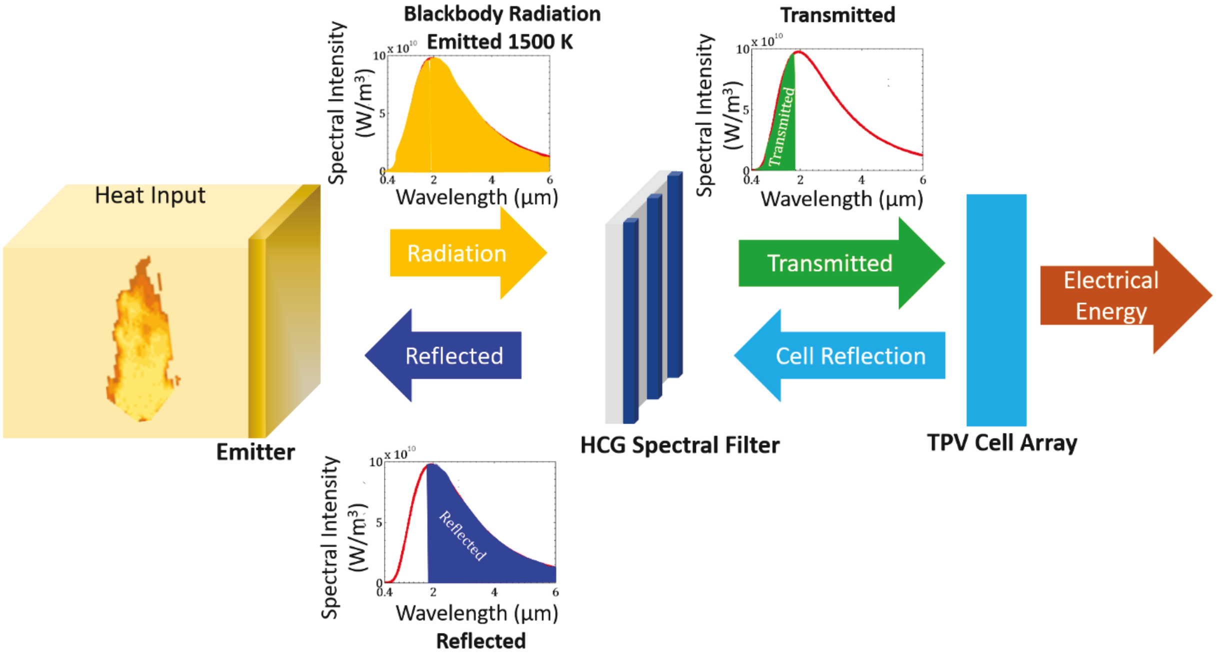

Figure 4 High contrast gratings as a spectral filter for TPV

To minimize the transmission of sub-bandgap photons, the gratings parameters (Λ, s, and tg) with respect to wavelength for a-Si are optimized. Here the grating period is chosen as 2.4 µm and the thickness of the grating is varied with respect to wavelength at duty cycles (DC) of 0.3, 0.4 and 0.5. The corresponding contour plots are as shown in Figure 5.

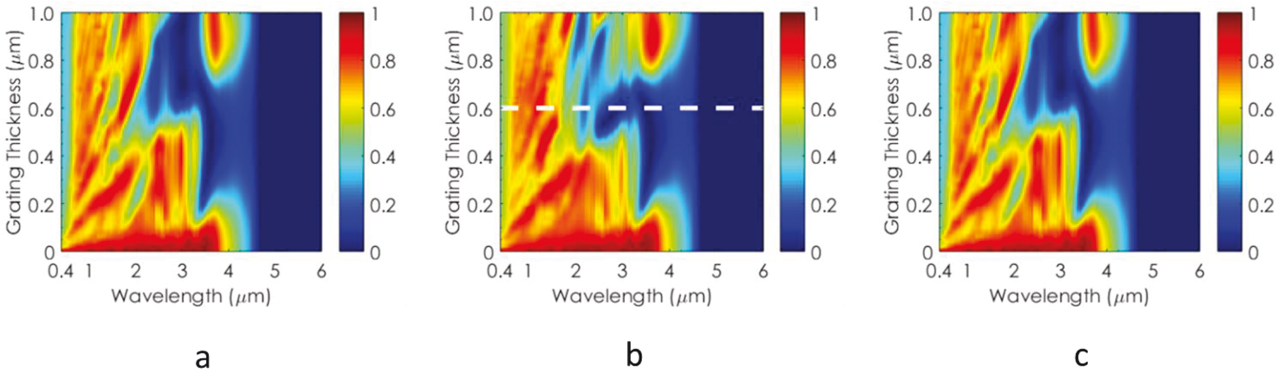

Figure 5 Contour plots of transmission spectrum for grating period of Λ = 2.4 µm. a) DC = 0.3 b) DC = 0.4 c) DC = 0.5.

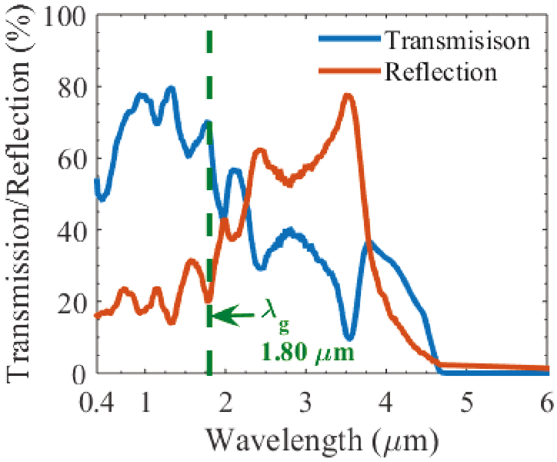

Figure 6 Transmission and reflection spectrum of optimized HCG filter with grating parameters: Λ = 2.4 µm, a/Λ = 0.4, tg = 600 nm.

Porous media

One of the effective methods to further improve the power output of such systems is to insert porous media as it increased the heat transferred to the emitter walls from high-temperature combustion products. In addition, the porous media also increases the contact area, leading to high wall temperature, resulting in an enhancement of radiant energy. In this study we have explored the use of a silicon carbide (SiC) porous foam that is placed between the combustor walls to improve radiant energy.

Reflective walls

For further enhancement we one of the quartz walls is replaced with a reflector element so that radiation is emitted only on one side of the combustor, which reduces the effective PV cell material needed for TPV conversion and improves the energy generation.

RESULTS AND DISCUSSION

The parametric study simulations are carried out for various input source temperature with porous foam, HCG filter onto the quartz walls of the developed micro-combustor model and the performance is evaluated. The details are discussed in the further sub-sections.

a) Source temperature variation on Quartz substrate

For these studies, the combustor walls are taken as quartz substrates and the input source temperature in the range of 2100 K to 2800 K. The output power density is evaluated for each of the input temperature within the wavelength range of 0.4 µm – 1.8 µm as shown in Figure 7.

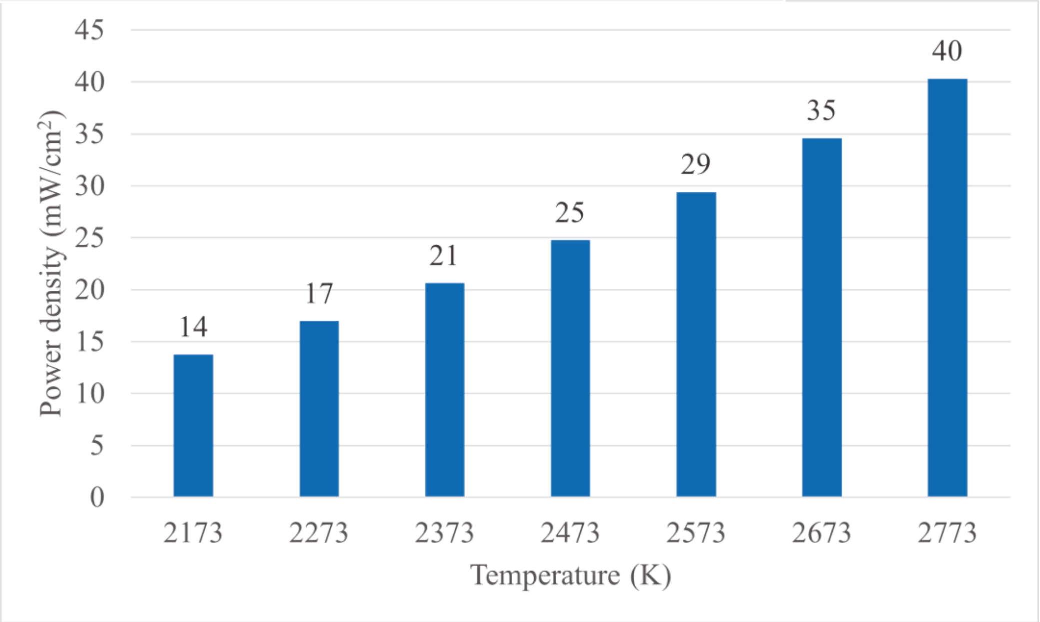

Figure 7 Input source temperature versus power density for quartz substrate

b) Quartz substrate with porous foam

One of the effective methods to improve the power output of TPV is by using porous media material in micro-combustion [17-18]. The porous media material has strong thermal interaction with the flame, i.e it can store the heat and therefore reduces heat losses from the combustor surface. Figure 8 shows the improvement in the power density for the temperature range of 2100 – 2800 K. It can be observed that there is an improvement in the power density with almost by factor of 6.5 times (at a temperature of 2773 K) in comparison to Figure 5 due to high emissivity of the SiC porous foam and because of its strong thermal interaction with the flame.

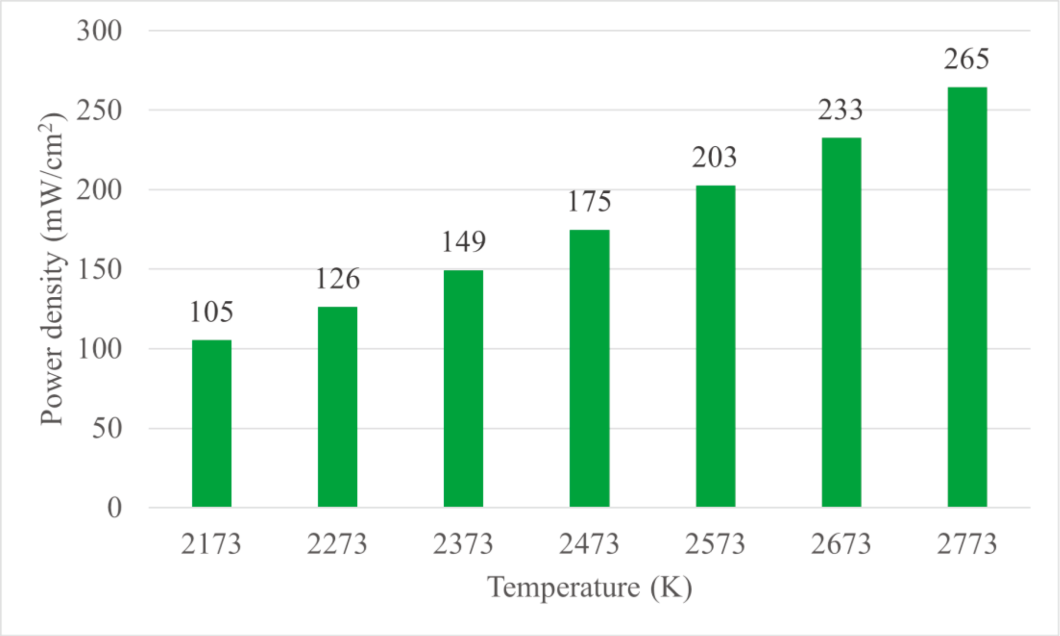

Figure 8 : Input source temperature versus power density for quartz substrate + porous foam

c) Quartz substrate with porous foam and high contrast grating filter

High contrast gratings integrated on to the quartz combustor walls tailors the spectral radiation that is emitted from the combustor surface. Figure 9 shows the output power density of the PV cell for the given input source temperature range of 2100 K – 2800 K. The power density output shown in Figure 9 has incremented by approximately 1.5 times in comparison to Figure 8 (at a temperature of 2773 K). This increment in power output is due to increase in temperature of the combustor wall due to reflection of sub-band gap energy from being transmitted. Therefore, HCG plays a significant role in up-conversion of low energy photons and enhances the combustion leading to high wall temperature resulting in increased power output.

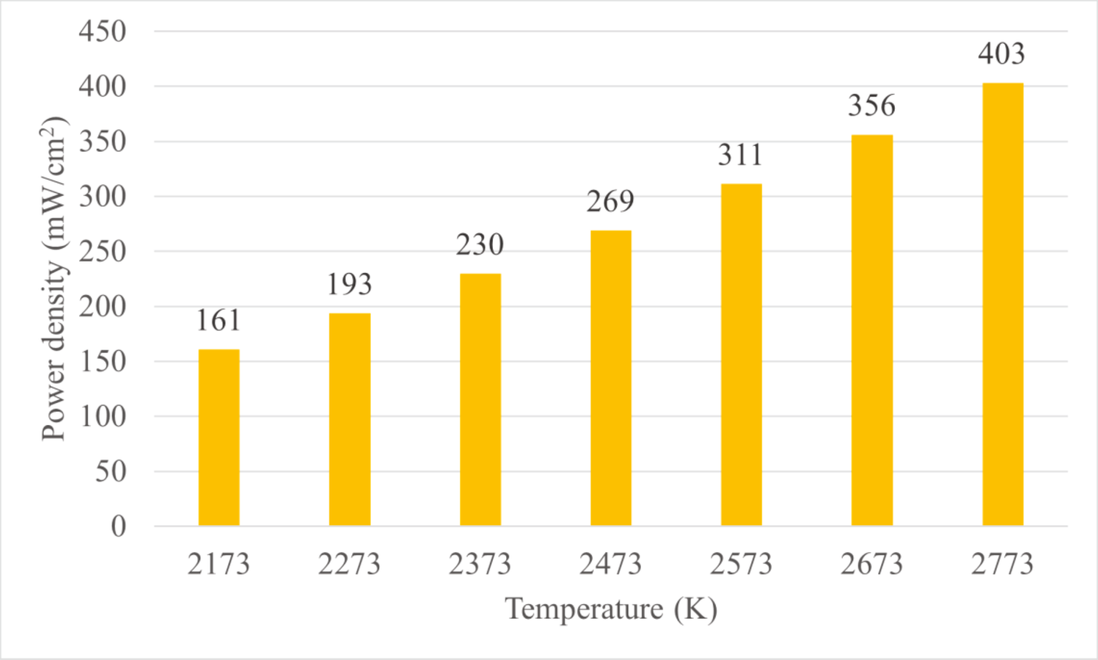

Figure 9 Input source temperature versus power density for quartz substrate + porous foam + high contrast gratings

d) Quartz substrate with porous foam, high contrast grating and a reflector

The developed numerical model uses a parallel plate combustor using quartz as combustor walls on both sides. Therefore, power is radiated on both sides and an additional PV cell needs to be used to capture the radiation on the other side of the combustor. Instead, to avoid the usage of additional PV cell material, a reflector element is placed replacing one of the quartz walls, so that the entire power will be radiated on to one side of the combustor. Figure 10 shows the power density output for the given input source temperature ranging from 2100 K – 2800 K.

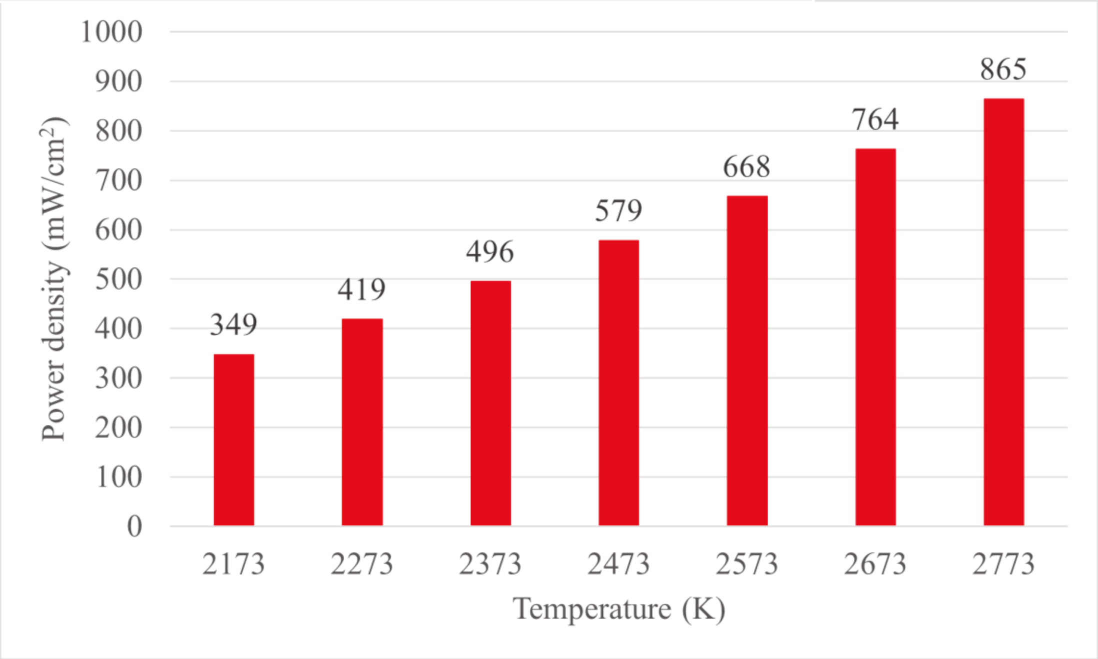

Figure 10 Input source temperature versus power density for quartz substrate + porous foam + high contrast gratings + reflector

It can be observed that in comparison to the Figure 9, the power obtained with the reflector has doubled. This is due to the reflector element that is blocking the radiation to emit from the other side of the combustor.

e) Overall enhancement of micro combustor TPV system

Beginning with basic configuration of quartz based parallel plate micro combustor, the methods to improve TPV power output are explored by using SiC porous foam, high contrast grating structures and reflector elements. The overall improvement in the power output and the increase in the temperature are shown in Figure 9. For the temperature of 2773 K, the TPV power is 40 mW/cm^2 (only quartz), 265 mW/cm^2 (quartz + SiC), 403 mW/cm^2 (quartz + SiC + HCG) and 865 mW/cm^2 (quartz + SiC + HCG + reflector), i.e. an improvement factor of 22 which is due to increase in the quartz wall temperature.

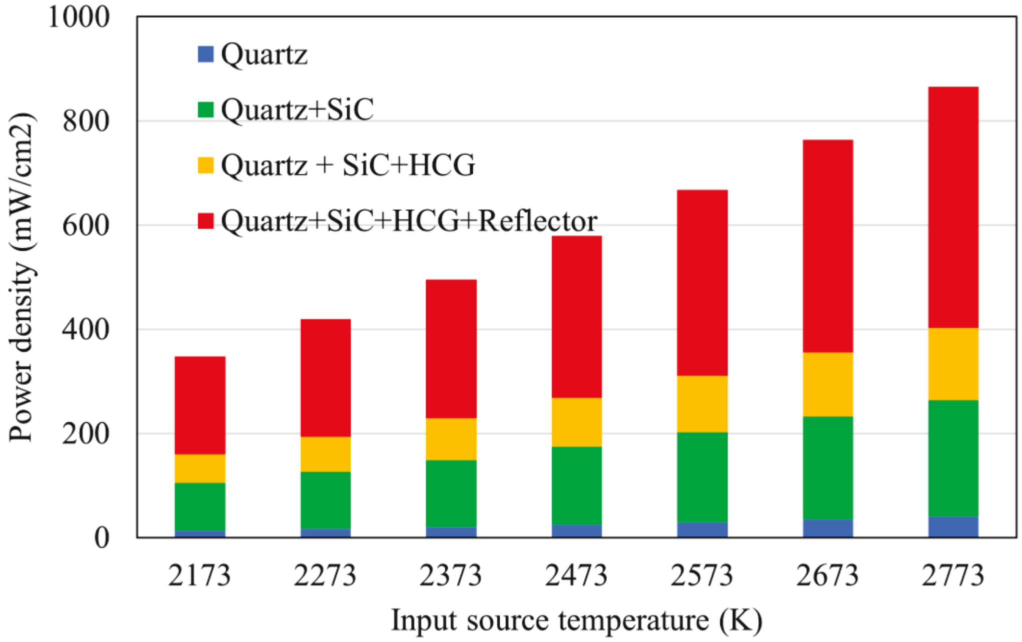

Figure 11 Overall enhancement of the micro combustor TPV system due to incorporation of SiC porous material, HCG gratings and reflector element

CONCLUSIONS

In this work, a steady-state three-dimensional heat transfer modeling is done for a parallel plate micro-combustor along with a PV cell. The modeling is done by considering all the material properties of the combustor walls, PV cell, SiC porous foam, high contrast grating, and reflector surface. We find that the low band tandem band PV cells integrated with high contrast grating based filters provide a high-power density. The combination is better suited to extract waste heat energy from industries like glass, cement etc. where the heat is being lost to the environment. The power density improvement for TPV cells (with porous foam, HCG, reflector) is approximately by a factor of 10 in comparison to the standard configuration when using only TPV cells.

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