Thermophotovoltaic applications in waste heat recovery systems: example of GaSb cell

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Abstract
In this study, it is aimed at evaluating real data in high temperature GaSb cell thermophotovoltaic (TPV) systems. The TPV systems are considered as an alternative energy source in terms of efficient use of waste heat, cost and efficiency. The TPV system can be defined as a system that converts waste heat energy emitted from heat sources into electrical energy at high temperature. In this context, efficiency and parameters of TPV GaSb cells have been determined in laboratory conditions. The conversion of the high temperature applied to the cell to electrical energy has been investigated by selecting the GaSb photovoltaic cell as the cell type. According to the analysis have been done so far, TPV high-temperature real graphics have been obtained using GaSb cell. The temperature parameters used are, namely, cell temperature and source temperature. With these graphs, energy efficiency, fill factor, effect of open-circuit voltage and short-circuit current values have been determined. While the efficiency value of the GaSb TPV cell systems was calculated, the radiation source temperature values have been taken in increments of 300 K between 1300 and 3100 K. In this analysis, the optimum energy conversion efficiency values of GaSb solar cell structure have been detected to be 21.57%. Opinions about the feasibility, efficiency and development of thermophotovoltaic energy conversion systems are stated, and suggestions are presented.

Keywords: thermophotovoltaic; waste heat; photovoltaic cell; GaSb cell; electricity generation; real data analysis

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1 INTRODUCTION
The increase in energy consumption causing shortening the life span of fossil energy sources and damaging the environment have contributed to search for new energy sources in the world, also to accelerate the search for maximum energy efficiency obtained from the used energy sources. In industrial systems, waste heat comes into play in the production phase. Waste heat is the low-grade energy heat generated by the work done in the system. Systems such as machines, ovens and stoves emit the heat for the duration of their work. Waste heat has been obtained during production phase from the furnace, from the heater (oven wall, stove etc.) and from the flue gas [1–4].

Waste heat recovery paths may vary depending on the industry. Waste heat recovery paths include heat exchangers, recuperators, heat boilers, passive air heaters, regenerative and economisers [5, 6]. Heat exchangers are often used to transfer exhaust gases to the combustion air entering the furnace. Recuperators are heat exchangers where the waste heat from the flue gas is transferred to the combustion air. Waste heat boilers are placed in front of the hot gas and the water is heated by utilizing the energy of the waste hot gas. Passive air heaters are devices that perform heat recovery from gas for low and medium temperature applications [7]. Economizers are used to recover heat from the exhaust gases used to heat liquids at low and medium temperatures. In addition to this system, the use of thermoelectric and thermophotovoltaic (TPV) systems for electricity generation has become widespread [8–11]. While thermoelectric systems work by direct heat conversion of heat, TPV systems aim to generate electricity by radiation.

The applications of TPV are residential [12], automotive [5], industrial [1, 7] and so on. It is seen that it has entered the sectors and brought an alternative to electricity generation. Electricity generation is possible by using existing waste heat in thermal systems. In industrial systems, the waste heat from the production...
phase recovered to the system and transformed into thermal energy electricity by TPV systems. Thus, electricity production from high-temperature waste heat is carried out, contributing to the current generation of electricity as clean and renewable energy. This method offers an alternative energy source in terms of cost, efficient use of waste heat and energy saving; at the same time, it is regarded as an environmentally friendly production model by reducing greenhouse effect. The discovery of TPV dates back to about 1956 [13]. Most of the related studies in the literature refers to Aigrain as a miracle of the TPV, which proposed the concept in several conferences in 1956 at MIT [14, 15]. Nelson has been informed by Kolm about a TPV system and a publication entitled ‘Power supply for solar batteries’ [16]. Until the mid-1970s, research in the United States focused on low-noise, independent military electric generators using fossil fuels as heat sources. In this period, three basic heat sources (solar, nuclear and combustion) and spectral control options (selective radiator, filter, PV cell front and rear surface reflector) have been described [16–18]. Industrial waste heat recovery using TPV conversion was proposed by Coutts at the end of 1990s [19]. In addition, at the end of the 1990s, basic research on the near field TPV started. From the beginning of the 2000s, the development of miniature TPV generators <10 W of electrical power has been accelerated [20–21]. Moreover, many theoretical studies have been carried out within the scope of the theoretical and experimental investigation of electricity generation by TPV system from low-medium-high grade temperature waste heat made by Utlu et al. [1, 2, 7, 22–24]. The experimental results of the system have been shared for the first time in order to determine the validity of existing theoretical studies. Within the scope of the literature examined, it is seen that studies on TPV applications increased and made a remarkable contribution to energy transformation and efficiency.

This paper is outlined as follows. Section 2 presents basic principles of TPV system. Section 3 determines the experimental analysis of TPV systems. Section 4 presents the results and discussion of the analysed system. Section 5 summarizes the study overall by reaching to a conclusion and provides suggestions for possible future researches.

2 MODELING OF TPV SYSTEMS

TPV systems are systems that convert thermal energy into electrical energy. These systems are an alternative to current electrical energy production. In this system, heat source, selective emitter, filters and photovoltaic cells are among the main components [25, 26]. In TPV systems, the sun can be used as a heat source as well as other heat sources such as combustion systems and fuels. The heat source is used to obtain photons in TPV systems. While the selective emitter is used to increase the system efficiency, the filter sends back the selective emitter by reflecting back the non-energized radiation. Photovoltaic cells convert photon energy from the emitter into electricity energy. TPV systems, which are considered as alternatives to the existing electricity generation, are cycles that generate electricity from heat and provide waste heat recycling. Figure 1 demonstrates general structure of TPV system.

2.1 Heat source

The heat source is the source of photons. Heat sources with operating temperatures between 1000 and 3000 K can be used in TPV systems [25]. These sources include sunlight, radioactive isotopes (β -photons) and flaming combustion. The heat energy from the heat source passes through the selective emitter, filter and cells by radiation. The heat source comes from the photovoltaic cells and allows photons to be obtained. Temperatures values of waste heat that is obtained from industrial sector, especially iron and steel processes, are suitable for TPV systems.

2.2 Selective emitter

The system is used to increase system efficiency. The selective emitter converts heat into the emission spectrum by providing the appropriate receiver cell sensitivity before transferring to the filters since the receiving cells can only use an energy absorber above the band spacing that leads to less electricity generation [9].

A Selective emitter is a body that emits all its radiation in a narrow wavelength range well matched to the receiver band gap wavelength. This idea has become reasonable since it was shown, at the beginning of the past decade, that a thermal radiation very different from that of a blackbody could be obtained, and that its spectral and directional control was possible [27]. Several authors focused on this kind of emitters and proposed genuine solutions based on 1D photonic crystals [28], single-defect photonic crystals [29] or random multilayer structures [30]. Others proposed solutions based on 2D and 3D nanostructured materials [31]. However, all these structures are still too complex to consider as an industrial process since they are composed of a large number of layers or necessitate a complex surface nanostructuring. Simpler structures based on resonant cavities have also been demonstrated in Figure 2 [32, 33].

Selective emitters radiate photons in a specific wavelength band that is spectrally matched to PV cells and increase the efficiency of the system. Yb2O3 can be used as the selective emitter. Furthermore, various spectral selective emitters such as earth selective emitter and micro structure emitter can be used. Also, selective
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2.3 Filter
In the absence of ideal emitters emitting photons only in a narrow band of energies slightly above the band gap of given photocells, one may utilize selective filters to reflect sub-band gap radiation back to the emitter. Some of these photons are absorbed by the emitter and reradiated with energies above the photocell band gap energy, hence increasing the spectral efficiency of the TPV device. Optical filters may also be used to reflect some of the excessively energetic photons back to the emitter to reduce the thermalisation losses in photocells and hence to further increase the overall efficiency of the TPV system. Similar photon-recycling features may also be created by back reflectors or other built-in optical components to increase the global efficiency of a TPV system [36].

The photons from the selective emitter reach the filter before they reach the cells. The filters have the same characteristics as the selective emitter: reflects non-energized radiation and sends the selective emitter back. Thus, the efficiency of the system increases [11].

2.4 Photovoltaic cells
Photovoltaic cells absorb photons from the emitter and convert them into thermal energy and/or electrical energy. The necessity of absorbing as many photons as possible obligates the use of materials with low band gap [26].

In general, GaAs and InGaAsSb cells are used. The bandwidths of these semiconductor materials are different from one another. The GaAs band gap equals 0.72 eV. This band gap has a very large scale for optimum efficiency and energy. In addition to these cells, GaSb and InGaAsSb are formed by forming quaternary alloys. GaSb has a band gap of 0.72 eV, which is a very narrow band gap. InGaAsSb can be adjusted between 0.38 and 0.55 eV depending on the ratio of the elements.

In this study GaSb cells have been selected for TPV modelling. The band spacing of these cells is suitable for study. The GaSb cells are connected in series and placed on the inner surface of the cooling system. Construction of GaSb cell is shown in Figure 3.

2.5 Working mechanism of TPV system
The working mechanism of TPV system shows in the Figure 4.

- The thermal energy (photons) obtained from the heat source (waste heat) is transferred to the selective emitter by radiation.
- The selective emitter translates the incoming heat to the appropriate emission spectrum to increase the efficiency of the system. A selective emitter is used to increase the amount of electricity generated.
- The photons passing through the selective diffuser pass through the filters.
- Filters have a feature like a selective emitter. The filter sends back the selective emitter by reflecting the non-energized radiation. Thus, the system efficiency is increased.
- The radiation from the selective emitter has enough energy to reach the cells. Filters also help to protect the selective emitter's temperature.
- Photons with sufficient energy come from photovoltaic cells and are converted directly into electricity.

Figure 5 is a schematic representation of the TPV system. Fuel is used as heat source in Figure 5. The fuel mixes with the air to...
form a selective emitter. Exhaust gas is thrown out of the system. The photons emitted from the selective emitter come to the optical filter by radiation and are reflected to the selective emitter, which filters the low-energy photons. Photons, which have an appropriate band gap in terms of energy, reach the photovoltaic cell. In a photovoltaic cell, thermal energy turns into electrical energy. This electrical energy is direct current (DC). The inverter converts the DC to alternating current (AC). The coolant attached to the system maintains the temperature of the cell by reducing the overheating of the photovoltaic cell. Both the cooling system and the filter prevent the cell from overheating.

2.6 Energy analysis of TPV system

Firstly, the TPV system has been analysed in three separate regions. The first region is the thermodynamic analysis of the energy source that reaches the filter by radiation of the heat source. The second region is where the filter, selective-emitter and photovoltaic cells, considered as photovoltaic systems, take place. The third region, which is expressed as the last zone, is considered to be the part where electric energy is stored. Within-the-energy analysis of each region has been conducted, and the system has been investigated by stated below method [7, 10].

2.6.1 First region

The power input by the heat source to the system is calculated as follows:

$$P_{\text{in}} = \dot{m}_{\text{fuel}} \times LHV.$$  \hspace{1cm} (Eq.1)

The fuel charge entering the system is calculated as follows:

$$P_{\text{fuel}} = P'_{\text{GAP}} + Q_{\text{th, gas}}.$$  \hspace{1cm} (Eq.2)

The fuel efficiency of the system is the rate at which the fuel power enters the system by the heat source.

$$\eta_{\text{cc}} = \frac{P_{\text{fuel}}}{P_{\text{in}}}. \hspace{1cm} (Eq.3)$$

Fuel loss is the difference between the power input by the system heat source and the fuel output.

$$P_{\text{fuel, loss}} = P_{\text{in}} - P_{\text{fuel}}.$$  \hspace{1cm} (Eq.4)
2.6.2 Second region
The formulas for the photovoltaic system we have defined as the second region are as follows. The thermal power output from the selective emitter is defined as follows:

\[ Q_{th,\text{gas}} = m_{\text{gas}} \cdot h_{\text{gas}} - m_{\text{air}} \cdot h_{\text{air}}. \]  
(Eq.5)

Radiant power entering the optical filter is equal to the emitter surface multiplied by the radiant power density:

\[ P_{\text{rad}} = q_{\text{rad}} \cdot S_{\text{em}}. \]  
(Eq.6)

Radiant power density is expressed by Stefan–Boltzmann law:

\begin{align*}
q_{\text{rad}} &= \epsilon \cdot S_{\text{em}} \cdot 2\pi \int_{0}^{\infty} I(\lambda, T_{\text{em}}) \cdot d\lambda \\
&= \epsilon \cdot S_{\text{em}} \cdot 2\pi \int_{0}^{\infty} \frac{h c}{\lambda^5} \left[ \exp \left( \frac{h c}{\lambda k T_{\text{em}}} \right) - 1 \right]^{-1} \cdot d\lambda. \\
&= \epsilon \cdot S_{\text{em}} \cdot 2\pi \int_{0}^{\infty} \frac{h c}{\lambda^5} \left[ \exp \left( \frac{h c}{\lambda k T_{\text{em}}} \right) - 1 \right]^{-1} \cdot d\lambda. \\
\end{align*}
(Eq.7)

\( k_b = 1.380 \times 10^{-23} \text{ JK}^{-1} \) (Boltzmann constant).
\( h = 6.626 \times 10^{-34} \text{ J} \) (Planck constant).
\( c = 2.99 \times 10^8 \text{ ms}^{-1} \) (speed of light).

The radiant efficiency entering the optical filter is the ratio of radiant power to fuel power:

\[ \eta_{\text{RAD}} = \frac{P_{\text{RAD}}}{P_{\text{fuel}}}. \]  
(Eq.8)

The filter efficiency is expressed as follows:

\[ \eta_{\text{F}} = \frac{P_{\text{GAP}}}{P_{\text{GAP}}}. \]  
(Eq.9)

Spectral power from optical filter:

\[ P'_{\text{GAP}} = P_{\text{RAD}} - Q_{\text{back}} \]  
(Eq.10)

\[ P'_{\text{GAP}} = \epsilon \cdot S_{\text{em}} \cdot \int_{0}^{\infty} I(\lambda, T_{\text{em}}) \cdot \tau(\lambda) \cdot d\lambda \\
= \epsilon \cdot S_{\text{em}} \cdot \int_{0}^{\lambda} \frac{2\pi h c}{\lambda^5} \left[ \exp \left( \frac{h c}{\lambda k T_{\text{em}}} \right) - 1 \right]^{-1} \cdot \tau(\lambda) \cdot d\lambda. \]  
(Eq.11)

Spectral efficiency can be expressed as

\[ \eta_{\text{GAP}} = \frac{P'_{\text{GAP}}}{P_{\text{RAD}}}. \]  
(Eq.12)

Power entering the photovoltaic cell

\[ P_{U} = P_{\text{GAP}} - P_{\text{loss}} = P'_{\text{GAP}} - P_{\text{loss}} - P_{\text{abs}}. \]  
(Eq.13)

\( P_{\text{abs}} \) are often neglected. \( P_{\text{loss}} \) is the power loss from the optical filter to the photovoltaic cell when the spectral power passes through it. The power from the photovoltaic cell is defined as the electrical power:

\[ P_{\text{el,dc}} = V_{oc} \cdot I_{sc} \cdot FF \]  
(Eq.14)

\[ V_{oc} = \frac{k_b T_{\text{em}}}{e} \cdot \ln \left( \frac{I_L}{I_0} + 1 \right) \]  
(Eq.15)

\[ I_{sc} = e \cdot \int_{0}^{\infty} \Phi(\lambda) \cdot \text{EQE}(\lambda) \cdot d\lambda \]  
(Eq.16)

where \( \text{EQE}(\lambda) \) is the external quantum efficiency and is the photon probability value of the wavelength absorbed by the cell. \( \Phi(\lambda) \) is the photon flux. Visibility factor efficiency is the spectral ratio of the power entering the photovoltaic cell:

\[ \eta_{\text{VF}} = \frac{P_{U}}{P_{\text{GAP}}}. \]  
(Eq.17)

The efficiency of photovoltaic cell is the ratio of the electrical power to the photovoltaic cell.

\[ \eta_{\text{PV}} = \frac{P_{\text{el,dc}}}{P_{U}}. \]  
(Eq.18)

The AC efficiency of the system is expressed as follows:

\[ \eta_{\text{dc/ac}} = \frac{P_{\text{el,ac}}}{P_{\text{el,dc}}}. \]  
(Eq.19)

The overall electrical efficiency of the TPV system is equal to the product of the above stated efficiencies:

\[ \eta_{\text{EL,TPV}} = \eta_{\text{cc}} \cdot \eta_{\text{RAD}} \cdot \eta_{\text{F}} \cdot \eta_{\text{GAP}} \cdot \eta_{\text{VF}} \cdot \eta_{\text{PV}} \cdot \eta_{\text{dc/ac}}. \]  
(Eq.20)

2.6.3 Third region
The formulas for the part where the electric energy we have defined as the third region is stored and where the cooling system is located is as follows. The TPV generator is based both on the cooling circuit of the PV cells and on the heat recovery:

\[ Q_{\text{TH,HX-PV}} = (1 - \eta_{\text{PV}}) \cdot P_{U} \]  
(Eq.21)

\[ Q_{\text{TH,HX-CP}} = \epsilon \cdot \eta_{\text{cc}} \cdot (1 - \eta_{\text{RAD}} \cdot \eta_{\text{GAP}}) \cdot P_{in}. \]  
(Eq.22)
2.7 General TPV system energy efficiency

In systems where heat and power coexist as defined is ALL. TPV yield is expressed as below.

\[ \eta_{\text{ALL,TPV}} = \eta_{\text{EL,TPV}} + \eta_{\text{TH,TPV}} \]  
(Eq.23)

\[ \eta_{\text{ALL,TPV}} = \eta_{\text{cc}} \left[ \eta_{\text{RAD}} * \eta_{\text{GAP}} * \eta_{\text{F}} * \eta_{\text{PV}} * \eta_{\text{dc,ac}} + \epsilon \left( 1 - \eta_{\text{RAD}} \right) \eta_{\text{GAP}} + \left( 1 - \eta_{\text{PV}} \right) \eta_{\text{RAD}} * \eta_{\text{GAP}} * \eta_{\text{F}} * \eta_{\text{VF}} \right] \]  
(Eq.24)

3 APPLICATION OF TPV SYSTEM

Within the scope of the analysis, GaSb cell TPV solar cell structure applied to laboratories conditions with high-temperature waste heat is designed. Graphical representations of the basic parameters against cell temperature, such as open-circuit voltage (Voc), short-circuit current (Jsc), fill factor (FF) and energy conversion efficiency values (\( \eta \)), have been presented graphically depending on the changing radiationsource temperature.

In the experimental analysis of the GaSb-cell TPV system installed on the laboratories conditions, the efficiency value was calculated while the radiation source temperature values were taken in increments of 250 K between 500 and 3000 K. Cell temperature values were taken from 300 to 400 K with 25 K increments. According to the final design, the optimum energy conversion efficiency value of the GaSb solar cell structure was found to be 21.58% at \( T_{\text{source}} = 2500 \) K and at the \( T_{\text{cell}} = 300 \) K.

3.1 TPV system installation

In the experimental set-up carried out under laboratory conditions, a red wire was used as a heat source. The effects of changing source temperature on cell temperature and stress values were investigated. GaSb cell was used as the cell type. Set-up of TPV system is indicated Figure 6. GaSb cell (1), voltmeter (2), data-logger (3) and thermocouple (4) are included in the experiment apparatus. Source temperature values were taken between 1000 and 3000 K. Furthermore, the highest temperature values on the blasted wire (5) were determined by measuring with a thermal camera.

The voltmeter connected to the system shows the measured voltage values in the cell. Data loggers (data recorders) are devices that record the temperature and voltage values measured on a GaSb cell for a certain period.

In the experimental work, thermal camera that has 1.5–2% sensitivity was used as another measuring device; this value was considered in the experimental work. Thermal cameras are an imaging system that uses infrared energy (heat) that is not visible and expresses the general structure of the image with the colours and shapes that it produces based on the infrared energy. The initial temperature of the experiment was set at 300 K in order to determine the cell temperature of the source temperature change and the effect of the stress generated. These experiments are shown in Figure 7.

It is observed that the red wire used as a heat source in the experimental direction started to emit radiation at the source temperature of 750 K. A visible glow appears when the source temperature is between 1000 and 1050 K. It has been determined that when the source temperature reaches 2500 and 3000 K, the temperature of the sources joint increases.

3.2 Experimental analysis of the TPV system

GaSb cell TPV analysis was performed with the test set-up established in the laboratory conditions. The obtained radiation temperature values are 1000, 1750, 2500 and 3000 K, and the cell temperature values are 300, 325, 350, 375 and 400 K. The cell values for each radiation temperature are shown in the below-mentioned graph (Figure 8). Figure 8 shows flow dependence of different cell temperature for 1000 K radiation temperature-voltage graph.
At 1000 K radiation temperature, current densities are seen according to the changing voltage values at different cell temperatures. For example, at 350 K cell temperature, when the voltage value is 0.05 V, the current density is 0.12 A/m², whereas when the voltage value is 0.12 V, the current density drops to 0.08 A/m². At 300 K source temperature, when the voltage value is 0.10, the current density is 0.10 A/m², whereas when the voltage value is 0.25 V, the current density drops to 0.04 A/m². In this case, as the voltage increases, the current density decreases. However, Figure 9 includes flow dependence of different cell temperature for 1750 K radiation temperature-voltage graph.

At 1750 K radiation temperature, current densities are seen according to the changing voltage values at different cell temperatures. For example, at 400 K cell temperature, when the voltage value is 0.05 V, the current density is 9.8 A/m², whereas when the voltage value is 0.15 V, the current density drops to 8 A/m². In this case, as the voltage increases, the current density decreases. In other words, Figure 10 shows flow dependence of different cell temperature for 2500 K radiation temperature-voltage graph.

At 2500 K radiation temperature, current densities are seen according to the changing voltage values at different cell temperatures. For example, at 400 K cell temperature, when the voltage value is 0.1 V, the current density is 66 A/m², whereas when the voltage value is 0.2 V, the current density drops to 60 A/m². In this case, as the voltage increases, the current density decreases.

Figure 11 gives flow dependence of different cell temperature for 3000 K radiation temperature-voltage graph.

At 3000 K radiation temperature, current densities are observed according to varying voltage values at different cell temperatures. For example, at a cell temperature of 375 K, when the voltage value
is 0.1 V, the current density is 150 A/m², whereas when the voltage value is 0.3 V, the current density drops to 110 A/m². In this case, as the voltage increases, the current density decreases.

4 RESULTS AND DISCUSSION

The analysis of GaSb cell TPV systems have been compared with the behaviour of values. This value is Voc, Jsc, fill factor (FF) and energy conversion efficiency value ($\eta$), which are basic parameters against cell temperature. These values vary depending on the radiation source temperature. Effect of cell temperature change on Voc is illustrated in Figure 12.

As a result of the experimental analysis made, the relationship between cell temperature and Voc is shown depending on the changing radiation temperature. For example, when the cell temperature is 300 K at the 2000 K source temperature, the Voc decreases to 0.25 V when the cell temperature is 0.4 V, while the cell temperature is 400 K. In this case, as the cell temperature increases, the Voc decreases.

Figure 13 shows effect of cell temperature change on Jsc.

As a result of the experimental analysis made, the relationship between cell temperature and Jsc is shown depending on the changing radiation temperature. For example, when the cell temperature is 300 K at 3000 K source temperature, the Jsc is $\sim$140 A/m², while when the cell temperature is 400 K, the Jsc is $\sim$150 A/m². In this case, it is observed that the Jsc rises as the cell temperature increases.

Figure 14 includes effect of cell temperature change in fill factor.

In the experimental analysis made, the relationship between cell temperature and fill factor is shown depending on the changing radiation temperature. For example, when the cell temperature is 300 K at a 1000 K source temperature, the fill factor is $\sim$70%, while the fill factor is $\sim$40% when the cell temperature is 400 K. In this case, as the cell temperature increases, the Jsc decreases.

Figure 15 consist of effect of cell temperature change on efficiency.

As a result of the experimental analysis made, the relationship between cell temperature and energy efficiency is shown depending on the changing radiation temperature. For example, when the cell temperature is 300 K at 3000 K source temperature, the energy efficiency is $\sim$140 A/m², while when the cell temperature is 400 K, the energy efficiency is $\sim$150 A/m². In this case, it is observed that the energy efficiency rises as the cell temperature increases.
temperature is 300 K at a 1000 K source temperature, the energy efficiency is \( \sim 1.5\% \). The system efficiency has highest value at low cell temperature and high radiation temperature at the same conditions.

Figure 16 indicates depend on varying radiation temperature, efficiency graph and effect of cell temperature change on efficiency. According to the experimental analysis made, the relationship between the radiation temperature and the energy efficiency is shown depending on the changing cell temperature. For example, when the cell temperature is 300 K at the 3000 K radiation temperature, the energy efficiency is 21.29\% when the cell temperature is 400 K; the energy efficiency falls to 15\%. In this case, as the cell temperature increases, the energy efficiency decreases as depend on varying radiation temperature.

Figure 17 indicates radiation temperature and effect of cell temperature change on efficiency. According to the experimental analysis made, the relationship between the cell temperature and the energy efficiency is shown depending on the changing radiation temperature. For example, when the cell temperature is 300 K at the 3000 K radiation temperature, the energy efficiency is 21.29\% when the cell temperature is 400 K; the energy efficiency falls to 15\%. In this case, as the cell temperature increases, the energy efficiency decreases as depend on varying radiation temperature.

5 CONCLUSIONS

The TPV energy conversion system has gained great importance in terms of recovery of existing waste heat to the system and generation of electricity; saving energy and cost is ensured by saving waste heat in the system.

In this study, TPV system applied on high temperature GaSb cell has been analysed and the related data obtained.

- The optimum energy efficiency obtained as a result of the prototype result on the system is 21.57\%.
- The highest filling factor is determined as 79.39\% at the radiation temperature 3000 K and at the cell temperature 300 K, while the lowest filling factor is 71.005\% at the radiation temperature 3000 K and at the cell temperature 400 K. As the temperature of the cell increases, the Jsc decreases.
- The current density has been 206.54 A/m\(^2\) at the highest 3000 K radiation temperature but decreased to 151.90 A/m\(^2\) at 3000 K radiation temperature in experimental analysis.
- The more the cell temperature increases, the more energy efficiency reduces and vice versa.
- As the temperature of cell increases, band gap decreases; additionally, the filling factor and efficiency reduce due to increased cell temperature.
- Cooling is very important problem in the increase of TPV systems efficiency. Therefore, heat must be removed from the cell surface in the highest temperature working conditions.
- The distance between the TPV cell system and the source of radiation adversely affects the efficiency.
- The cost of TPV cells is very expensive, so it is examined at laboratory conditions.
- For the system to operate effectively, the radiation must be continuous.
- These systems can be used very effectively in industrial sectors which has high temperatures waste heat.
The TPV system installed in the laboratory conditions in accordance with the experimental analysis obtained can contribute to the current electricity production with an efficiency of $\sim 21.58\%$.

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