POLİTEKNİK DERGİSİ

JOURNAL of POLYTECHNIC

ISSN: 1302-0900 (PRINT), ISSN: 2147-9429 (ONLINE)
URL: http://dergipark.org.tr/politeknik

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Bu makaleye şu şekilde atıfta bulunabilirsiniz(To cite to this article): İşyarlar B., Menlik T., "Evaluation of applicability of thermophotovoltaic system in combi boiler", ***Politeknik Dergisi***, 23(2): 581-586, (2020).

Erişim linki (To link to this article): http://dergipark.org.tr/politeknik/archive

DOI: 10.2339/politeknik.631730

Evaluation of Applicability of Thermophotovoltaic System in Combi Boiler

Araştırma Makalesi / Research Article

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(Geliş/Received : 10.05.2019 ; Kabul/Accepted : 23.07.2019)

ABSTRACT

In this study, thermophotovoltaic (TPV) system components are examined and introduced, and theoretically, it is given information about the applicability of the system in a combi boiler. The latest developments in the components of the TPV system, heat source, emitter, filter and TPV cell, are explained. Also, the study state how the TPV system should be integrated into a combi boiler. It is estimated that the TPV system integrated into the combi boiler can produce 36.96 kWh per month in the case that it has 2% electrical efficiency. The study is stated that the higher TPV system electric power output can be achieved if the emitter, the filter and the TPV cell are matched in harmony with each other in the combi boiler, the distances of these components and the emitter-filter dimensions are arranged. Thus, a standard family in Turkey can be supplied a certain amount of monthly energy demand. Also, it is explained in the study the issues that should be taken into consideration when this system is integrated into the combi boiler.

Keywords: Thermophotovoltaic, combi boiler, electrical generation.

1. INTRODUCTION

In today's world, fossil fuels are widely used. Unless there is a change in the policies followed, it is clear that these fuels will be depleted in a short period for reasons such as technological developments and population growth. In 2018, 37.3% of Turkey's electricity generation was obtained from coal, 29.8% from natural gas, 19.8% from hydropower, 6.6% from wind, 2.6% from solar energy, 2.5% from geothermal and 1.4% from other sources [1]. Turkey imports 99.3% of its natural gas demand [2]. To use the imported natural gas more efficiently, it is more appropriate to design natural gas-consuming devices following this purpose.

In Turkey, combi boilers are widely used as the individual heating system. The aim of this study is theoretically to show that the thermophotovoltaic system can be integrated into a combi boiler. In this way, while heating a house during the winter months, the electricity demand of the house can also be supplied.

2. THERMOPHOTOVOLTAIC SYSTEM

Thermophotovoltaic systems are systems that convert heat energy into electricity. The TPV system consists of four main components to convert heat energy into electricity. These components; heat source, emitter, filter and TPV cell [3-5]. The components of the TPV system in figure 1 are shown [6, 7].

2.1. Heat Source

In TPV systems, any heat source with the operating temperature above 1000 °C can be used. In the literature, TPV systems operating at low temperatures are also available [5, 8-10]. For example, Xu has prepared a dissertation on the thermal change of a system consisting of an emitter with an emitter temperature ranging from 76.85 °C to 276.85 °C and a photovoltaic (PV) material [11].

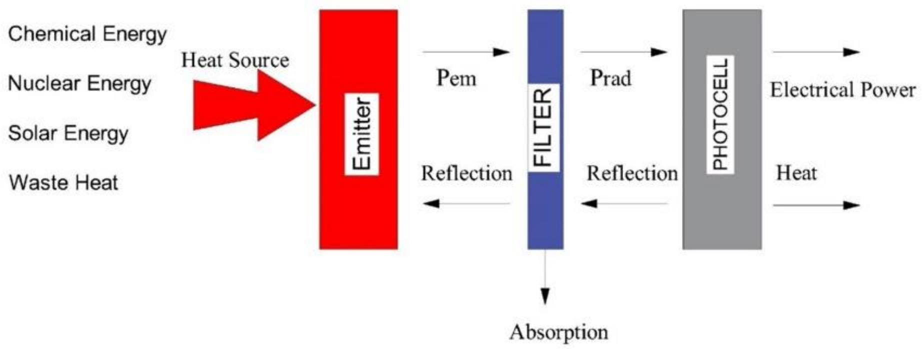

Figure 1. The components of the TPV system (P_{em}: Radiant power of emitter, P_{rad}: Radiation power)

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2.2. Emitter

It is not appropriate to apply the electromagnetic radiation from a heat source directly to the TPV cell. Instead of applying electromagnetic radiation directly, the use of a selective emitter is beneficial for several reasons. The heat sources used in TPV systems have a temperature in the range of 1000-1500 °C. Also, TPV cells can absorb photons with only energy above the band gap (E_g: band gap energy). Because of this, only a certain part of the radiation radiated can be converted into electrical energy. A selective emitter must be used to increase system efficiency. For example, a black body at 1526.85 °C radiates only 6% of the radiation power of the silicon TPV cell having a band gap energy of 1.1 eV. One way to increase the radiation power above the band gap energy is to use a selective emitter that ideally radiates these photons above the band gap energy. But photons with low band gap energy cause an increase in the temperature of the TPV cell continuously. An increase in the temperature of TPV cell reduces cell efficiency. Emitters applied in TPV systems are also used to prevent unnecessary absorption, which reduces cell efficiency. Emitters carry out this process by preventing the introduction of sub-band gap photons into the TPV cell. Reflective coatings and filters are used to reflect sub-band gap photons into the emitter. Some of these photons that are reflected in the emitter by reflectors and filters are again absorbed by the emitter. Then, it is radiated again these photons having energies above the band gap of TPV cell [7, 12].

Increasing the TPV system efficiency according to TPV cell selection depends on the ideal temperature of the emitter. To increase the electrical efficiency of the system, the power density of the system must also be increased. One way to increase power density is to increase the emitter temperature. The other way is the size of the emitter surface area. The surface area of the emitter should be optimized to maximize power density [13-15]. The ideal temperature of the emitter for different cells of the TPV is given in table 1 below [13].

Table 1. The ideal temperature of the emitter for different cells of TPV

TPV cell	E_g (eV)	The ideal temperature of the emitter (K)
InGaAs	0.55	1285
GaSb	0.72	1682
Si	1.1	2570

Selective emitters are generally made of ceramic oxides. The elements commonly used as emitters are ytterbium, erbium, holmium and neodymium. In TPV systems, it is used in broad-band emitters like silicon carbide [12,16]. Many emitters, both selective and broad-band, have been investigated for TPV systems. Photonic crystals and materials, solidified Al_2O_3-$Yb_3Al_5O_{12}$ eutectics, new meta-materials such as anti-reflection coated tungsten, enable to the strengthening of the selective emitters and precisely to be controlled the properties of electromagnetic waves [17-20].

2.3. Filter

Most of the radiated photons have lower energies than the band gap of the TPV cell for broad-band radiation. Therefore, these photons with low energy cannot be converted into electricity by the TPV cell. To increase TPV system efficiency and prevent unnecessary heating of the TPV cell, it is necessary to send these photons back to the emitter. System efficiency with a suitable filter may be increased. Many different filters are used in the TPV cells. These are interference, plasma, photonic crystal, tandem filters [6, 7, 16, 17, 19, 21].

2.4. Thermophotovoltaic Cells

TPV cell is the component that converts photons sent by the emitter into electricity. Using a semiconductor material with a low band gap energy is crucial for electricity generating because it can absorb more photons [8]. For this reason, it is more appropriate to choose a semiconductor material with low band gap energy in TPV systems. The cells used in TPV systems are described below.

Silicon (Si): If the silicon with a band range energy of 1.1 eV is matched with a selective emitter that indicates the same radiation as ytterbium oxide (Yb_2O_3), it is suitable for use in TPV systems. Si cells are relatively inexpensive compared to low-band cells such as gallium antimonide (GaSb). Also, a significant advantage of these cells is that they are commercially available in large quantities. [4, 6, 7, 22].

Germanium (Ge): Germanium is a band gap energy of 0.66 eV. TPV system with the Germanium cell, when matched with erbium oxide (Er_2O_3) emitter, provides higher spectral efficiency than the spectral efficiency which would be attained by matching a silicon cell with Yb_2O_3 emitter [6, 7].

Silicon germanium (SiGe): SiGe is used as a double compound in TPV systems. This compound allows adjusting the band gap energy depending on germanium content [6,7].

Gallium antimonide (GaSb): GaSb cell with a band gap energy of 0.72 eV and the ability to operate under high radiation intensity can be preferred in TPV systems. On the other hand, GaSb cells have a high cost and should be considered in the use of TPV systems of these cells as they cause toxicity at high temperatures [7, 23].

In TPV systems, binary compound materials such as gallium arsenide (GaAs), indium phosphite (InP) and indium arsenide (InAs) are used, and also ternary or quaternary compound materials such as InGaAsSb, AlGaAsSb, InAsSb, InGaSb, InGaAs, $CuInGaSe_2$ and InAsSbP [3, 5-7].

3. THEORETICAL INVESTIGATION OF THERMOPHOTOVOLTAIC SYSTEM IN COMBI BOILER

One of the most important advantages of a thermophotovoltaic system is that the components forming the system can be easily applied to the combustion chamber. As a result of the application of this system to the combustion chamber, TPV systems having a power density between 300 mW/cm^2 and about 1 W/cm^2 are included in the literature. Another advantage of a thermophotovoltaic system is that there are no mechanical components in the system. For this reason, the sounds and vibrations of this system are very low [3, 7, 24].

In recent years, many research groups have made prototypes related to the thermophotovoltaic system. The efficiency of TPV systems of these groups varies between 0.04% and 24%. Prototypes of these groups can produce electricity ranging from 10 W to 3 kW [25]. A research group in Canmet made the TPV prototype for residential heating. This prototype has a GaSb cell. This system is deemed to be suitable for residential heating because of the high power density [18].

The study indicating the comparison of TPV system electricity generation with conventional electricity generation methods is given in [26]. In terms of the cost of electricity generation, the analyzed system suggests that it could be competitive with conventional electricity generation methods in 2003.

There are many combi boiler products in the market, and these products are designed and manufactured in different heat power. The combi boilers need different amounts of electric energy to perform their functions. For example, a combi boiler with 12-20 kW thermal output power needs to 100-120 W of electrical energy to perform its function. Therefore, less than 1% TPV system efficiency is sufficient for such a combi boiler needing to 100-120 W electrical energy [7, 27].

The combi boiler examined in this study is the Buderus Logamax Plus GB062. Characteristics of the Buderus Logamax Plus GB062 combi boiler are given in table 2 [28]. The combi boilers with a maximum heating power of 24 kW in the individual apartments are widely used in Turkey. The Buderus Logamax Plus GB062 brand with a maximum heating power of 24 kW was preferred in this study as it is easily accessible on the official website. It should be noted that the TPV system can be integrated into the Buderus Logamax Plus GB062 combi boiler stated in the study, as well as other combi boilers with a maximum heating power of 24 kW.

The performance results of the TPV boiler system are given in table 3 [27]. When the table is examined, it is seen that there is 158 W electrical power output and 1.86% electrical efficiency with 8.5 kW fuel input. According to these results, the electrical energy required by the Buderus Logamax Plus GB062 combi boiler even in the minimum heating power can be achieved with 1.86% efficiency. Furthermore, it is understood that 246.4 W electric power output and 2% electrical efficiency is obtained with 12.3 kW fuel input when the table is examined again. Consequently, it is foreseen that the combi boiler will provide a higher power density at the maximum heating power and therefore higher electrical power output.

Table 2. Characteristics of the Buderus Logamax Plus GB062 combi boiler

Technical characteristics	
Minimum heating power (80/60ºC)	6.7 kW
Maximum heating power (80/60ºC)	23 kW
Minimum heating power (40/30ºC)	7.3 kW
Maximum heating power (40/30ºC)	24.1 kW

The monthly electricity demand of a family in terms of the minimum standard of living in Turkey is about 230.4 kWh [29]. When table 3 is considered, it is produced 0.2464 kW electricity with a TPV system which has 2% electrical efficiency. Assuming that this combi boiler functions 5 hours a day (during the heating season), the monthly electricity generation of the TPV system integrated into the combi boiler is 0.2464 x 5 x 30 = 36.96 kWh. This combi boiler can supply a certain amount of the electrical energy demanded by a family in Turkey. In this case, it can be supplied with higher electricity generation when provided more heating power. Following this purpose, the desired electric power output can be increased if the emitter, the filter and the TPV cell are appropriately matched to each other, the distances of

Table 3. The performance results of the TPV boiler system

Fuel input power (kW)	Electric power output (W)	Electrical efficiency of the system (%)
8.5	158.0	1.86
10.1	175.2	1.73
11.7	209.6	1.79
12.3	246.4	2.00

these components and the dimensions of the emitter-filter are properly adjusted. Thus, a family's monthly electric energy demand in Turkey will be supplied.

A combustion chamber design is important for the TPV system applied in a combi boiler. In existing combi boilers, combustion chambers are designed as a cylindrical or rectangular prism. To integrate the TPV system into these combustion chambers and to provide the desired efficiency of this system, the system components must be well designed. Also, it should be noted that the efficiency of TPV cells decreases with increasing temperature. Therefore, TPV cells placed in the combustion chamber must be properly cooled to provide the desired efficiency [30]. An example to cool the TPV cell is given in Figure 2 [25]. However, it will not be appropriate to use this cooling system in the combi boilers. There are two reasons for this. The first reason; it is necessary to continuously use cooling water from an external source. The second reason; the structure of existing combi boilers needs to be changed to implement the system. Therefore, it will not be economical to choose this cooling method.

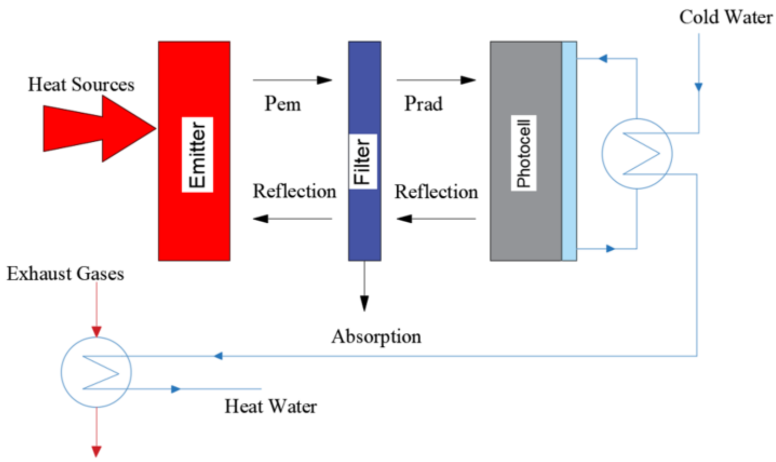

Figure 2. Cooling of the TPV cell

In this study, the TPV system design applied to the combi boiler which has the rectangular combustion chamber is shown in Figure 3. The TPV system can be integrated by optimizing as shown in Figure 3 without any changes to the combustion chamber of the combi boiler. Also, the reflectors are placed on the upper and lower parts of the TPV system integrated into the combi boiler. The use of these reflectors may be useful for more photon absorption [31].

5. DISCUSSION AND CONCLUSIONS

Combi boilers are widely used for an individual heating system the housings in Turkey. When taken into account the size of the combi boiler sector in Turkey and that this sector will continue to grow, it should be considered that TPV systems may have large market potential in the combi boilers.

The application of the present TPV system in a combi boiler has high cost and low system efficiency. However, these problems can be overcome by appropriately matching the emitter-filter-TPV cell as well as the low-cost system components and by optimizing the distances

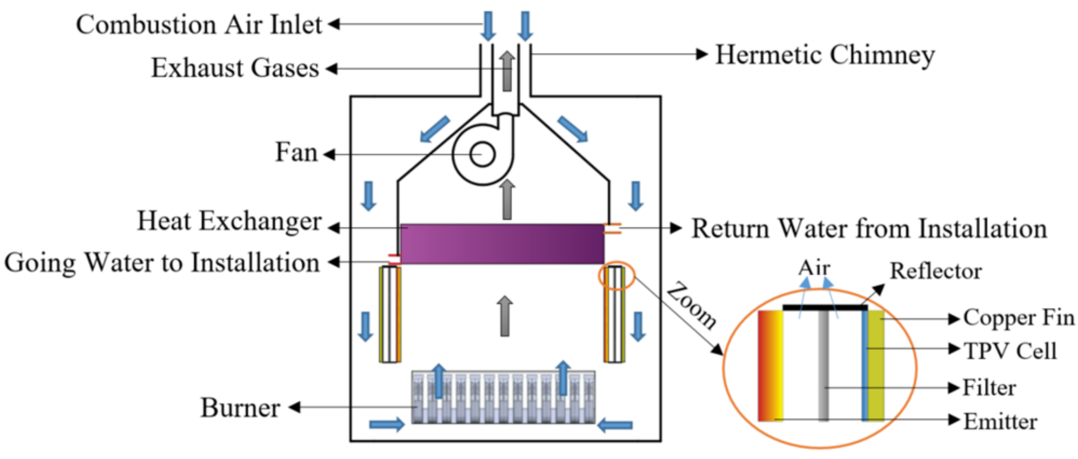

Figure 3. The drawing of the TPV system integrated into the combi boiler

of these matched system components with each other and with the heat source. By arranging the thickness of the TPV system components and their distances, and by using different TPV system components, it should be attempted to obtain the highest TPV system efficiency at a reasonable cost.

In an attempt to reduce the cost of a TPV system in the combi boiler, a TPV system with a silicon cell can be used. Because silicon cells are already used in PV cells to generate electricity from solar energy. In other words the usage area is wide. However, it cannot absorb low energy photons because silicon has a wide band gap compared to other semiconductors used TPV cells. Therefore, its efficiency may be low compared to TPV cells with a lower band gap. If it is desired to have more efficiency of the TPV system, costly TPV cells with a lower-band gap such as GaSb, Ge, and InGaAsSb should be used.

According to After Sales Services Regulation of the Republic of Turkey Ministry of Trade, the service life of a combi boiler is 15 years [32]. However, the service life of a combi boiler given in the regulation may change due to factors such as its operating time, whether its periodic maintenance is performed during the year or not. It should be taken into account that the service life of a combi boiler having a TPV system may be changed because it requires a continuous operation to provide the above-mentioned electricity generation.

In addition to these, it should be investigated how the performance of the heat exchanger (see Fig. 3) will be affected by the addition of the TPV system to the combustion chamber. If the TPV system is properly integrated into the combi boiler with a maximum heating power of 24 kW, this combi boiler will supply 36.96 kWh part of a family's monthly electricity demand in Turkey.

Given the above-mentioned information, the TPV system can be applied properly to the combi boiler stated in this study.

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