Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2019) 27: 2938 – 2946

doi:10.3906/elk-1801-202

# Design of energy recovery systems: thermoelectric combi boiler generator and power analysis

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**Received:** 22.01.2018 • **Accepted/Published Online:** 29.03.2019 • **Final Version:** 26.07.2019

**Abstract:** Gas-fired combi boilers are commonly used to meet the need for heating and general-purpose hot water in developing countries. In this study, a thermoelectric combi boiler generator (TECBG) was developed. When the boiler is operated, cold water flows through the cold surface of TECBG and enters the boiler. In the same way, it is used by flows through the hot surface of TECBG in heated water. Thus, temperature difference occurrs between the surfaces of TECBG. The temperature difference is converted into electrical energy by Seebeck effect. The proposed system was implemented on a domestic combi boiler. The maximum temperature difference between the designed system and the TECBG surfaces was recorded as 48 $^{\circ}$C. 12V9AH battery was used to charge through a DC-DC charge regulator. About 14.28 Wh power was generated by the TECBG when the temperature difference of the TECBG, current, and voltage were 48 $^{\circ}$C, 1.18 A, and 13.8 V, respectively. The electrical energy consumed by the combi boiler was measured as 115 Wh. Although the obtained energy is not quite high, it is an important gain in terms of energy efficiency because according to data recorded in Turkey, there are 15 million combi boiler users. Assuming that a single heating boiler runs for 4 h, it is possible to produce 306.6 GWh/year, derived from 14.28 Wh $\times$ 4 h $\times$ 365 days $\times$ 15,000,000 heating boiler. The proposed system provides significant advantages and thus can decrease power consumption.

**Key words:** Thermoelectric generator, combi boiler, energy recovery, power generation

## 1. Introduction

With the increasing population and the developing industry, the need for energy is increasing day by day. As the fossil fuels like oil and coal used for generating such energy damage the environment, accelerate global warming, and are being depleted, humanity is compelled to make progress towards renewable energy sources [1]. Today, the efforts to obtain energy through renewable energy resources like wind, solar, biomass, hydraulic, geothermal, and hydrogen are rapidly continuing [2].

The energy efficiency is important as well as the energy production. The energy efficiency is an important step in the protection of the Earth. Reducing the amount of energy consumed without affecting the economy and reducing welfare is the easiest way to achieve energy efficiency. Increasing energy efficiency means less fossil fuel use, less greenhouse gas emission, and a cleaner environment, which constitutes a justification for energy efficiency. Sustainable growth makes important contribution to the national economy and ultimately to the global economy. Within the framework of a strategy plan for the UK, the benefits of energy efficiency are listed as follows.

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- Accelerating growth and providing employment,
- Savings for home and business
- Creating a more sustainable and secure energy system,
- Providing a cost-effective climate change targets,
- Reduction of energy imports.

Energy efficiency is achieved by reducing the amount of energy consumed without shaking the economic balances. The ways to make it possible include avoiding the losses that occur during the energy consumption, recycling the wastes, and reducing the consumption by increasing efficiency through technological innovation. Systems that produce their own electricity have a high-energy efficiency potential and energy is the most effective way of ensuring energy security. The development of such devices are important for energy efficiency both for industrial and household customers. The efforts have been concentrated on the conversion of various types of energy emerging during human life activities into electrical energy. When the existing studies are reviewed, it is seen that thermoelectric modules (TEM) have been used to generate electric energy by using hot–cold balance. However, these studies have not been applied in the technologies we use in everyday life. The studies are made mostly for the geothermal power generation in industry. Thermoelectric generators are used in the conversion of geothermal energy into electrical energy. As thermoelectric generators use waste heat as input source, they are completely environmentally friendly in electricity generation and allow efficient use of energy [3].

Thermoelectric generators (TEGs) have important advantages, such as no moving parts, long-term maintenance requirements, long life, reliability, and convert the heat energy directly into electrical energy. Although its efficiency is low, it is the most important alternative to convert heat energy into electrical energy [4]. In recent years, as the demand for sustainable and maintenance-free sensor types and their networks increases, the energy needs of sensors are becoming more prominent. Most sensors in the market require batteries or power supplies. For this reason, the development of automated sensors without any batteries is a priority. TEGs are an important alternative in the development of such sensors [5]. It is possible to obtain electric energy from geothermal sources by using TEGs. It is possible to obtain electricity by using the temperature differences between hot spring water at 70 to 100 $^{\circ}$C and the mains water. In recent years, geothermal TEG works have been accelerated thanks to better quality materials [6].

Obtaining electricity by using TEG in the residential generation focuses on two different systems. The first one is the conversion of the thermal energy for heating or heating water, usually in the solid fuel boilers, without the need for electricity to work. The second one is conversion of thermal energy into electrical energy, which is obtained from the gas-fired heating systems that heats by using electrical energy. At the combustion surfaces of solid fuel boilers, TEG works have been made by using the empty surfaces at the flue exits [7–11]. In a TEG study on flue gas, the probability of thermoelectric power generation was investigated by using waste flue gas in small-scale pellet boilers. The effect of this operation on the heating boiler is investigated and it was found to have no adverse effect on the operation and the efficient burning of the fuel [11]. The TEG studies on natural gas systems have generally oriented towards the use of the generated electricity by the system that produces it. Thus, it is aimed to create autonomous gas fuel systems that can operate on their own without the need for any power source. In this sense, studies have been conducted on central thermoelectric residential heating systems, which produce their own electricity, and a TEG with a power generation capacity of 550 W generating its own energy from thermal energy has been developed and sufficient power for all the subcomponents of the system has been produced [12–14].

The studies on heating boilers have concentrated on integration of high-effiency TEGs between the combustion region and the water channels. The aim is to obtain a high temperature difference between the surfaces of TEGs [13]. In another study on condensed heating boilers, a numerical analysis was performed to determine the most efficient position of TEG in the heat cells in the heating boiler. It was found that with the energy produced, the boiler can work independently from the network [14]. In another study, the residential heating systems have been studied and the $Bi_2Te_3$-based TEG has been designed. The TEG placed between the heat cells has a power generation capacity of approximately 36 W. Thirty percent of the energy consumed is recovered [15].

Literature studies show that there are not enough studies on recovery from widely used heating boilers. The researches on this matter show that it is very hard to place the designed systems in the existing heating boilers. However, it is possible to use this new system by integrating it into recently produced heating boilers. The heating systems in the heating boilers do not only consist of heat cells and combustion chambers. The heated water and flue gas incidental to combustion contains a considerable amount of thermal energy. According to HVAC data as of 2016, there are 15 million combi boiler users in Turkey. This study aims to design a TEG that can be easily integrated into existing combi boilers and can produce the energy required by the heating boiler using the temperature difference between the hot water and the mains water. Because of the low temperatures compared to previous studies, 20 high-efficient ALTEC-GM-1 brand and coded modules were used. The modules used to have a power generation capacity of 7 W in temperature difference of 100 °C. The electrical and thermal parameters were measured by integrating it into the designed TECBG system.

## 2. Materials and methods

### 2.1. Thermoelectric

Thermoelectric modules have three effects called Seebeck, Peltier, and Thomson. Seebeck effect is the basis of TEG modules. The Seebeck effect was discovered by Thomas Seebeck in 1821. The Seebeck effect is the conversion of heat directly into electricity at the junction of different types of wire. When the two different electrical conductors or semiconductors are kept at different temperatures, the system results in the creation of electrical potential. The TEG modules consist of a combination of p-n pairs (Figure 1).

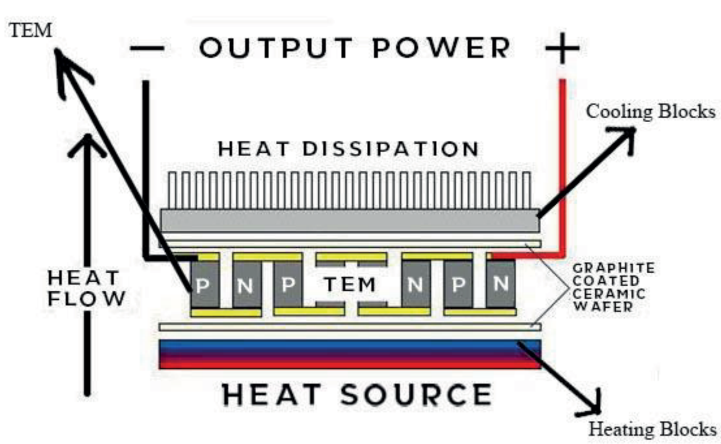


**Figure 1**. Construction of TEM.

### 2.2. The use of thermoelectric modules as generator

The use of a TEM as generator mode is shown Figure 2. A TEG consists of three parts; heating and cooling blocks and a TEM. If there is a temperature difference between the surfaces, heat is transferred from the hot surface to the cold surface because according to the second law of thermodynamics, heat always flows from the hot surface to the cold surface. In this case, a DC voltage drop occurs at the TEG terminals. If a load is connected to the output of the TEG for current to flow through the load, an electrical power is obtained at the output of TEG. The electrical power P and the current obtained from the TEG depend on the temperature difference $\Delta$T, the properties of the semiconductor materials and the values of exteSrnal load resistance $R_L$ [16].

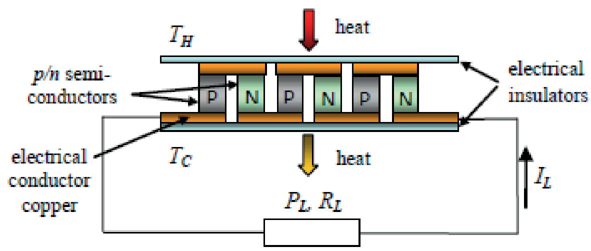


**Figure 2**. A TEM in the generator mode.

### 2.3. Efficiency of thermoelectric generators

The efficiency of a TEG is given by following equation:

$$\eta = \frac{\text{Energy supplied to the load}}{\text{Heat energy absorbed at hot junction}} = \frac{P_I}{P_O} \tag{1}$$

where $P_I$ is input power and $P_O$ is output power [17]. A semiconductor power measurement used in a TEG is given as the figure of merit (ZT). The semiconductor power measurement of the figure of merit ZT is given by:

$$ZT = \frac{\propto^2}{KR_{in}}T \tag{2}$$

where T is the temperature (Kelvin), $\alpha$ the Seebeck coefficient (V/°C), K is the thermal conductivity (W/mK), and Rin is the electrical resistance. The efficiency is given as a function of the ZT and in the temperature difference $\Delta$T in the TEG. In recent years, ZT of the produced TEGs is higher and there has been a significant increase in efficiency [18].

The TEG efficiency is also expressed in terms Carnot efficiency. Carnot efficiency is given by the following equation:

$$\eta_{\max}\frac{T_H - T_C}{T_H}\frac{\sqrt{1+ZT_{ave}}-1}{\sqrt{1+ZT_{ave}}+\frac{T_C}{T_H}} \tag{3}$$

where Tave is avarage TEG temperature ($T_H$ + $T_C$) / 2, $T_H$ is the TEG hot side temperature, and $T_C$ is the TEG cold side temperature.

The highest value of voltage produced by the TEG is when the TEGs ends open. Open circuit voltage $V_{OC}$ is given by the following equation:

$$V_{OC} = N(\alpha_p - \alpha_n)(T_H - T_C) \tag{4}$$

where the TEG open circuit voltage $V_{OC}$ is directly proportional to the number of thermoelements N, the temperature difference $\Delta T$ between hot side and cold side temperature of the TEG, p-type $\alpha p$ and n-type $\alpha n$ material Seebeck cofficients [19].

### 2.4. Output characteristic of thermoelectric generators

The output power of TEG is expressed as follows:

$$P_L = I_L V_L = I_L \left[\alpha\Delta T - I_L R_{in}\right] = \alpha^2 \Delta T^2 \frac{R_L}{\left(R_{in}+R_L\right)^2} \tag{5}$$

where $P_L$ is the electrical power (W), $V_L$ voltage (V), $I_L$ current of the load (A), Rin the internal resistance, and $R_L$ is the load resistance $(\Omega)$. The maximum power ($P_{Lmax}$) is when connected load resistance ($R_L$) and internal resistance ($R_{in}$) of the TEG are equal ($R_L = R_{in}$).

$$P_{Lmax} = \frac{\alpha^2 \Delta T^2}{4R_{in}} \tag{6}$$

### 2.5. Experimental setup

The designed TECBG is shown in Figure 3. In order to determine the performance of TECBG in real working conditions, an experimental system was set up by connecting it to a working boiler installation as shown in Figure 4. The water that enters into the combi boiler to heat after the hot tap water is opened first passes through the cold aluminum plates forming the TECBG and is heated in the combi boiler by using natural gas. The dimensions of aluminum plates were chosen according to TEG modules. Ten TEGs were placed on the surface area. The inside of the plates is equipped with water channels for water flows. Three plates with a surface area of 25.5 × 10.2 cm were used.

The physical connection enabling this circulation was realized by using the valves. The TECBG can be deactivated manually by opening and closing the valves when required.

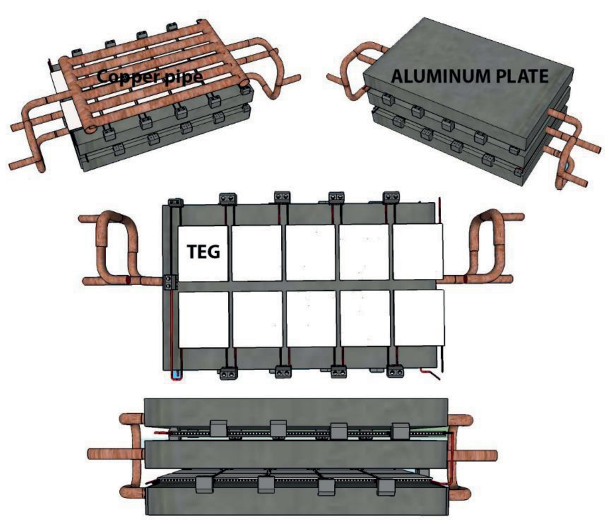


**Figure 3**. Construction of TECBG.

**Figure 4**. Connection of the combi generator and the experimental setup.

The experimental setup consists of Demirdoküm brand condensed combi boiler TECBG, Prodigit brand electronic load, and Lutron brand power analyzer and measurement system. Mobile phone charging system and battery charging system were used to test the charged operation of TECBG (Figure 4).

## 3. Results and discussion

### 3.1. Performance analysis

Before the experiments, the system was opened up to the end of the hot water tap and measured at 3.75 L/min. While the ambient temperature was 14 °C, the mains water temperature was measured as 17 °C using a mercury thermometer. In Figure 5, the output power (Po) curve has been given depending on the hot surface temperature ($T_H$) of the TECBG. $T_H$ has been raised from 17 to 69 °C. In this status an output power variation curve from 0 to 14.28 W has been obtained from the TECBG.

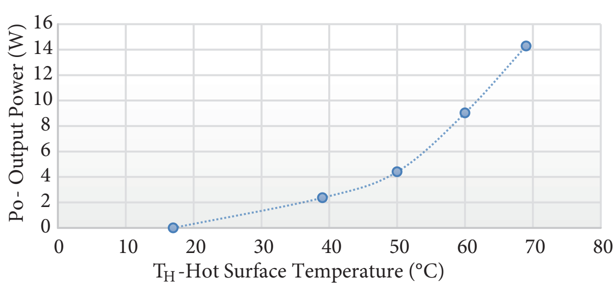


**Figure 5**. Po curve as a function of $T_H$.

Thermoelectric generators have parameters related to temperature. The provided catalog information is given for a constant temperature or temperature difference. However, the parameters of the modules change when the system is running. The most important parameter for TEGs to transfer maximum power to the load is internal resistances ($R_{in}$). In order to obtain the value of TECBG's internal resistance at different temperatures, the combi boiler thermostat was set to maximum. The maximum temperature difference was obtained when $T_H$ = 69 °C and $T_C$ = 21 °C. In this case $\Delta T$ = 48 °C and the unloaded voltage at TECBG ends was measured as 17.9 V. Initially, the running water temperature was 17 °C, when the system was running it reached 21 °C with an increase of 4 °C. In the catalogs related to thermoelectric modules, the internal resistances of the modules are usually given according to the hot side temperature. The internal resistance of TECBG was measured and recorded for temperatures of 20, 30, 40, 50, 60, and 69 °C in order to determine the change of internal resistance according to $T_H$ of TECBG. Values are given graphically in Figure 6. When $T_H$ was 69 °C, the internal resistance was measured as 15.3 Ω. This value is the $R_{in}$ value in the maximum power expression given in Eq. 6. In order to obtain maximum power transfer at the obtained temperature difference, $R_L = R_{in}$ should hold.

In this analysis, power analysis was done depending on the load resistance ($R_L$). The value of the load resistance is increased when ΔT is at the maximum level. Output power was calculated by measuring current and voltage. The obtained results are shown in Figure 7.

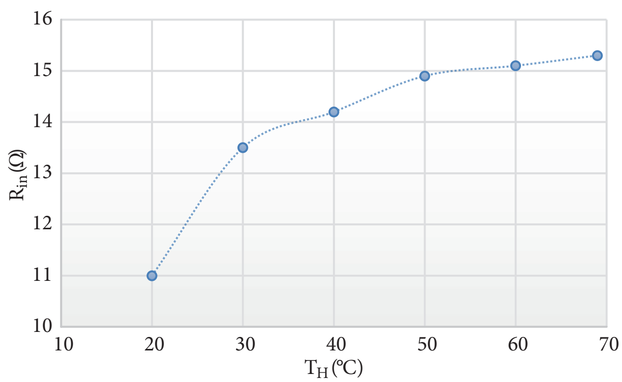


**Figure 6**. $T_H$-$R_{in}$ curve.

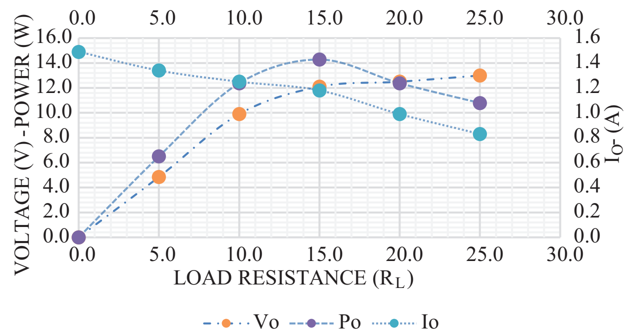


**Figure 7**. $R_L$-$I_O$, $R_L$-$V_O$, and $R_L$-$P_O$ curves.

In this analysis, the load resistance ($R_L$) was set to 15.3 Ω. ($V_O$) and ($I_O$) values were measured depending on ΔT and output power ($P_O$) was calculated. The results of analysis are given in Figure 8.

When the temperature difference between the surface of the TECBG was changed from 20 to 48 °C, the voltage ($V_O$) and the current ($I_O$) was measured as from 4.3 to 12.1 V and from 0.6 to 1.2 A, respectively, and then the output power ($P_O$) was calculated as from 2.4 to 14.3 W.

This efficiency calculation is based on the electrical power the combi boiler consumes. A recovery rate of 12.42% was achieved when the power of the boiler was calculated as 230 V × 0.5 A = 115 W when fully powered. The results of analysis are given in Figure 9.

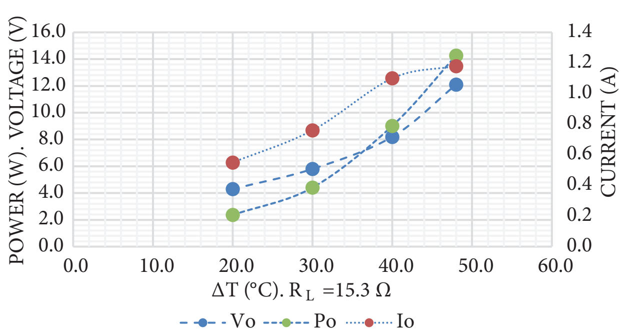


**Figure 8**. ΔT -$I_O$, ΔT -$V_O$, and ΔT -$P_O$ curves.

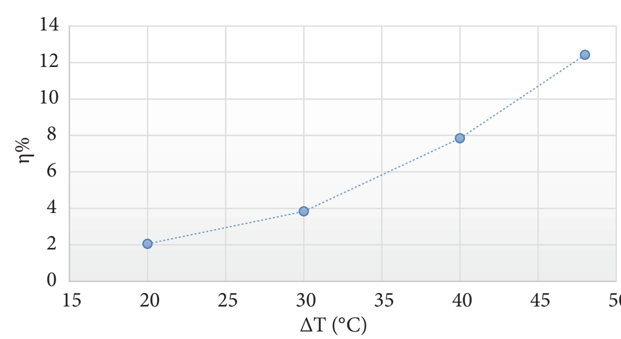


**Figure 9**. The conversion efficiency curve as a function of ΔT.

As a result, the designed thermoelectric combi boiler is an important technology in terms of energy saving and recovery. By improving the properties of the thermoelectric materials, it is possible to design higher-yield recovery devices.

## 4. Conclusion

This article contains a performance analysis of a TECBG that can be easily assembled into combi boilers. While the combi boiler was running, the hot surface temperature ($T_H$) and cold surface temperature ($T_C$), the output voltage (Vo), and output current (Io) of the TECBG were measured and the output power was calculated. Power measurements were made when a battery was being charged. As a result of the analysis, the following results were obtained.

1. In the tests made with the designed boiler generator, when the boiler was used in the maximum temperature setting, a temperature difference of 48 °C was obtained. When $T_H$ was 69 °C, the open circuit voltage was measured as 17.9 V.

2. When the electronic load was set to 15.3 Ω to provide maximum power transfer; 12.1 V voltage, 1.18 A current was measured and 14.28 W power was obtained.

Based on the power consumed (115 W) electrically, it was calculated that the thermoelectric generator recovers this power by 12.42%. The TEG output is connected to the battery charge regulator. It was used to charge an uninterruptible power supply battery (cgbb-12V 9a). The charge current and voltage were measured as 0.6 A and 13.8 V, respectively.

It is seen that it is possible to achieve energy saving or autonomous combination by using this power obtained by thermoelectric method. Sensitivity in energy saving, especially in recent years, has reduced the need for energy as well as the risk of environmental risk factors. Energy saving devices are important in the framework of "the cheapest energy is saved energy" policy. With this generator, it is possible to recover 12.42% of the power consumed.

### Acknowledgments

This work was supported by Gaziosmanpaşa University Scientific Research Projects Unit project number 2014/111. I thank Prof. Dr. Raşit AHISKA for his support.

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