CHAPTER 7

THERMOPHOTOVOLTAIC SYSTEM SETUP AND ANALYSIS WITH USING GALLIUM ANTIMONIDE (GaSb) CELL IN HIGH TEMPERATURE

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INTRODUCTION

Energy is one of the most important consumption items and an indispensable civilization tool in our age. Energy consumption, which is one of the most important needs of countries with a high level of development, is constantly increasing. We have consumed energy in order for the opportunities offered by technological developments to continue in our lives (Koçali, 2016; Le & Nguyen, 2019; Wen et al., 2021; Lee et al., 2022). Energy is one of the cornerstones of civilization we have today and has been an indicator of the development (Zhang, 2021).

The most current energy production and consumption techniques, however, use energy sources that cannot be replaced by new ones. Research and development require the use of renewable and ecologically friendly energy sources (Ishaq et al, 2020; Salim & Alsyouf, 2020). The use of fossil resources in energy production is not preferred today in terms of harming the environment (Lou & Li, 2016). In this case, the fact that the use of renewable energy sources, which is the natural product of our environment, is increased day by day, instead of these energy sources, which were ignored before, and the use of which is gradually increasing with the development of the industry, the damages it causes in the way of development and industrialization are better understood day by day (Li et al, 2021; Koçali & Erçetin, 2021; Agyekum, 2021).

The principle put forward for the operation of thermophotovoltaic batteries dates to the Photovoltaic Event. The origins of TPV date back to the early 1960s. In 1839, Becquerel, for the first time, observed that the angerylum formed between electrodes immersed in electrolyte changed according to the light coming on the electrolyte and explained the Photovoltaic Phenomenon. In 1876, selenium crystals were first tested in accordance with the photovoltaic phenomenon by G. W. Adams and R. E. Day. Studies carried out in the following years enabled the use of photo diodes based on copper oxide and selenium in light meters for photography (Aigrain, 1961; White et al, 1961; Guazzoni et al, 1968; Yerebakan, 2010).

The discovery of TPV trace back to about 1956. An article is given by Nelso Un and Kolmar about TPV system that solar cells power supply (Wedlock, 1963; National Research Council, 2001; Bauer, 2011). TPV has attracted praiseworthy interest as a possible participant in a combustion-driven power generation system. Work on TPV energy generation began

irregularly in the 1960s, but because high efficiency converters are now widely available, a number of projects have noticeably advanced in the past ten years (Coutts, 1999; Coutts, 2001).

Until the mid-1970s, three main heat sources (nuclear, solar and combustion) and spectral control options (PV cell front, filter, eluent radiator, and rear surface reflector) were defined in line with research conducted in the USA (Bauer, 2011; Önal & Utlu, 2017). Due to the emergence of high-performance converters, TPV technology underwent a period of hibernation in the 1980s but has recently experienced exceptional growth (White & Hottel, 1994; Yamaguchi & Yamaguchi, 1999). Applications for TPV have been used in a wide range of fields, such as in glass processing (Bauer et al, 2003) extreme industrial temperatures (Coutts, 2001) integrated TPV and TE power system (Qui & Hayden, 2012), co-generation systems (Bianchi et al, 2012), space exploration (Teofilo et al, 2006), military devices (Nelson, 2003). The key features of TPV technology have greatly benefited continued interest in the disciplines described above. The inherent advantages of TPV systems, such as their high-power density, mobility, lightweight design, maintenance-free operation, and fuel adaptability, have boosted their acceptance in a variety of energy sectors (Coutts, 1999; Coutts, 2001). Despite not having a significant market share, the TPV power system represents a favorable environment for research and development. The discussion that follows quickly examines the fundamental ideas behind the TPV power system before presenting a thorough analysis of the technical features to guide and captivate the reader on this fascinating topic (Fraas et al, 1998; Kruger et al, 1998; Colangelo et al, 2003). High power density, fuel flexibility, mobility, silent operation, sun-independent operation, and minimal maintenance costs are some of the potential benefits of TPV. Other potential uses include large-scale recovery of high-temperature waste heat from industrial processes like the production of glass; stand-alone domestic gas furnaces; power systems for sailing boats; silent power supplies on recreational vehicles; co-generation of electricity and heat; and many others (Fraas et al, 2003; Qui & Hayden, 2003; Aicher et al, 2004).

Electrical energy can be produced from thermal infrared radiation using thermophotovoltaic (TPV) cells. Due to its many benefits and the development of low bandgap (0.50-0.74 eV) TPV cells like GaSb, GaInAs, and GaInAsSb cells, TPV energy generation is gaining technical interest (Qui & Hayden, 2003; Qui et al, 2006). In industrial systems with high temperature

waste heat recycling thermophotovoltaic applications an example of theoretical modeling has been made, and in line with the study by Utlu and Önal (2017), the efficiency of In0.2 Ga0.8 As0.18 Sb0.82 cell was higher when compared to the GaSb cell at the same source temperature. The system was divided into three low, medium and high temperature regions by Önal and Utlu (2018), and the thermodynamic analysis of the system was made.

MATERIAL AND METHODS

It is important to examine the structure of the thermophotovoltaic system within the scope of the study and to clearly reveal the formulas required for the analysis. Because the study will be among the main studies for the system installation in Turkey with the GaSb cells used in the experimental installation. For this reason, system setup for simple system setup and experimentation should be in accordance with scientific rules and international regulations.

Structure of Thermophotovoltaic System

Thermal radiation from terrestrial heat sources is converted into electricity by thermophotovoltaics (TPVs). A TPV device is made up of three major parts: a TPV cell that turns incident photons into electricity; a vacuum gap between the emitter and the cell; and an emitter that radiates photons by absorbing thermal energy from a heat source (Akhtar et al, 2015; Mustafa et al, 2016). The heat source, selective emitter, cooling system, filter, and photovoltaic cell are all included in the system. The thermal energy from the heat source is transferred to the solar cells after passing via the selective emitter and filters. In photovoltaic cells, thermal energy is transformed into electricity (Andreev et al, 2004; Andreev et al, 2005; Ferrari et al, 2014). A standard TPV setup includes a heat source (such as a flame, radiative isotope, or the sun), a radiator, a semiconductor converter, a way to recycle sub-bandgap photons to save energy, and a power conditioning system that operates at temperatures between 1000 and 1500 °C (Coutts, 1999; Coutts, 2001). Thermal energy is transformed into electrical energy as the TPV's primary operating mechanism. Thermophotovoltaic systems used for central heating have an operating temperature of 1000–1300 °C (Önal, 2017).

In thermophotovoltaic systems, not only the sun can be used as a heat source, but also the waste heat from the combustion system, fuels, and industrial processes during the production phase. In TPV systems, the heat source is utilized to produce photons, and the selective emitter is used to boost

system effectiveness. The filter reflects insufficiently energetic radiation and sends it back to the selective emitter. As opposed to this, photovoltaic cells transform the photon energy from the emitter into electrical energy. Photovoltaic cells convert solar energy into electrical and thermal energy. The obtained linear current can be converted into alternating current and electrical energy can be used in different areas (Datas & Algora, 2010; Utlu et al, 2017; Utlu & Önal, 2017; Önal, 2017; Utlu & Önal, 2018). Thermophotovoltaic systems are being investigated as an alternative to the way electricity is now produced since they produce electrical energy from heat and reuse waste heat (Fraas et al, 1998; Home et al, 2000) in Figure 1.

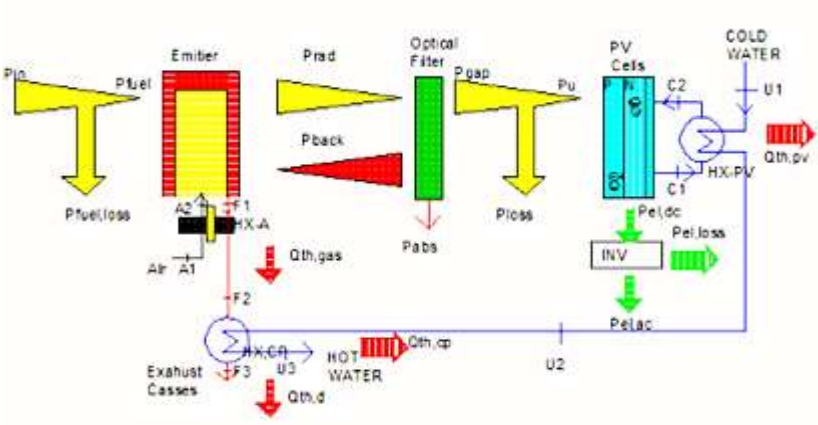


Figure 1: Schematic Representation of the TPV System

The reflector on the rear of the TPV cells, which is used to reflect low-energy photons to reheat the emitter, is how the best photon recycling technology works. In actuality, the low-energy photons are absorbed by the TPV cell material before they reach the back reflector since TPV cells are often made to a thickness of several hundred microns (Li & Xuan, 2022). The fuel enters the selective emitter and mixing with the air. The system discharges exhaust gas. Photons from the selective emitter travel with radiation to the optical filter, and low-energy photons are reflected from the filter to the selective emitter. The photovoltaic cell is reached by photons with a suitable band gap in terms of energy (Amin, 2022; Xue et al, 2022). Direct current is the type of electricity that the solar cell produces. Direct current (DC) is changed into alternating current (AC) via an inverter (converter) (AC). The system's cooler regulates the temperature of the solar cell and

keeps it from overheating. The filter also stops the cell from overheating (Ouremchi et al, 2022; Hasan et al, 2021).

The behavior of values has been compared between real and theoretical analyses of thermophotovoltaic systems using GaSb cells. These values are fill factor (FF), short circuit current (Jsc), energy conversion efficiency value (η) and open circuit voltage (Vc); which are fundamental parameters versus cell temperature. These values vary linked in the radiation source temperature (Green, 1981; Fentahun et al, 2021; Herterich et al, 2022; Khaledi et al, 2022; Talbi et al, 2022):

- Fill factor (FF); It is the value found by dividing the maximum power obtained from the panel by the theoretical power found by multiplying the open-circuit voltage by the short circuit current.
- Short-circuit current (Jsc); during the short-circuit at the short-circuit point is the flowing current. It is a time-varying function in alternating current systems.
- Energy conversion efficiency (η) is the energy expression of the ratio between the useful output and input of the energy conversion. The useful output can be electrical power, mechanical power, or heat.
- Open circuit voltage (Vc); It is the voltage value of the thermophotovoltaic panel when there is no electrical load, that is when it is not producing current. This value is the voltage value used when calculating the inverter and battery. According to this value, the panels are connected in series or parallel to make them suitable for the system voltage.

In the literature, it was observed that the effect of the change in the energy efficiency of the cell temperature at different source temperatures decreased, and the cell temperature increased the energy efficiency (Utlu & Önal, 2017; Utlu & Önal, 2018). The equations used for the analysis of the thermophotovoltaic system are as follows in Table 1 (Fraas et al, 1998; Coutts, 2001; Fraas et al, 2003; Colangelo et al, 2003; Lee et al, 2005; Qui & Hayden, 2006; Qui et al, 2006; Butcher et al, 2011; Ferrari et al, 2013; Önal, 2017).

Table 1: The Equations for the Analysis

Incoming energy into the photovoltaic cell	$P_U = P_{GAP} - P_{loss} = P'_{GAP} - P_{loss} - P_{abs}$ P_{abs} is frequently ignored. P_{loss} is the term for the power lost from the photovoltaic cell to the optical filter.	(1)
Electrical power is the definition of the solar cell's power	$P_{el,dc} = V_{OC}$ x I_{SC} x FF $V_{OC} = (kbT_{em} / e)$ x ln $(I_L / I_O + 1)$ I_{SC} = e. $\int\Phi(\lambda)\, EQE(\lambda)\, d\lambda$ EQE (λ) is the external quantum efficiency of the wavelength absorbed by the cell and the photon probability value. Φ (λ) is the photon flux.	(2) (3) (4)
The overall electrical efficiency of the TPV system is equal to the multiplication of the below-mentioned efficiencies	$\eta_{EL,} = \eta_{CC}.\ \eta_{RAD}.\ \eta_{GAP}.\ \eta_{F}.\ \eta_{VF}.\ \eta_{PV}.\ \eta_{dc/ac}$	(5)
η_{CC}, the system's fuel efficiency is determined by the proportion of fuel power to heat source power entering the system.	$\eta_{CC} = P_{fuel} / P_{in}$	(6)
The ratio of radiant energy to fuel power is known as η_{RAD}, or radiant efficiency entering the optical filter.	$\eta_{RAD} = P_{RAD} / P_{fuel}$	(7)
η_{GAP} spectral efficiency	$\eta_{GAP} = P_{GAP} / P_{RAD}$	(8)
η_{F} efficiency of the filter	$\eta_{F} = P_{GAP} / P'_{RAD}$	(9)
The ratio of the power entering the solar cell to the spectral power is known as the visibility factor efficiency.	$\eta_{VF} = P_U / P_{GAP}$	(10)
The ratio of electrical energy to the power entering the solar cell is known as the photovoltaic cell efficiency.	$\eta_{PV} = P_{el,dc} / P_U$	(11)
Direct current is the type of electricity produced by the solar cell. A current inverter is used to change direct current to alternating current.	$\eta_{dc/ac} = P_{el,ac} / P_{el,dc}$	(12)

System Setup

The usage areas of GaSb cells in Turkey are quite limited and experimental studies are generally carried out. For this reason, besides the experimental and real application comparisons mentioned above, it is of great importance to specify the points to be considered during the installation of the system. Sunlight is converted using a wide range of methods, most of which are based on semiconductors. The National Renewable Energy Laboratory (NREL) tests the efficiency of various solar cell and module designs to guarantee the reliability and consistency of measurements of photovoltaic performance. While the experimental set was being set up, the user manual of the GaSb cell manufacturer was examined and compared with the manuals of other companies producing similar products in the market. Published standards regarding the established experimental set were also examined. There are 203 standards in 2018, 331 standards in 2019, and 261 standards in 2020. When the countries that published standards are examined, it is seen that China published 203, United Kingdom 164, Iran 129, Denmark 125, Netherlands 124 standards (Nanotechnology Standards, 2023).

Most of the national standards like International Labor Organization (ILO) conventions, OHSAS 18001 Occupational Health and Safety Management System (2023) are consisting of five main title which are policy, planning, implementation and operation, control and corrective action and management review. There is no specific standard published on TPV systems and nanotechnology in Turkey.

In Turkey, there are the Occupational Health and Safety Law numbered 6331 which came into force in 2012 to take Occupational Health and Safety, and the TS-18001 Occupational Health and Safety Management Systems Requirements standards by the Turkish Standards Institute. In the regulations mentioned above information about the obligations of the employer and employees, definitions about risk assessment and the responsibilities of the safety council are given. The purpose of risk assessment is to pre-determine and record the hazards that may arise from risks in the workplace, and to take precautions and work with current methods. With the works done, it is ensured that the hazards that may arise from the risks are determined in advance and Occupational Health and Occupational Safety measures are taken, and that the damages that may occur are at the minimum level or that the damage does not occur and while the risk assessment is being prepared, the identified risks are determined to be responsible for and control. Risk assessment analysis is carried out in many projects application and it

purpose is to determine in advance the negativities that may arise from the risks that may arise during the execution of the project. Aim of the identified risks is ensuring that the cost of the invested project is kept at a determined level. In addition, thanks to the risk assessment analysis prepared, taking safety measures in terms of occupational health and safety ensures that the reliability of the security measures taken is checked. Risk assessment analysis is important in the installation of energy systems. Because there are many unexpected factors during installation. The reliability of the risk assessment analysis ensures that the plant installation is completed on time and that the employees work in a healthy environment. Risk assessment analysis should be done in accordance with national and international standards and legal framework. The most important step in energy systems risk assessment analysis is the selection and calculation of the energy panels and inverters to be used in the planning phase. Because if the panel and the inverters are not compatible, even if high voltage and current are produced in the operation of the system due to the high voltage, there may be incompatibility within the legal limits. The important stages in this part are installation, commissioning, and operation of the plant. During the installation phase, electricity production begins with the placement of the panels and since the system does not work and is not connected to the grid, the electricity produced stops in the field environment. Therefore, employees are exposed to electric current and voltage. During the commissioning phase, the final tests of the plant are carried out. The most important of the tests is the grounding and leakage current protection test. When grounding and leakage current protection calculations are calculated incorrectly, excess current and voltage occur during the operation of the system. With the formation of excess current and voltage, the risk of passing over the workers is high. During the operation of the system, the annual maintenance of the plant and its control are provided by the remote monitoring system. There is also the possibility that workers or maintenance people may be exposed to high current and voltage during the cleaning of electricity generating panels. Occupational health and safety apply occupational health and safety rules, explains the purpose and importance of occupational health and safety, takes necessary precautions by listing the methods of protection from work accidents and occupational diseases, takes necessary precautions against risks arising from hazards and takes necessary measures in emergencies. Measuring physical sizes in renewable energy systems measures physical dimensions in accordance with the nature of the size by taking occupational health and safety measures. It measures the

length, area, and volume values by using a measuring device suitable for the nature of the quantity to be measured. It measures temperature with temperature measuring instruments and measures cross-section and diameter using diameter measuring tools. Measures resistance with a resistance measuring instrument and measures the inductance value with the LCR meter. Makes capacity measurement using measuring instruments, current meter with the help of ammeter and voltage meter with the help of voltmeter, frequency measures with frequency meter measuring instrument. Work and power meter with the help of counter and wattmeter. Basic operations in energy mechanics performs basic operations in energy mechanics in accordance with its technique by taking occupational health and safety measures and uses control and screw tightening tools suitable for the work piece. Uses simple cutting and shaping tools according to occupational health and safety rules. Performs surface and angle control according to the given size, using tools suitable for the job. Hand operations in energy mechanics takes occupational health and safety measures and performs hand operations in accordance with the technical drawing of the work piece. Files to bring the plane surface to the desired size and files for profile surface cleaning. Performs measurement and control in accordance with technical drawing dimensions. It makes marking to do basic operations on the work piece and performs the cutting process in accordance with the given dimensions. Drilling and screwing in energy mechanics, by taking occupational health and safety measures, performs drilling and screw operations in accordance with the given dimensions and makes hole drilling operations according to the given size by using appropriate apparatus and machine. It guides manually according to the material and the size on the work piece picture and draws a sheet by hand in accordance with the material and the size of the work piece picture and combines with screw-bolt. Mechanical parts and electrical-electronic diagram drawing, draws solar energy connection diagrams in accordance with standards by taking occupational health and safety measures. It draws panel electrical wiring diagrams in accordance with national and international standards and the mechanical parts of the panels in accordance with the different types of establishments. Fundamentals of electricity in renewable energy makes basic applications about electric current with generation and effects by taking occupational health and safety measures and uses electrical energy and resources. Makes calculations about electric current according to OHM's law. Benefit from the effects of electric current by taking occupational health and safety measures. It produces voltage according to

voltage generation methods by taking occupational health and safety measures. Fundamentals of direct current generated in cells makes circuit solutions and connections for the direct current produced in the cells by taking occupational health and safety measures. It takes the occupational health and safety measures and makes the cable connections of the GaSb batteries in accordance with the connection diagram and performs measurement and calculation processes in direct current (DA-DC) circuits. By taking occupational health and safety precautions, it makes direct current source cable connections in accordance with the Indoor Installation Regulation. Panel systems establish in accordance with the project by taking occupational health and safety measures and determines the radiation angle at the place of use with suitable measuring instruments according to the geographical location. It ensures the assembly of metal components according to the dimensions determined in the project and places the panels on the construction according to the sequence determined in the project. It makes panel cable transitions in accordance with its technique in accordance with the project and connects inter-panel and system grounding transition conductors using connection apparatus. By taking occupational health and safety measures, panel maintenance maintains the panels without interrupting the production and according to the technical specifications of the manufacturer. Controls the mounting bolts of the panel by taking occupational health and safety measures. It cleans the surface of the panels by taking occupational health and safety measures and controls the cable connections between the panels by taking occupational health and safety measures (Occupational Health and Safety Law No. 6331, 2012; Occupational Health and Safety Risk Assessment Regulation No. 28512, 2012; Regulation on Occupational Health and Safety Boards No. 28532, 2013; National Occupational Health and Safety Board Regulation No. 28550, 2013; Regulation No. 28861 on Supporting Occupational Health and Safety Services, 2013; Koçali, 2018; Koçali, 2021).

Experimental Setup

The experimental setup in the laboratory environment within the scope of the study consists of voltmeter (a), datalogger (b), GaSb cell (c) and heat source (d). Hot wire was used as a heat source in the experimental setup. As a result of opening the experimental set (f), open flame (e) was produced at the heat source (d). The temperature produced was also controlled with a thermal camera (f) to control the experimental temperature. When the desired temperature was reached, the values obtained with the voltmeter (a) and

datalogger (b) connected to the GaSb cell (c) were recorded. Dataloggers are devices that record the temperature and voltage values measured on the GaSb cell for a certain period. Figure 2 shows the entire experimental set.

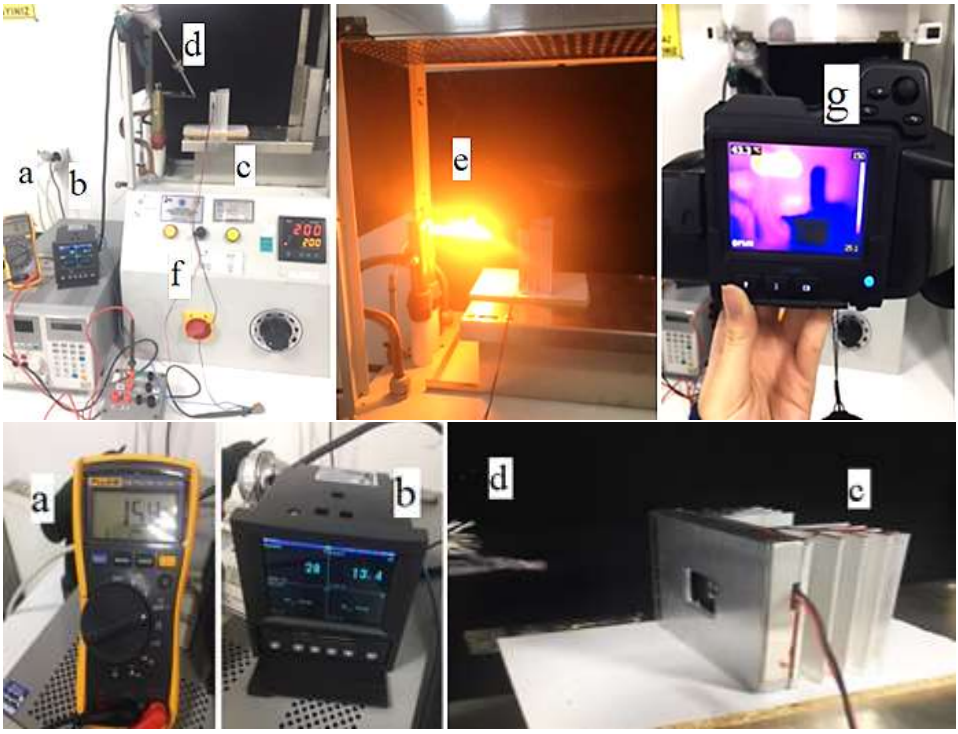


Figure 2: Experimental Study Setup

In the experimental study, a thermal camera was used as another measuring device. Thermal cameras are imaging devices that make use of infrared radiation, which cannot be seen but expresses itself as heat in the form of colors and forms that express the general structure of the image. Thermal cameras, which are non-contact measuring devices, detect the invisible infrared energy emitted by objects and display it as a thermal image on the camera screen. As seen in Figure 3, In the experiment, the highest temperatures on the hot wire were measured using a thermal camera.

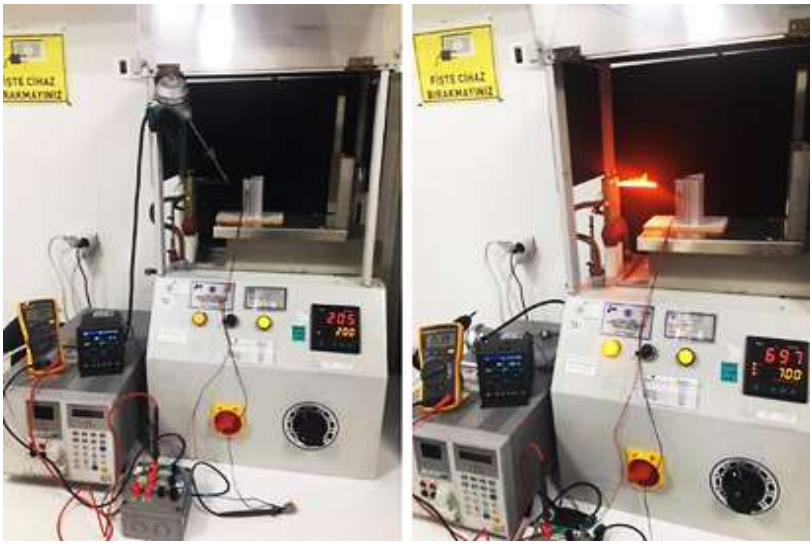


Figure 3: Voltage Values and Cell Temperature at 205 and 697 °C Source Temperature

RESULTS

As shown in Figure 3, the effect of voltage levels and varying source temperature on cell temperature was investigated using the GaSb cell type. Values for the source temperature ranged from 200°C to 1000°C. Additionally, as shown in Figure 2, the hot wire's maximum temperature values were measured using a thermal camera.

GaSb cell was used as the cell type in the thermophotovoltaic system which theoretically modeled by using high temperature waste heat. The temperature values applied on the cell are between 1000 K and 3000 K. As seen in Table 2, the optimum energy conversion efficiency value for an ideal GaSb TPV cell has been calculated as 33.15% in the analysis performed. This value is an optimal value. Table 3 and Figure 4 show the statistical results of cell efficiency (%) values obtained depending on radiation and cell temperature at theoretical analysis.

Table 2: Cell Efficiency (%) Values Obtained as Depend on Radiation and Cell Temperature of Thermophotovoltaic Systems at Theoretical Analysis

Cell temperature Radiation temperature	300 K	325 K	350 K	375 K	400 K
1000 K	24.02	18.27	12.74	7.73	3.80
1250 K	28.41	23.15	17.89	12.86	8.25
1500 K	30.89	25.99	21.11	16.30	11.72
1750 K	32.25	27.68	23.11	18.58	14.16
2000 K	32.93	28.65	24.35	20.07	15.86

2250 K	**33.15**	29.13	25.08	21.03	17.03
2500 K	33.08	29.28	25.45	21.62	17.81
2750 K	32.81	29.21	25.58	21.94	18.32
3000 K	32.40	28.98	25.53	22.07	18.62

The correlation obtained as a result of the error analysis made with the OriginPro 2021 software is as follows:

$$y = Intercept \sum_{i=0}^{n} A_i . x^i \quad (13)$$

The correlation obtained when analyzing using five different cell temperatures is as follows:

$$y = A_0 + (A_1.x) + (A_2.x^2) + (A_3.x^3) + (A_4.x^4) + (A_5.x^5) \quad (14)$$

According to actual analysis, the relationship between energy efficiency and radiation temperature is demonstrated dependent on the fluctuating cell temperature. For instance, the energy efficiency is 9.68% when the radiation temperature is 2000 K and the cell temperature is 400 K. In the statistical calculations, in Table 3, it was calculated that the error rate at 300 K temperature was the lowest. It was found to be 99.99% related to 2250 K radiation temperature. It is demonstrated in this instance that energy efficiency rises as radiation temperature rises.

Table 3: Statistical Results of Cell Efficiency (%) Values Obtained Depending on Radiation and Cell Temperature (Theoretical Analysis)

Cell temperature	300 K	325 K	350 K	375 K	400 K
Number of points	9	9	9	9	9
Residual sum of residual	4.50E-04	9.62E-04	1.15E-04	3.90E-06	0.00168
R-Square (COD)	0.99999	0.99999	0.99999	0.99999	0.99999
Adj. R-square	0.99998	0.99998	0.99999	0.99999	0.99998
Sum of squares	0.03178	0.03538	0.03941	0.04459	0.04998
Mean square	0.00636	0.00708	0.00788	0.00892	0.01
F value	1136.25	1156.47	2158.39	3589.91	1593.2
Prob>F	4.11E-05	4.00E-05	1.57E-05	7.34E-06	2.47E-05

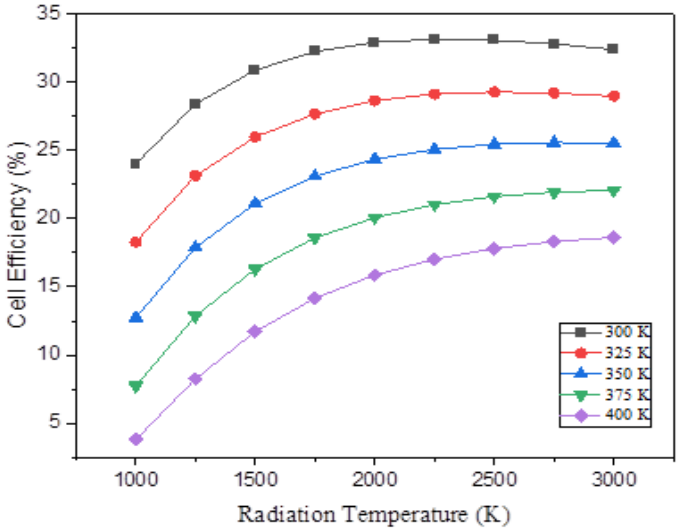


Figure 4: Cell Efficiency (%) Values Obtained as Depend on Radiation and Cell Temperature (Theoretical Analysis)

Table 4 shows that the optimal energy conversion efficiency of the GaSb solar cell structure has been determined to be 21.57%, according to the final design, in the real (lossy) analysis of the GaSb-cell TPV system installed on the final design. Table 5 and Figure 5 show the statistical results of cell efficiency (%) values obtained depending on radiation and cell temperature at real analysis. In the statistical calculations, in Table 5, it was calculated that the error rate at 300 K cell temperature was the lowest. It was found that there is a 99.99% correlation with 2500 K radiation temperature.

Table 4: Cell Efficiency (%) Values Obtained as Depend on Radiation and Cell Temperature of Thermophotovoltaic Systems at Real Analysis

Cell temperature Radiation temperature	300 K	325 K	350 K	375 K	400 K
1000 K	14.43	10.62	7.02	3.91	1.71
1250 K	17.62	14.05	10.57	7.29	4.40
1500 K	19.51	16.17	12.89	9.70	6.72
1750 K	20.61	17.49	14.39	11.36	8.44
2000 K	21.23	18.29	15.37	12.48	9.68
2250 K	21.51	18.74	15.98	13.24	10.57
2500 K	**21.57**	18.95	16.33	13.74	11.18
2750 K	21.48	19.00	16.51	14.04	11.61
3000 K	21.29	18.92	16.56	14.21	11.89

Table 5: Statistical Results of Cell Efficiency (%) Values Obtained Depending on Radiation and Cell Temperature (Real Analysis)

Cell temperature	300 K	325 K	350 K	375 K	400 K
Number of points	9	9	9	9	9
Residual sum of residual	9.90E-05	1.95E-04	7.94E-05	6.12E-04	0.0013
R-Square (COD)	0.99997	0.99999	0.99999	0.99999	0.99999
Adj. R-square	0.99999	0.99999	0.99999	0.99998	0.99997
Sum of squares	47.32012	66.45043	85.93328	99.13671	99.99875
Mean square	9.46402	13.29009	17.18666	20.02734	98041.77
F value	286761.6	204352.9	649133.5	20.01974	46257.46
Prob>F	1.03E-08	1.71E-08	3.02E-09	5.14E-08	1.59E-07

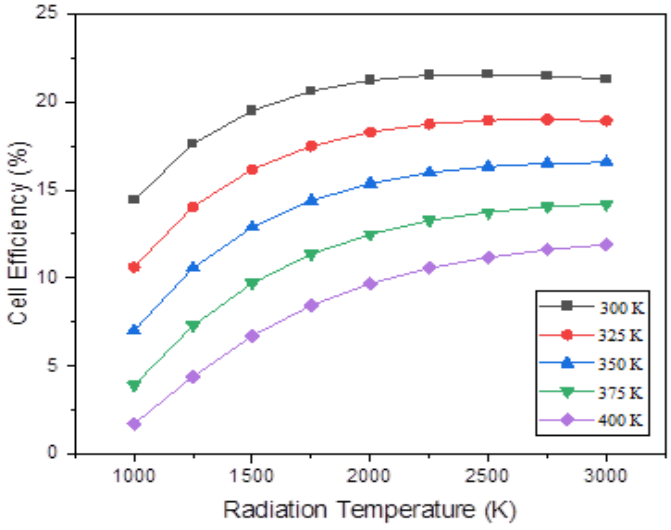


Figure 5: Cell efficiency (%) Values Obtained as Depend on Radiation and Cell Temperature (Real Analysis)

According to the shifting radiation temperature in the theoretical analysis, fill factor, short circuit current, open circuit voltage, and energy conversion efficiency values were determined and displayed in Table 11. According to Table 7, the real (lossy) analysis's highest open circuit voltage was 0.44 V at the 3000 K radiation temperature. In the statistical calculations in Table 8, the error rate at 300 K temperature was calculated to be the lowest. It was found to be 99.99% related to 3000 K radiation temperature. Table 8 and Figure 6 show the statistical results of temperature-dependent variation of open circuit voltage (v) values obtained in real (lossy) analysis.

Table 6: Variable Parameter Values Dependent on Radiation Temperature in Theoretical Analysis

Radiation temperature	V_{OC} (V)	J_{SC} (A/m^2)	FF (%)	η (%)
1000 K	0.28	0.16	71.00	24.02
1250 K	0.33	0.17	73.83	28.41
1500 K	0.33	4.52	75.53	30.89
1750 K	0.39	12.38	76.66	32.25
2000 K	0.41	27.21	77.52	32.93
2250 K	0.42	51.58	78.23	33.15
2500 K	0.44	87.99	79.03	33.08
2750 K	0.45	**138.87**	78.68	32.81
3000 K	0.46	206.53	79.39	32.40

Table 7: Temperature-dependent Variation of Open Circuit Voltage (V) Values Obtained in Real (Lossy) Analysis

Cell temperature Radiation temperature	300 K	325 K	350 K	375 K	400 K
1000 K	0.25	0.20	0.15	0.10	0.05
1250 K	0.31	0.26	0.21	0.16	0.11
1500 K	0.34	0.29	0.25	0.20	0.15
1750 K	0.37	0.32	0.28	0.23	0.19
2000 K	0.39	0.34	0.30	0.26	0.22
2250 K	0.41	0.36	0.32	0.28	0.24
2500 K	0.42	0.38	0.34	0.30	0.26
2750 K	0.43	0.39	0.35	0.31	0.27
3000 K	**0.44**	0.40	0.36	0.32	0.28

Table 8: Statistical Results of Temperature-Dependent Variation of Open Circuit Voltage (V) Values Obtained in Real (Lossy) Analysis

Cell temperature	300 K	325 K	350 K	375 K	400 K
Number of points	9	9	9	9	9
Residual sum of residual	1.67E-05	1.83E-05	1.09E-05	7.45E-06	1.88E-05
R-Square (COD)	0.99947	0.99948	0.99972	0.99983	0.99962
Adj. R-square	0.99859	0.99862	0.99926	0.99955	0.99999
Sum of squares	0.03178	0.03538	0.03941	0.04459	0.04998
Mean square	0.00636	0.00708	0.00788	0.00892	0.01
F value	1136.25	1156.474	2158.3957	3586.912	1593.208
Prob>F	4.11E-05	4.01E-05	1.57E-05	7.34E-06	2.48E-05

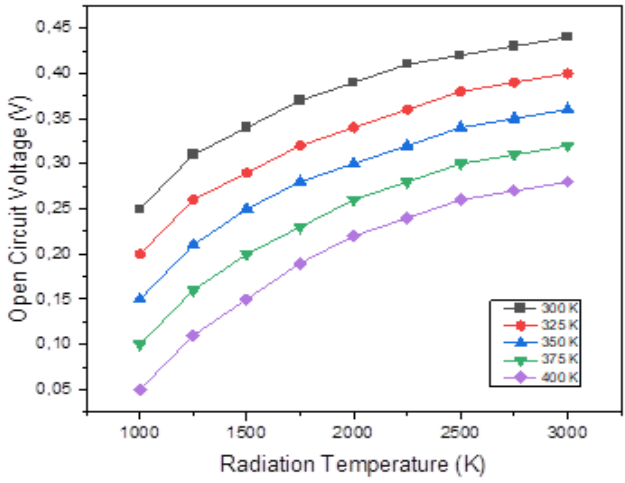


Figure 6: Temperature-dependent Variation of Open Circuit Voltage (V) Values Obtained in Real (Lossy) Analysis

Table 9 shows that the highest temperature dependent variation of filling factor value has been 78.77% at the 3000 K radiation temperature in the Real (Lossy) analysis. Table 10 and Figure 7 show the statistical results of temperature-dependent variation of filling factor (%) values obtained in real analysis. In the statistical calculations, in Table 9, it was calculated that the error rate at 300 K was the lowest. It was found to be 99.99% related to 3000 K radiation temperature.

Table 9: Temperature Dependent Variation of Filling Factor (%) Values Obtained in Real Analysis

Cell temperature Radiation temperature	300 K	325 K	350 K	375 K	400 K
1000 K	69.46	63.34	55.47	45.50	35.92
1250 K	72.88	68.22	62.43	55.22	46.53
1500 K	74.75	70.83	66.07	60.24	53.57
1750 K	75.89	72.30	68.30	63.45	57.61
2000 K	76.90	73.68	69.89	65.36	60.27
2250 K	77.41	74.40	70.84	66.96	62.33
2500 K	77.83	75.20	71.80	68.16	63.84
2750 K	78.30	75.69	72.64	69.08	64.89
3000 K	**78.77**	76.13	73.07	69.84	66.05

Table 10: Statistical Results of Temperature Dependent Variation of Filling Factor (%) Values Obtained in Real Analysis

Cell temperature	300 K	325 K	350 K	375 K	400 K
Number of points	9	9	9	9	9
Residual sum of residual	0.02184	0.03345	0.03597	0.02746	0.07083
R-Square (COD)	0.99977	0.99976	0.99986	0.99995	0.99991
Adj. R-square	0.99992	0.99936	0.99964	0.99986	0.99976
Sum of squares	72.80465	139.84884	264.87025	505.06917	795.65546
Mean square	14.56093	27.96977	52.97405	101.01383	159.13109
F value	2000.0765	2508.3901	4417.9727	11037.49	6740.2909
Prob>F	1.76E-05	1.26E-05	5.37E-06	1.36E-06	2.85E-06

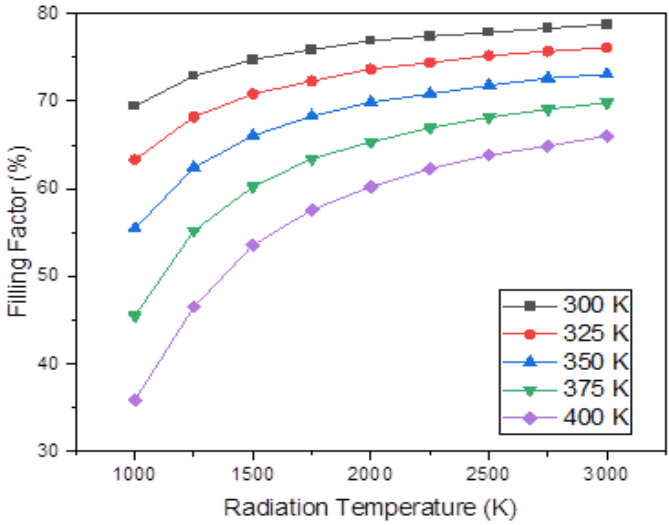


Figure 7: Temperature Dependent Variation of Filling Factor (%) in Real Analysis

Table 11 shows that the highest temperature dependent change of short circuit current value has been 151.90 A/m^2 at the 3000 K radiation temperature in the Real (Lossy) analysis. Table 12 and Figure 8 show the statistical results of temperature-dependent change of short circuit current (A/m^2) values obtained in real analysis. In the statistical calculations, in Table 12, it was calculated that the error rate at 400 K was the lowest. It was found to be 99.99% related to 3000 K radiation temperature.

Table 11. Temperature Dependent Change of Short Circuit Current (A/m^2) Values Obtained in Real Analysis

Cell temperature Radiation temperature	300 K	325 K	350 K	375 K	400 K
1000 K	0.10	0.11	0.12	0.13	0.14
1250 K	0.74	0.79	0.84	0.90	0.96
1500 K	2.94	3.09	3.25	3.42	3.59
1750 K	8.18	8.51	8.86	9.22	9.60
2000 K	18.17	18.73	19.44	20.08	20.76
2250 K	34.71	35.70	36.72	37.77	38.85
2500 K	59.57	61.03	62.53	64.07	65.63
2750 K	94.47	96.49	98.54	100.64	102.78
3000 K	141.05	143.69	146.38	149.12	151.90

Table 12: Temperature Dependent Change of Short Circuit Current (A/m^2) Values Obtained in Real Analysis

Cell temperature	300 K	325 K	350 K	375 K	400 K
Number of points	9	9	9	9	9
Residual sum of residual	2.80E-04	0.00255	3.24E-04	5.48E-04	2.44E-04
R-Square (COD)	0.99991	0.99976	0.99986	0.99995	0.99998
Adj. R-square	0.99976	0.99936	0.99964	0.99986	0.99992
Sum of squares	19584.91	20331.14	21097.97	21898.05	22724.08
Mean square	3916.9828	4066.2279	4219.5954	4379.6114	4544.8177
F value	4.19E+07	4.79E+07	3.90E+07	2.39E+07	5.58E+07
Prob>F	5.82E-12	1.50E-10	6.48E-12	1.35E-11	3.79E-12

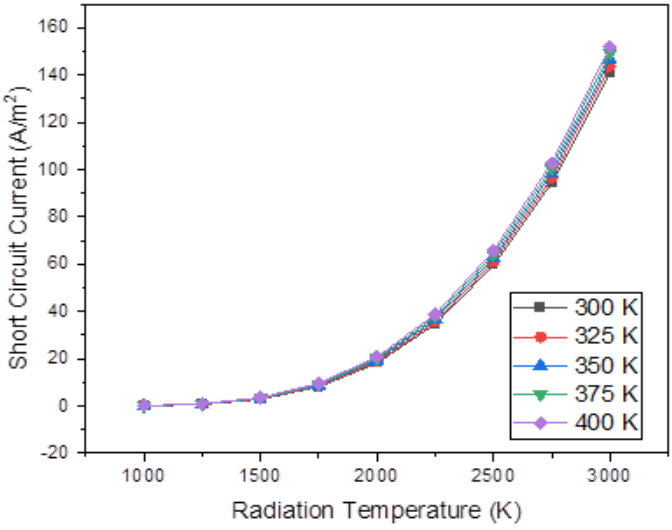


Figure 8: Temperature Dependent Change of Short Circuit Current (A/m^2) Values Obtained in Real Analysis

CONCLUSIONS

The usage areas of GaSb cells in Turkey are quite limited and theoretical studies are generally carried out. For this reason, besides the experimental and real application comparisons mentioned above, it is of great importance to specify the points to be considered during the installation of the system. The TPV system installation in our study was carried out within the scope of international standards and occupational health and safety. Not only national standards for system installation, but also seen that the experimental installation can be established within the framework of international standards accepted in this field. In addition, for researchers who plan to work in the field of thermophotovoltaics, guidance was provided on the installation of experimental setup. This system applied on high temperature GaSb cell was theoretically and really analyzed and compared in this study. In addition, statistical calculations were made for both analyzes using OriginPro software and the accuracy of the experiments was proved by obtaining the correlation covering the whole system.

This system applied on high temperature GaSb cell was theoretically and really analyzed and compared in this study. In addition, statistical calculations were made for both analyzes using OriginPro software and the accuracy of the experiments was proved by obtaining the correlation covering the whole system. The results obtained are as follows:

- While the optimum energy efficiency is 33.15% because of the theoretical modeling. The optimum energy efficiency obtained because of the real analysis is 21.57%. This difference happened as a result of lossless calculations under ideal conditions.
- The maximum energy efficiency is 33.15% at 2250 K radiation temperature. The minimum energy efficiency is 24.02% at 1000 K radiation temperature in theoretical analysis.
- When theoretical analysis is examined, as the tension rises, the current density drops. The lowest filling factor is 71.00% while the highest filling factor is 79.39%.
- The short circuit current reduces as the cell's temperature rises. As cell temperature increases, energy efficiency also decreases. As the cell's temperature drops, energy efficiency rises. The band gap closes as the cell's temperature rises, reducing the TPV cell's open circuit voltage.

Furthermore, higher cell temperature reduces filling factor and efficiency.

- According to the theoretical analysis, the maximum open circuit voltage was 0.46 V at 3000 K radiation temperature. However, this value dropped to 0.44 V at this temperature for the highest open circuit voltage.
- The short circuit current was 206.53 A/m^2 in the theoretical analysis at the highest radiation temperature of 3000 K, however it was only 151.90 A/m^2 in the real analysis.
- When the filling factor was examined, the maximum value in the theoretical analysis was 79.39%, however this value reduced to 78.77% in the real analysis.
- In the statistical calculations made with the OriginPro software, a correlation of 99.99% accuracy was obtained at the cell temperature of 300 K and the radiation temperature of 2500 K for real analysis. In the theoretical analysis, the same ratio was obtained at a cell temperature of 300 K and a radiation temperature of 2250 K.
- In general, it is shown that the real analyses' values are a little bit lower than the theoretical data. This is because the losses were not considered in the theoretical study. According to the real analysis, the thermophotovoltaic system may contribute to the present electricity production with an efficiency of about 21.57%.

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